The GESDA 2023 Science Breakthrough Radar

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

In partnership with: FONDATION POUR GENÈVE

2023

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A Letter from the Chairmen:

Citizens of the world deserve more than belated debates such as those surrounding AI and ChatGPT

Anticipation in the service of science and diplomacy is not only our raison d'être but also one of our most prominent distinguishing features.

By projecting ourselves into the future, we aim to detect in advance the major scientific and technological advances that will change the ways we live, think, and behave. Consequently, society should have the time it needs to prepare for these changes with the best possible transitions.

With this in mind we can learn a lot from the current debates raging over this year's rapid adoption of artificial intelligence, which is changing almost every industry and starting to impact society in ways we are just beginning to understand. Many of these debates are occurring in a rushed atmosphere that is hardly conducive to the emergence of constructive long-term solutions.

To this end, our 2023 edition provides you with an update signed by Professor Emmanuel Abbé, Chair of Mathematical Data Science at EPFL, re-exploring possible developments in 5-, 10- and 25-years' time in light of the dazzling developments of the past year. They will fuel the political segment of this year's Geneva Science and Diplomacy Anticipation Summit organised by GESDA.

This segment is organised jointly by the Swiss Minister of Foreign Affairs and GESDA Foundation. It was inaugurated last year by the President of the Swiss Confederation and ministers from the United Arab Emirates, Singapore, Mexico, Morocco, and Estonia. The main theme this year, Augmented Thought in the Age of AI and Quantum, extends to the need to develop new types of partnerships between humans and machines.

We've also tackled topics in our 2023 Radar that will undoubtedly provoke similar and possibly even more intense debates in the future in key thematic areas such as Neurotechnology, the Future of Peace and War, and the Human Right to Science. These topics build upon the three main deep dives that we've presented in this third edition of our trademark GESDA Science Breakthrough Radar®.

Questions regarding interventional neurotechnologies were explored in depth at a dedicated seminar in Villars, Switzerland under the guidance of Professor Michael Hengartner, chair of the GESDA Academic Forum and the Science Breakthrough Radar Advisory Board, and Professor Patrick Aebischer, neuroscientist and vice-chairman of the GESDA Board of Directors. The spring 2023 symposium gathered 30 top-level scientists from around the world.

We used the same approach in our discussions on the Future of Peace and War during two seminars in Geneva and New York. These were organised in collaboration with the Director of the Geneva Center for Science Policy (GCSP) Thomas Greminger and Professor Jean-Marie Guéhenno from Columbia University's School of International and Public Affairs in New York.

The Human Right to Science was discussed by 40 scientific experts at Geneva's Brocher Foundation in the fall of 2022 under the guidance of Professor Samantha Besson, Collège de France & University of Fribourg; Professor Bartha Knoppers, Chair of the Center of Genomics and Policy at McGill University; Professor Jean-Dominique Vassalli, a former Rector of the University of Geneva, and Dr Gérard Escher, a neuroscientist and senior advisor to GESDA.

This year's Radar contains five global science frontier issues, 42 emerging topics, 27 breakthrough briefs, 324 possible science breakthroughs at 5, 10, and 25 years, and 9 invited contributions on new topics.

We warmly thank the 1,542 scientists who contributed to the Radar's first three editions.

GESDA is more than a think tank; it's also a do tank. We seek international public-private partnerships and projects that lead to proposals of solutions for current and future technological challenges. Once they are approved by all shareholders, we work to transform these solutions into opportunities that open and widen the circle of beneficiaries from scientific and technological advances.

In that spirit we are pleased to present a project that is ready for launch: The Open Quantum Institute (OQI), which is the most advanced component of GESDA's Quantum for All Initiative.

It represents the culmination of efforts that can be traced to the first edition of our Radar, published in 2021. Our emphasis on the importance of future quantum technology — and the need to ensure that everyone can benefit from it — continued through our two subsequent Geneva Science and Diplomacy Anticipation Summits. We designed the project in 2022 along with 40 partners from the academic, diplomatic, business and philanthropy sectors. Over the last 12 months we developed it further to be ready for launch. In this year's Radar, we report on the one-year incubation of the Open Quantum Institute.

Quantum technology, combined with advanced artificial intelligence, will have a huge impact on our society. We still don't know when and whether this technology will live up to all of the expectations placed on it, but experience teaches us that technological progress — like the unexpected proliferation of AI tools this year — can slow to a crawl then suddenly pick up the pace and sprint faster than we anticipate. So, let's all work together on developing potential use cases early enough to be prepared for when this new technological dimension becomes a reality!

As a young foundation created in 2019, GESDA quickly hit its stride. We greatly look forward to continuing to pursue our ambitious objectives. We offer the Radar as a vital tool for navigating this era's acceleration of scientific and technological advances – and for transforming them into universal solutions for the great many global challenges we face now and in the future, for the benefit of mankind and the planet earth.

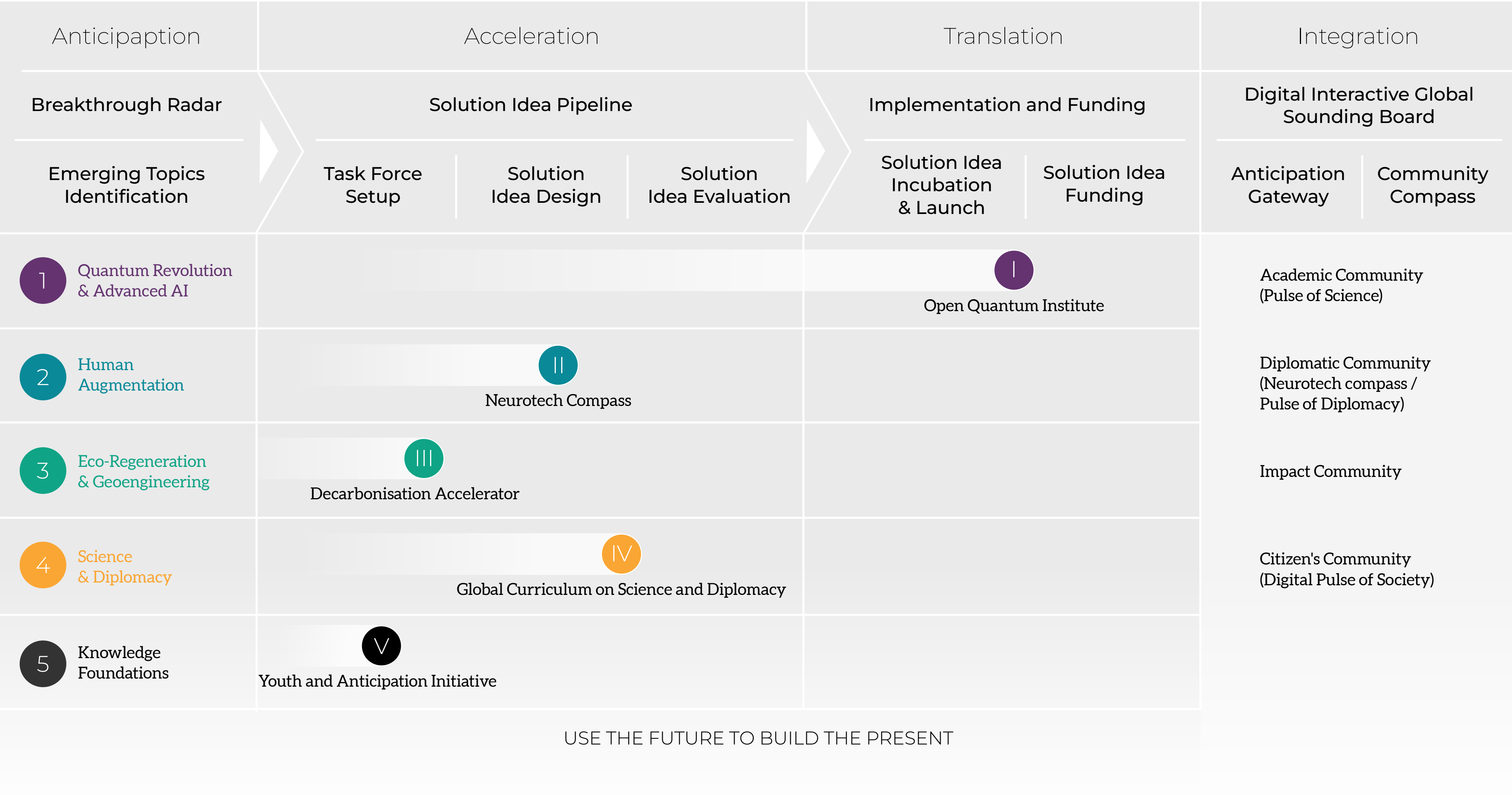
Peter Brabeck-Letmathe
Chairman of the Board of Directors
GESDA

Patrick Aebischer
Vice-Chairman of the Board of Directors
GESDA

Geneva, Switzerland, October 2023

GESDA in a nutshell:

Anticipatory Situation Room pipeline of activities



GESDA's three questions

GESDA's vision is to "Use the future to build the present" by bringing together different communities in order to jointly anticipate scientific and technological advancements and, based on these anticipations, develop inclusive and global solutions for a sustainable future.

Three fundamental questions guide GESDA's mission and drive our work:

Who are we, as humans?

What does it meant to be human in the era of robots, gene editing and augmented reality?

How can we all live together?

What technology can be deployed to help reduce inequality, improve well-being and foster inclusive development?

How can we ensure the well-being of humankind and the sustainable future of our planet?

How can we supply the world population with the necessary food and energy while regenerating our planet?

Science Diplomacy:

An opportunity for Geneva

The Fondation pour Genève works tirelessly to promote Geneva's attractiveness and reputation as a city that is open to the world, partnering closely with authorities at every level: federal, cantonal, and municipal. Above all, our Foundation teams up with multilateral institutions that drive effective global governance and which have been instrumental in designing solutions to the most pressing challenges facing our world for generations.

When it comes to scientific innovations such as artificial intelligence, geo-engineering, or the quantum revolution, we cannot afford to be mere bystanders — we must act. Regulation and anticipation are crucial and demand our full attention.

With the establishment of GESDA, supported by our Federal and Cantonal authorities and the support of our Foundation, Switzerland got it right. It anticipated that in upcoming years, certain scientific advances will be questioned and raise new global governance challenges. The Radar, updated each year by GESDA, enables us to be aware and up to date with scientific breakthroughs before they affect our societies. It helps us reap the benefits for the common good. The interplay between GESDA's anticipatory approach and the dynamic Geneva ecosystem propels this Radar into the realm of pivotal tools for International Geneva.

We are convinced that there is no substitute to a revitalised multilateralism that functions as a cohesive force, fostering collaboration and promoting anticipation, as we have recently underlined in our in-depth study “International Geneva State of Affairs 2023, Science diplomacy: An opportunity for Geneva”, published by the Observatory of the Fondation pour Genève.

The Fondation pour Genève has been a keen supporter of this innovative key project, born in International Geneva, that shapes scientific diplomacy to address global issues.

Marc Pictet
Président, Fondation pour Genève

Geneva, Switzerland, October 2023

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.

Visit: radar.gesda.global

Scientific Platform	6 Deep Dives for 2023	27 Breakthrough Briefs 3 new topics added for 2023 in **bold**	11 Invited Contributions 9 new topics added for 2023 in **bold**
1 Quantum Revolution & Advanced AI	**The Opportunities of Quantum & Advanced AI:** GESDA Pulse of Diplomacy	1.1 Advanced AI 1.2 Quantum Revolution **1.3 Unconventional Computing** 1.4 Augmented Reality 1.5 Collective Intelligence	• The Technology Opportunity for Digital Humanities and Art • AI for Science • **Robotics & Embodied AI** • **Digital History**
2 Human Augmentation	**Neuro-augmentation**	2.1 Cognitive Enhancement 2.2 Human Applications of Genetic Engineering 2.3 Healthspan Extension 2.4 Consciousness Augmentation 2.5 Organoids 2.6 Future Therapeutics	• **Future of Psychedelics Medicine**
3 Eco-Regeneration & Geoengineering		3.1 Decarbonisation **3.2 Earth Systems Modelling** 3.3 Future Food Systems 3.4 Space Resources 3.5 Ocean Stewardship 3.5 Solar Radiation Modification 3.7 Infectious Diseases	• **Deep-sea Mining** • **Fungal Pandemics**
4 Science & Diplomacy		4.1 Science-based Diplomacy 4.2 Advances in Science Diplomacy **4.3 Prediction, Foresight and Futures Literacy** 4.4 Democracy-Affirming Technologies	• **Misperceptions, Meta-perception and Conflict** • **Understanding the Reality of Multilateral Relations with Computational Diplomacy**
5 Knowledge Foundations	**The Future of People, Society and the Planet(s)** – GESDA Philosophical Lens **The Future of Peace and War** – GESDA Geopolitical Lens **The Human Right to Science** – GESDA Science Lens **GESDA Digital Pulse of Society:** People's expectations about science throughout the world	5.1 Complex Systems Science 5.2 Future of Education 5.3 Future Economics, Trade and Globalisation 5.4 The Science of the Origins of Life 5.5 Synthetic Biology	• **Future of Archaeology** • **Responsible Anticipation and Self-Regulation**

Facts and Figures

The GESDA Science Breakthrough Radar has **5** scientific platforms, **42** emerging topics and **324** breakthroughs at 5, 10 and 25 years.

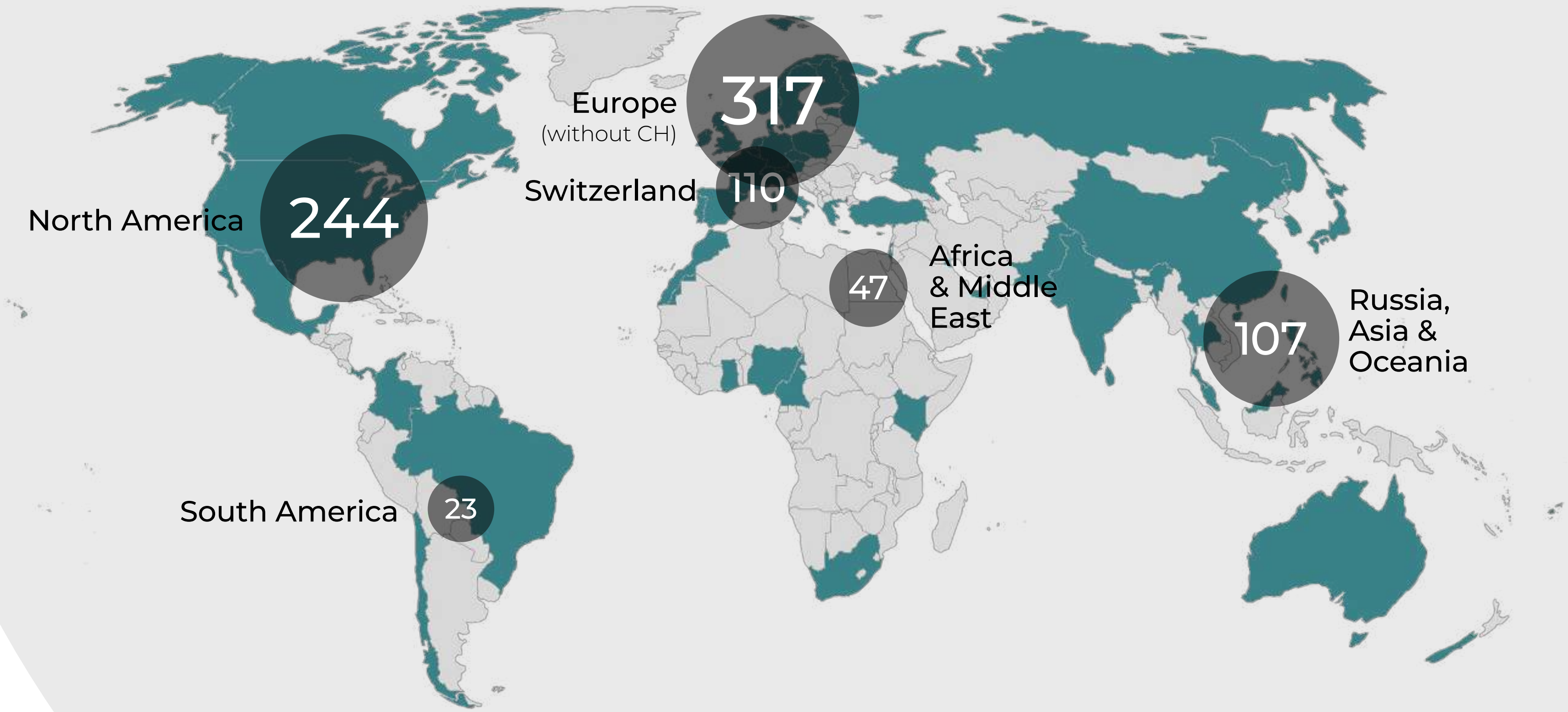
It contains **3** lenses on philosophy, geopolitics and science on **3** fundamental questions about the future of humanity, debated by **84** scholars from philosophy, social sciences, humanities and geopolitics. More than **1,500** scientists have been involved since the creation of the Radar In 2021:

- **543** scientists from **53** countries in 2021
- **774** scientists from **70** countries in 2022
- **848** scientists from **73** countries in 2023

It includes analysis of over **10 million** social media posts and **1.3 million** articles in mainstream media in order to take the pulse of society on what people do and say about emerging scientific topics on the five scientific platforms.

It presents the Open Quantum Institute 2023 incubation report, GESDA's first Solution Idea ready for pilot implementation.

Countries of host institutions of contributing scholars via surveys, workshops and interviews: 848



Introductory Essay of the Radar Advisory Board

The Value of Science Anticipation

Prof. Michael O. Hengartner
Chair GESDA Academic Forum,
President ETH-Domain

Sir Peter David Gluckman
President of the International Science Council (ISC) and 2014-2021 Foundation Chair of the Advisory Group of the International Network of Government Science Advice (INGSA)

Prof. Michel Mayor
Prof. Emeritus at University of Geneva and 2019 Physics Nobel Prize Co-Laureate. Representative of the Fondation pour Genève

Prof. Marie-Laure Salles
Director of the Graduate Institute of International and Development Studies

Prof. Michael Schaepman
President University of Zurich

With the rapid pace of science and technology breakthroughs driving significant changes to our world and how we live in it, having agency over our future has never been more important. One of the tools we have for this is anticipation, through which we can use our assessment of what might happen in the future to direct action in the present. GESDA's aim is to enable this process of anticipation by laying out in its Science Breakthrough Radar the possibilities scientists envisage for the future. In this way, GESDA aims to act as an honest broker between the scientific community and society to encourage open debates about how we wish to shape the future and what opportunities for action can be taken today.

The natural inclination of human beings is to believe that the future is already baked into the present, and is to a large extent inevitable. For example, when we consider any discrete set of data over time, we usually focus on its incremental nature, whether that's demographic trends, economic growth (or decline) or climate change. We are notoriously bad at understanding and acting in prevision of unexpected events or large-scale disruptions.

Anticipation, by contrast, gives us the capacity to treat the future as a range of possibilities, empowering us to make decisions in the present which can influence what happens in the future. The original Greek meaning of the word "anticipate", prolambano, conveys the martial idea to "seize beforehand". From its earliest meaning, therefore, anticipation has combined a forward-looking attitude with the potential for action, occurring when consideration of the future is used as a deciding factor in the present. Through this ability to act, we are freed to consider aspects of our future being malleable to creative forces and novelty — as long as suitable enabling conditions are given today.

The need to anticipate and therefore use the future to build the present is more important than ever. In only a few decades, science 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. And there is no indication that the rate of change is going to slow down: the rapid pace of scientific and technological development in the time we are living today may well be more disruptive than anything humans have experienced in the past. As with the Industrial Revolution — but at a much faster rate — this science and technology revolution is affecting virtually every field of human activity. Take, for example, the data and artificial intelligence revolution. It permeates all sectors of science, our economies and our social and personal interactions — and the quantum revolution has the potential to exponentially accelerate these changes. Similarly, advances in neuroscience, combined with developments in AI, are reshaping how we understand, read and act on our own brains, and science and technological advances are already redistributing and reshaping world power, globally.

To live in a fair and sustainable society in the future means that there is an imperative to anticipate — but how? For GESDA, anticipation translates as the capacity to open the horizon of possibilities as a basis to debate and forge global and inclusive coalitions before science and technology breakthroughs are deployed without full consideration of possible impacts — or advantageous developments are not deployed at all. The wide coverage of anticipated advances detailed in the GESDA Science Breakthrough Radar® assist in providing the enabling conditions for action to happen in the present to build towards a more intentional future.

Anticipation itself comes with its own inherent risks. For example, the risk we take by producing information about what has not yet happened (and may indeed never happen) is that we reduce the complexity of future developments, and in doing so, risk reducing the inherent openness of the future. Likewise, the act of practicing anticipation conjures a strong temptation to consider the future as "factual" and "perceptible", where projections of the future are a matter of picking up signals that can function as evidence. It is also tempting to consider the future through the lens of our own values, and what we perceive as "right" or "wrong". This obscures our understanding of what is possible or probable by our own hopes or fears.

However, the purpose of anticipation in the GESDA Science Breakthrough Radar® is, in the spirit of honest brokering, to open up the space of possibilities for the international community, setting up enabling conditions for action, and refraining as much as possible from projecting our own normative or preferred visions of the future. By practicing anticipation, we strive to embrace complexity and uncertainty and resist the urge to clear pathways towards an imagined future. It is impossible to consdier the process of science and technology development in isolation from the complexities involved in why and how it is being developed, or how it will be deployed once a breakthrough has occurred. The GESDA Science Breakthrough Radar® is therefore consciously restricted to anticipating just the science and technology breakthroughs themselves, in order to anticipate how science and technology might develop given their current trajectories. We use the term "science anticipation" to emphasise both the need to anticipate science and technology, and also 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 as an engine of anticipation — the capacity to make disciplined inquiries into those things we need to know but do not know yet; i.e., the capacity to systematically increase the horizons of one's current knowledge.

Science anticipation comes with its own challenges, notably around diversity, inclusivity and equity. While foresight has become more common and global, it directs its focus to established sets of concerns and fails to address issues shared by under-represented regions and communities. The GESDA Science Breakthrough Radar® is not immune to this tendency and GESDA is working to improve the inclusion of communities and geographies that are currently underrepresented in its processes.

We are certain that the world will continue its rapid change in the coming decades — and science and technology will certainly be among the drivers of that change. The GESDA Science Breakthrough Radar® uses science anticipation as a means of preparing us for the changes to come, setting the enabling conditions for the global community to act — or in the words of the ancient Greeks, to take the ground in time ––and design ambitious initiatives inclusive of all relevant communities in the spirit of an effective and renewed multilateralism.

To this extent, the Radar is set up to function as a neutral broker and convener between the different disciplines, sectors and communities involved in science and technology and its governance. Our ambition is to develop it as a dynamic, living tool: as it matures, we will further grow the community of contributors, including members of scientific communities in parts of the world and sectors of society that are still under-represented. The debates and opportunities sections in the Radar provide the first bridges into the broader territories where those advances can be contextualised and decisions taken, in partnership with the relevant actors and communities.

Anticipation rooted in science is needed now more than ever, but this anticipation needs to happen in an inclusive and transparent manner if we are to engender societal trust in the pursuit of science and its benefits.

Executive Summary

Welcome to the 2023 GESDA Science Breakthrough Radar®. Here we showcase the most consequential developments in emerging science and technology in 2023 and anticipate how these fields will develop over the next 5, 10 and 25 years. This third edition of the Radar builds on the 2021 and 2022 editions by providing updates in a rolling mode and in-depth reviews of current and future trends, as well as the addition of new emerging topics, reflecting the collective work of more than 1,500 scientists. For the first time, we also provide scientific deep dives into three major themes of the 2023 GESDA Science Breakthrough Radar: neuro-augmentation, the future of peace and war, and the human right to science.

These deep dives provide a detailed exploration of three important topics related to human agency at a time when recent breakthroughs in artificial intelligence, ideological fragmentation between nations and accelerating climate change raise questions about what it means to be human, how we can all live together in society and how we can ensure the well-being of humankind and the sustainable future of our planet. Year on year, it is becoming ever more important to anticipate future breakthroughs and emerging trends in all areas of science, including natural, social and engineering sciences as well as the humanities and philosophy. This knowledge and understanding can then be used to nurture and broker honest debates between scientists, diplomats, citizens, philanthropists and the private sector, in order to steer humanity towards the most desirable outcomes.

New to the 2023 edition of the GESDA Science Breakthrough Radar®:

- The expansion of the Radar scientific community to 1,542 contributors since 2021, including 58 lead authors and scientific moderators, 265 workshop participants and 525 survey respondents.
- An increase in the number of emerging science and technology topics from 37 in 2022 to 42 in 2023.
- An in-depth scientific deep dive on the future of neuro-augmentation, the result of a GESDA symposium of world-leading experts convened in Villars in 2023.
- Three expanded lenses through which to consider the anticipated breakthroughs and trends within the Radar:

1. **The Philosophical Lens: The Future of People, Society and the Planet(s)**
   An update of previous work on the three fundamental GESDA questions by a collective of 18 leading philosophers.
2. **The Geopolitical Lens: The Future of Peace and War**
   The outcome of two workshops held in Geneva and New York in collaboration with the Geneva Centre for Security Policy (GCSP) and the School of International and Public Affairs (SIPA) at Columbia University.
3. **The Science Lens: The Human Right to Science**
   The result of a three-day GESDA symposium at Fondation Brocher in Geneva.

- The development of the Actions and Debates section of the Radar into a full, in-depth analysis of mainstream and social media to take the pulse of society across all topics covered in the 2023 Radar, and its evolution since the creation of the radar.
- An exclusive presentation of the one-year incubation phase report of the Open Quantum Institute (OQI), GESDA's most advanced Solution Idea, in the Opportunities chapter of the Radar.
- A summary of the GESDA 2022 Summit proceedings in the Opportunities section of the Radar.

Taking the Pulse of Science: our core approach to anticipating scientific breakthroughs

Our core approach to anticipating scientific breakthroughs remains the same: based on the inputs of the Academic Forum and with the high-level guidance of the Advisory Board, we collate the opinions of researchers working in key emerging areas of science through targeted interviews, high-level workshops and a global survey. From their input, the academic moderators — top scientists acting as curators in their respective fields of expertise and members of the GESDA Academic Forum — select the topics with the highest potential implications for people, society and the planet.

These are then presented in the GESDA Science Breakthrough Radar® as carefully vetted, scientifically peer-reviewed anticipatory Breakthrough Briefs. The Briefs analyse the key developments in the selected emerging topics, and anticipate how these topics will evolve in 5, 10 and 25 years.

Alongside the Breakthrough Briefs, we also include Invited Contributions from leading experts giving their perspective on emerging nascent fields, with a view that these topics may evolve into full Breakthrough Briefs in future editions of the Radar.

Using the GESDA Science Breakthrough Radar®

Each of the briefs on emerging topics in the **Trends section** of the Radar — **Taking the Pulse of Science** — provides a reliable overview of the status of science and technology in relation to that topic for an interested but non-specialist audience. These briefs are also freely available via the GESDA Science Breakthrough Radar® online platform at https://radar.gesda.global, where they are enriched with key references from the scientific literature and landmark reports.

We have explored three lenses through which the anticipated breakthroughs in the Radar may be interpreted. These are:

- The Philosophical Lens: The Future of People, Society and the Planet(s)
- The Geopolitical Lens: The Future of Peace and War
- The Science Lens: The Human Right to Science
- For each of these lenses, scientists, social scientists, philosophers and political practitioners take the Trends described in the Radar as a basis and provide an analysis on how these advancements may shape the future of philosophy, geopolitics, and science.

Moving beyond science and research, the **Actions & Debates** section of the Radar — **Taking the Pulse of Society** — analyses mainstream and social media to assess public opinion, sentiment and actions with respect to the emerging topics described in the Trends section. Using this data, we can visualise how sentiment and action around each topic is taking shape and changing, providing insights into society's interests and priorities for the future.

Our **Opportunities** section — **Taking the Pulse of Diplomacy** — consolidates the information from the Trends and Actions and Debates sections to identify opportunities for multilateral action. It provides a high-level analysis of the main outcomes of the yearly high-level Geneva Science and Diplomacy Anticipation Summit, showcasing how leaders from science, diplomacy, impact and citizen communities consider the implication of the emerging topics presented in the Radar. Finally, the Open Quantum Institute Incubation Report illustrates how GESDA's anticipatory methodology results in concrete initiatives for the common good.

2023 Highlights: Deep Dives

New for the Trends section of the 2023 edition of the GESDA Science Breakthrough Radar® is a set of scientific deep dives into specific aspects of the Radar, which provide expert evaluations of key themes. Each deep dive was developed through a series of workshops and symposia where global experts and practitioners in scientific research, social sciences, political sciences, philosophy and law came together to discuss the most pressing issues facing science and society highlighted by the GESDA Science Breakthrough Radar.

Going beyond the views of experts and subject specialists, in the **Actions and Debates** section we have also analysed public discourse and its evolution in both mainstream and social media, using AI to identify and process millions of media articles to bring a significantly updated Pulse of Society to the Radar in 2023.

And as a highlight in the **Opportunities** section, we have included in this year's Radar the exclusive presentation of the incubation report of GESDA's most mature solution idea, the Open Quantum Institute.

Villars High Level Anticipation Workshop:

2023 Villars High Level Anticipation Workshop: Deep Dive on Neuro-augmentation

Platform 2: Human Augmentation, page 72

Recent advances in fundamental neurosciences, neurotechnologies and brain-inspired computing have been staggering and are likely to accelerate in the years to come, opening the door to new interventions to cure neuro-degenerative diseases or augment our cognitive capacities.

For example, brain-monitoring devices, brain-machine interfaces, and other ways of reading and writing the electrical signals of the nervous system are on the cusp of wide adoption across society. Their ubiquity could change everything from workplace rights to what it means to be human. In parallel, advances in brain organoids, interspecies chimeras and work on genetically modified primates are encroaching on established ethical boundaries. Finally, it is conceivable that applying fundamental knowledge about how the human brain works to computing devices and robotics could one day lead to the emergence of new forms of consciousness.

At the inaugural GESDA Villars High-Level Anticipation Workshop, leaders from relevant disciplines met to discuss issues pertinent to the future of "neuro-augmentation". The participants outlined the current status of the science of neuro-augmentation and identified areas of immediate, mid-term and long-term impact and concern, and how this should drive the focus of diplomatic and ethics intervention. Topics discussed include the state of the art methods by which machines can read and write to the human brain today, as well as where these methods may take the field in the future; hybrid brain development based on human and animal tissues; the hardware and software of artificial cognition today and what this may look like in the future; ethical considerations for ourselves and other entities, and our ethical imperative to anticipate responsibly when it comes to research into neuro-augmentation technologies.

The three GESDA lenses:

GESDA Philosophical Lens: Deep Dive on The Future of People, Society and the Planet(s)

Platform 5: Knowledge Foundations, page 248

A panel of leading philosophers, convened by GESDA, developed and contributed their perspective on how the advances anticipated in the Radar will transform who we are as humans, how we live together as societies, and how we relate to the planet. For example, the possible development of conscious machines requires us to reflect on our purported uniqueness of being human, and which properties we may wish to actively preserve as the sole remit of human beings. Likewise, emerging digital technologies have the potential to directly target basic human social structures and practices at a fundamental level, from notions such as responsibility, trust, security, friendship and privacy through to democracy, justice and citizenship. Understanding how technology can instead be deployed to reduce inequality, improve well-being and foster inclusive development is a key challenge. Additionally, a key challenge posed by climate engineering technologies will be to consider the limits of how we perceive nature as a resource under our control in the context of anthropogenic environmental disruption. This work endeavours to bring in fundamental considerations on the future of humanity in order to open the space for solutions and alternative choices.

GESDA Geopolitical Lens: Deep Dive on The Future of Peace and War

Platform 5: Knowledge Foundations, page 256

Often resulting in violence or conflict, increasing tensions between countries and power blocks are often aggravated by climate change and competition in the field of digital technologies. Anticipation and foresight informed by an understanding of science and technology is therefore essential in the field of peace and war. Anticipation makes it possible to create and implement appropriate programmes and strategies to prevent or contain conflict, and to advance the more promising approaches to peace. Applying GESDA's anticipatory methodology to mapping the future of peace and war involves plotting social and political scientists' anticipations of the future. Unlike anticipating breakthroughs or new applications in the field of technology, foresight in the fields of social and political sciences entails more fragile projections with greater uncertainty, unanticipated tipping points and black swan events. In a series of two high-level workshops held in Geneva and New York in 2023, the three convening organisations — GESDA, the Geneva Centre for Security Policy (GCSP) and the School of International and Public Affairs (SIPA) at Columbia University — brought together experts in the field of peace and war to develop and apply a methodology for anticipating how advances in science and technology will influence the distribution of power in the next 10 to 25 years.

GESDA Science Lens: Deep Dive on The Human Right to Science

Platform 5: Knowledge Foundations, page 264

Article 27 of the Universal Declaration of Human Rights mentions the participation and the right to benefit from science. Article 15 of the International Covenant on Economic, Social and Cultural Rights places obligations on governments to encourage, facilitate and not to interfere with an individual's work as a scientist, except as demanded by ethical and legal standards. Often overlooked, the right to science advocates for the responsible development and use of scientific progress and its applications. The right to science is therefore a crucial tool for anticipating both the benefits and the harms of scientific progress and its application. The Brocher Expert Workshop on the Human Right to Science with a Focus on Health was convened by GESDA in 2022. In the resulting report, 29 leading scholars and experts from the fields of international and humanitarian law discuss how incorporating a human rights framework into the scientific process provides an opportunity for a collaborative, holistic, and inclusive approach that goes beyond the mere mitigation of risks and enables the responsible exploration of the opportunities offered by scientific and technological progress.

GESDA Pulses of Society and Diplomacy:

GESDA Digital Pulse of Society: Deep Dive on people's expectations about science throughout the world

Actions and Debates, page 275

Current and future breakthroughs in science and technology are already capturing the interest of a broad swathe of society, affecting how we see ourselves as human beings, our interactions and our relation to the planet. Understanding public sentiment towards current and future breakthroughs in science and technology is therefore crucial for understanding society's concerns for the future. Using artificial intelligence (AI) to analyse both mainstream media outlets and online social media platforms, we have provided an in-depth analysis of how much each of the topics in the Radar are talked about, how these topics link to conversations about other themes within and outside of the Radar, and how sentiment is changing towards these topics over time, for different geographies and demographics. Finally, we use our monitoring tool to discover what actions civil society is taking with relation to their concerns and interests about each topic, highlighting significant initiatives and actors that have emerged over the last year. This year, for the first time, we have also captured how society's opinions, sentiment and actions have evolved over the past year.

GESDA Pulse of Diplomacy: Deep Dive on The Opportunities of Quantum & Advanced AI

Scientific update on Advanced AI: Trends, page 30

Open Quantum Institute Incubation Report 2023: Opportunities, page 316

In 2023, the rapid incorporation of AI and advanced computing technologies into our everyday lives has been extraordinary. In this 2023 edition of the GESDA Science Breakthrough Radar®, we have renewed our anticipatory briefing on Advanced AI, and added a brand-new Brief on Unconventional Computing to describe advances in alternative computing technologies which are likely to one day surpass the capabilities of current state-of-the-art AI. Alongside these Briefs, two new invited contributions detail how AI is changing the way we think about the past, and how neuromorphic computing has the potential to develop robots with true "embodied" intelligence. But GESDA was not created to be solely a think-tank: it is also a “do-tank”. Starting from the robust scientifically vetted knowledge captured in the Radar, GESDA is committed to ideate and design solution ideas for effective multilateralism with its science diplomacy community, enabling it to act in anticipation of scientific breakthroughs.

The Open Quantum Institute (OQI) is the first initiative to be incubated by GESDA. This exclusive report details the development of the OQI from the scientific anticipation of quantum technologies to its inception as a validated solution idea for science diplomacy, first announced at the GESDA Summit 2022. It includes details on establishing the OQI as the “go-to” place for SDG applications of quantum computing, how it works with its partners to provide more inclusive access to quantum computers, how vital educational and training plans will be associated with the institute, and a proposal for shaping a multilateral governance enabling quantum computing to be leveraged for the SDGs. In addition, we describe how the engagement of a supportive community of stakeholders will co-create the OQI's unique value proposition, securing its value for a society where quantum technologies work for all, not the few.


AI

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Trends

Taking the Pulse of Science: The GESDA Science Breakthrough Radar®

The 2023 GESDA Science Breakthrough Radar® aims to identify emerging research and map major science advances at 5, 10 and 25 years. Those 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 GESDA Science Breakthrough Radar® focuses on what scientists in the world's most advanced laboratory say about future advances in their fields. It does not have the ambition at this stage to discuss the implications of these advances on society and diplomacy, nor does it take sides on whether the mentioned breakthroughs are desirable or not.

That said, anticipating the science in this 25-year timeframe can contribute to accelerating broad-based debates about the social and political implications, providing a basis for the collective identification of meaningful solutions to today's and tomorrow's most pressing challenges.

This section describes science trends that have been anticipated in 42 scientific emerging topics, covering a broad range of research areas in natural sciences, engineering sciences, social sciences and the humanities. Those 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 Geneva and the international community can play within it. The trends and related breakthroughs are updated on a rolling basis through constant engagement with the global academic 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

More than 1,542 scientists from 73 countries contributed through surveys, workshops, and interviews. Their insights were used to define the "anticipation potential" of those topics and to create comprehensive briefs that list 324 potential breakthroughs, providing a basis for further discussion.

The list of topics presented in this section is not exhaustive: it is a subset of areas where the GESDA Academic Forum believes relevant impactful breakthroughs will happen in the next 25 years. Invited contributions from leading scientists provide a glimpse into additional emerging topics that are not covered in depth in this version of the report, but will be expanded in future editions.

Because significant anticipatory work is also promoted by other key actors, and as science is progressing constantly, the briefs are extended by a collection of referenced reports and curated articles through the GESDA Best Reads. They are updated constantly through the digital platform showcasing the GESDA Science Breakthrough Radar®: https://radar.gesda.global

Anticipating what is happening in the world's laboratories is essential if, as a society, we are to have the knowledge and the tools to build the world that we want.

That is why GESDA has developed a methodology for capturing the anticipation potential of possible scientific breakthroughs, with findings summarised in the GESDA Science Breakthrough Radar® presented here. The methodology and research behind the Radar is laid out over the following pages, and is based on insight and data drawn directly from scholars working in key fields of scientific research covering GESDA's five frontier issues. It is a rolling assessment that will be updated year after year as our knowledge in those fields expands.

How to read the Radar

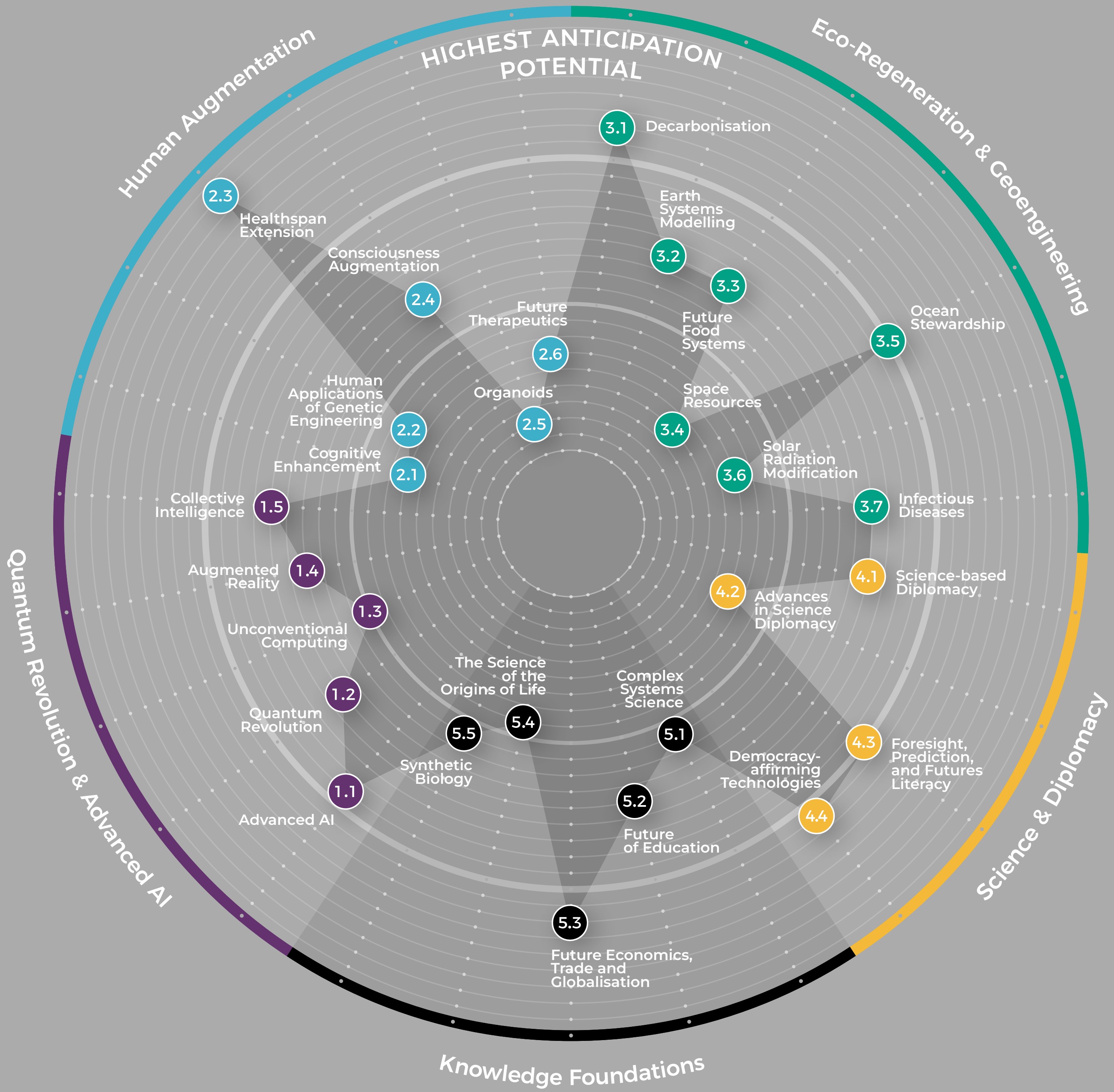
Our Radar screen measures and illustrates the "anticipation potential" of each of the scientific emerging topics. Each frontier issue is represented by one section of the Radar, and each scientific emerging topic by a dot. The farther the dot is from the centre of the radar screen, the higher the opportunity for the translation of the anticipatory effort into a positive outcome for humanity.
This anticipation potential enables comparison of developments in a wide diversity of fields, including advances in social sciences and humanities, and overcomes the common bias towards prioritising today's trends over longer-term but potentially more significant developments. By focusing our efforts on immediate issues, we can overlook, and thus fail to address, the more fundamental questions and potential opportunities related to scientific advances at 25 years.

Each dot on the Science Breakthrough Radar represents a scientific emerging topic with the potential for significant breakthroughs in the coming 25 years — breakthroughs that enhance our understanding of, or the capabilities of, an individual human being by changing the ways in which they interact and societies are organised and operate, or by transforming the natural and artificial environment. We asked panels of scholars to evaluate and discuss, for each emerging topic, the:

- expected time to maturity
- expected transformational effect across science and industries
- current state of awareness among stakeholders and
- possible impact on people, society and planet

From their answers we constructed the anticipation potential, which reflects how important it is to anticipate, accelerate and translate developments in this field today. This is in full alignment with GESDA's vision: use the future to build the present.

All the texts presented in the Radar have been reviewed and endorsed by the moderators and the scholars involved in their preparation. For more information on the methodology, please view the Appendices on the digital report at https://radar.gesda.global/appendices/methodology


HIGHEST ANTICIPATION POTENTIAL
Human Augmentation
Eco-Regeneration & Geoengineering
Science & Diplomacy
Knowledge Foundations
Quantum Revolution & Advanced AI
3.1 Decarbonisation
3.2 Earth Systems Modelling
3.3 Future Food Systems
3.4 Space Resources
3.5 Ocean Stewardship
3.6 Solar Radiation Modification
3.7 Infectious Diseases
2.1 Cognitive Enhancement
2.2 Human Applications of Genetic Engineering
2.3 Healthspan Extension
2.4 Consciousness Augmentation
2.5 Organoids
2.6 Future Therapeutics
1.1 Advanced AI
1.2 Quantum Revolution
1.3 Unconventional Computing
1.4 Augmented Reality
1.5 Collective Intelligence
4.1 Science-based Diplomacy
4.2 Advances in Science Diplomacy
4.3 Foresight, Prediction, and Futures Literacy
4.4 Democracy-affirming Technologies
5.1 Complex Systems Science
5.2 Future of Education
5.3 Future Economics, Trade and Globalisation
5.4 The Science of the Origins of Life
5.5 Synthetic Biology

1

Introduction to Quantum Revolution & Advanced AI

Our lives are intricately intertwined with the flow of data, and the information revolution has transformed the way we live and work, as well as our understanding of our environment. However, the impact of today's information technology could nonetheless be minor compared to the consequences of innovations coming over the horizon.

Artificial Intelligence (AI), already a world-changing technology, is growing in power and influence. It is clear that our current systems realise only a small part of AI's potential, and recent advances with generative AI such as Chat GPT show that as it grows more powerful and flexible it will affect us ever more profoundly. Ongoing global conversations to help us shape **advanced AI** to be reliable, transparent and equitable, will require a deep reappraisal of how these technologies are developed and deployed. But there is a need to also look now at what technology is coming next; there is much more in the AI pipeline that we need to anticipate.

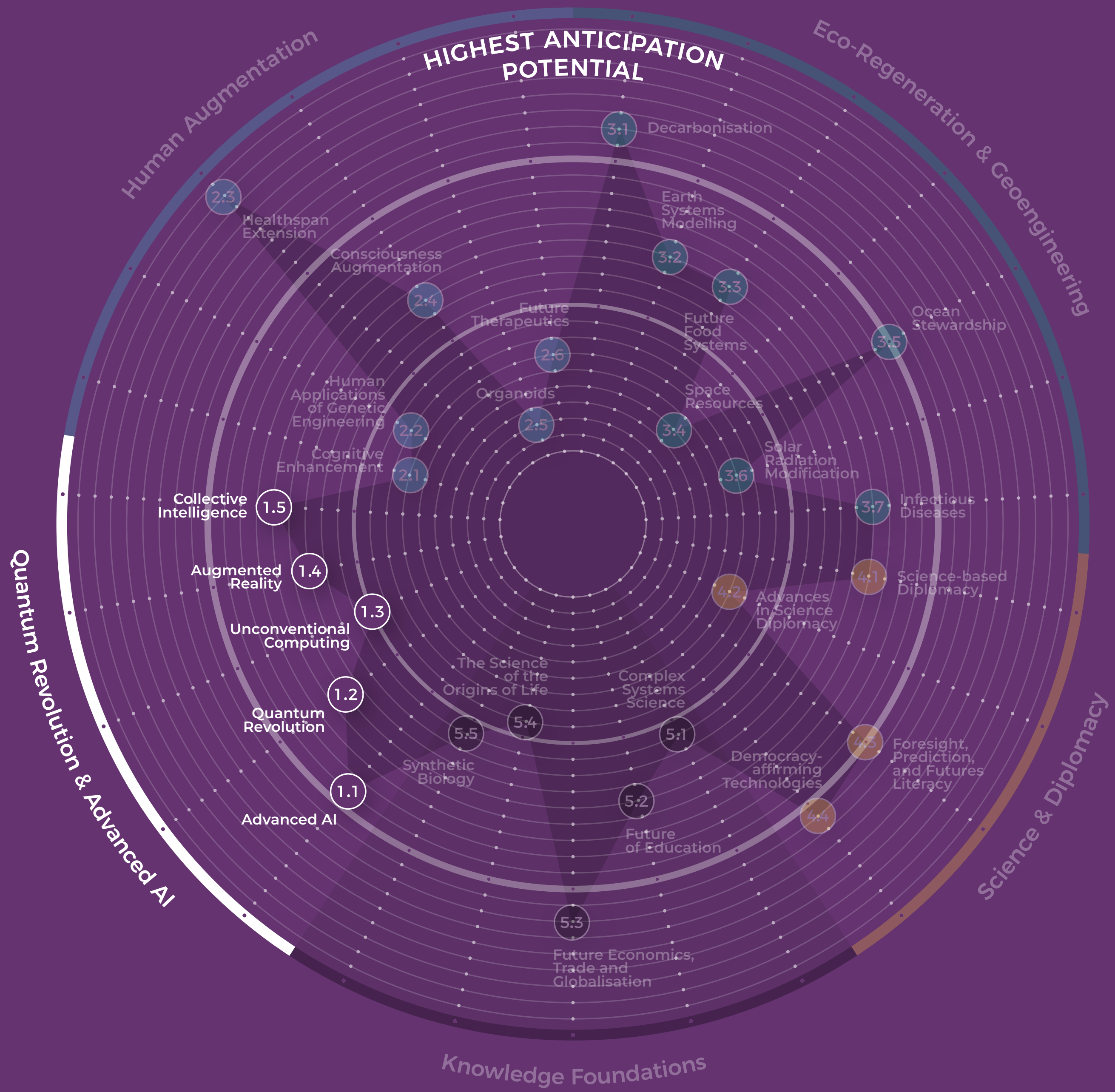
The effort to process information in entirely novel ways using the unique properties of subatomic particles has also made significant progress in recent years. **Quantum technologies** are already having an impact on sensing, imaging and metrology, and quantum computing and communications are also drawing close to meaningful real-world applications. The potential exists for quantum technologies to radically alter medicine, materials development, finance and online commerce, and to accelerate scientific discovery.

Research is now looking to widen the scope of information processing to explore the potential of a range of approaches. **Unconventional computing** might harness biological innovations honed through millions of years of evolution, for instance. If researchers can achieve even a fraction of the energy efficiency and processing power of the human brain, we will have unleashed an extraordinary new era of computing. Other novel possibilities arise from the biological processing power of organoids and cellular material, which may be a route to more efficient environmental sensing, remediation of pollution and medical diagnosis. The properties of photons — the particle form of light – are also redefining information processing's possibilities, offering radical new computing applications.

The speedup of digital communications, combined with developments in hardware and software, means that we can now receive real-time data and sensory experiences that enhance our normal interaction with our environment. Such overlays of **augmented reality** are already being used to train people in virtual work environments and to improve certain leisure activities, such as online gaming. Companies such as Apple and Meta are committing resources to improving the offering: as the technology progresses, the hardware — such as glasses that provide a view of information about our surroundings and the objects within them — will become ever more ubiquitous. Augmented reality is likely to change the nature of our daily interactions with other people and with our surroundings, and even the way we switch between the real world and virtual environments such as the metaverse.

Human intelligence is already remarkable. However, the potential to combine the intelligence of individuals with accumulated wisdom and experience, online repositories of learning and the powers of technologies such as AI, offers the chance to move to a new level. The field of **collective intelligence** is truly multidisciplinary, involving psychology, economics, computer science and a range of other fields. It is far from mature, but has enormous promise. If we can harness human capabilities, collective intelligence has the potential to help solve a wide range of societal challenges, from politics to business to conservation, in local and global organisations.

All of these innovations require attention if they are to achieve their full potential for improving human well-being and deployment in a way that enhances 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.



1.1 Advanced AI

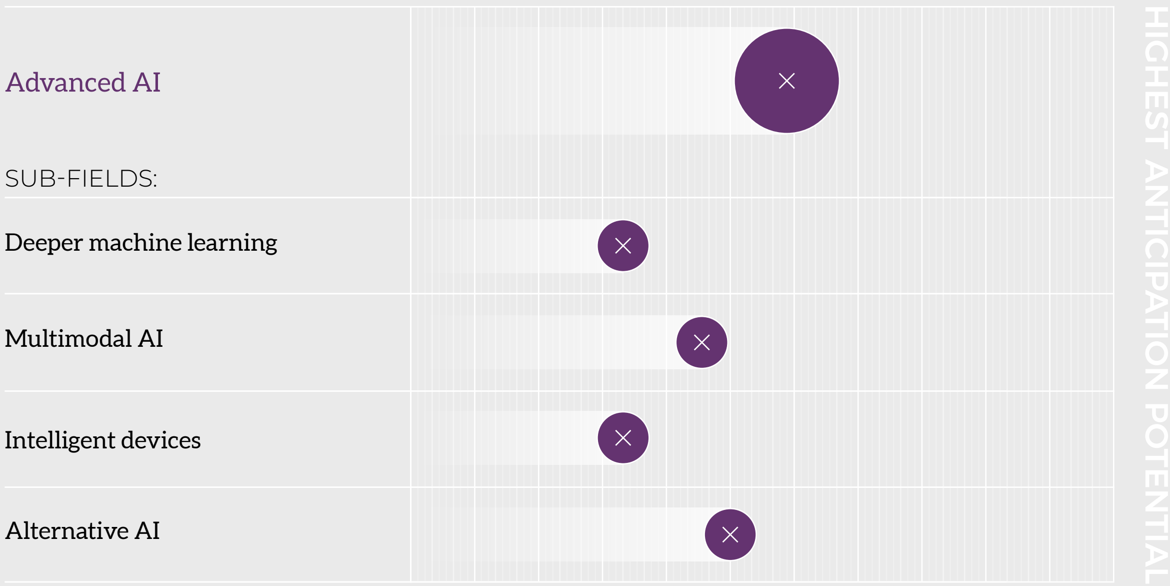
Artificial intelligence (AI) aims to build machines that can behave in ways we associate with human activity: perceiving and analysing their environment, making decisions, communicating and learning. There are various approaches to achieving this, but in recent years a technique called deep learning has achieved groundbreaking results and brought the technology out of academia and into the real world.

Deep learning relies on an information processing architecture known as neural networks, which are loosely modelled on the brain. When fed large amounts of data, neural networks learn to recognise statistical patterns, which can then be used to solve a variety of complex tasks in areas like vision, language or game playing. Systems powered by deep learning have crossed some impressive milestones over the past decade. Computer vision systems identified objects better than humans in 2015.[1] The following year, they beat a Go champion and started playing complex video games.[2] Autonomous cars have driven tens of millions of kilometres with very few accidents.[3] Last year, AI predicted the structure of nearly every protein known to man and brought chatbots with powerful linguistic capabilities to the general public.[4,5]

This rapid progress is primarily due to the increasing availability of training data and computing power. There is growing evidence that AI capabilities scale reliably with model size, leading many AI research labs and organisations to focus on building ever larger systems.[6,7] However, deep learning-based AI remains prone to bias and often cannot generalise what it has learned to new situations. 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 other approaches will be required to achieve more adaptable, efficient and trustworthy AI that can be deployed broadly across society.[8] That said, many in the field believe continued scaling could soon resolve these outstanding challenges, and that society needs to prepare for the disruptive effects of AI that can outperform humans in a wide range of tasks.

Emmanuel Abbé
Full Professor, Chair of Mathematical Data Science, EPFL

Anticipation Potential



SURVEY OBSERVATIONS:

The past year has seen staggering developments around Deep Learning and Large Language Models, with, for example, the release of ChatGPT and other very large models. While the future is very hard to predict, the impact on society and on the environment of Advanced AI is rated as very high. However, because of its short path to maturity (and as it has already received considerable attention), the Anticipation Scores are relatively low. Alternative approaches to AI could nonetheless be transformative in 10 years, suggesting more work is needed to understand its potential implications.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

'The 2023 AI Index' by Stanford University Institute for Human-Centered Artificial Intelligence provides a comprehensive snapshot of AI's trajectory this year, ranging from the growing ethical discussions surrounding AI to notable strides in diversity within the field. Published in March 2023, 'Neurosymbolic AI: the 3rd wave' by Artur d'Avila Garcez and Luís C. Lamb pioneers into the realm of neurosymbolic computing, illuminating a future where neural networks intertwine with symbolic reasoning, setting the stage for more trustworthy and interpretable AI systems. 'An analog-AI chip for energy-efficient speech recognition and transcription' was presented in August by a collaborative effort from US and Japanese researchers. The paper underscores the revolutionary potential of analogue in-memory computing (analog-AI) in optimising energy efficiency for vast AI models.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r1-1

1.1.1 Deeper machine learning

Many of the advances in deep learning have involved humans laboriously labelling vast amounts of data for the algorithms to be trained on. More recently though, a new paradigm known as self-supervised learning has accelerated progress. It relies on a new kind of neural network called a transformer, which is able to generate its own labels from unlabelled data and therefore train on far more data than before.[9]

This has led to rapid improvements in AI language and coding capabilities and is also showing promise in other domains like vision.[10,11] So far, transformer performance scales reliably with model size, and the largest systems demonstrate emergent capabilities that they were not explicitly trained for, such as creativity and limited reasoning.[12] They have also been applied to scientific problems such as protein-folding with considerable success.[13] However, it is still possible that the current "scale" approach is learning mainly from a memorisation-based approach, as its performance is much less impressive in tasks having to do with mathematics and logic. There is a significant need to make trained neural networks perform better on reasoning benchmarks, and new methodologies may be required there.

A further concern is that the imperative to build ever larger models means that cutting-edge AI research is increasingly accessible only to well-funded private labs. Because these models are statistical in nature, they also readily learn biases from training data and in some cases confidently "hallucinate" facts that are not true.[14] More fundamentally, these models have no memory of their previous actions and their capabilities are baked-in at training, which means they are unable to learn continuously from their interactions. There is significant debate within the field as to whether these capabilities will emerge with greater scale, can be built in explicitly, or whether we will need to move onto new architectures. Part of the problem is that the theory of machine learning is still far behind the practice.

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; the models are significant assets, assisting a wide variety of human task performance. Most countries adopt AI regulations to limit the potential negative impacts of AI such as bias, misinformation and privacy invasion.

10-year horizon:

Workforce disruption necessitates radical intervention from policymakers

Deep learning systems outperform human knowledge workers in a wide-range of professions. The resultant workforce disruption requires policymakers to rethink employment and wealth distribution policies. Two currently open possibilities about exponential increases in model size are resolved. One is whether they outpace hardware improvements and data availability, leading to a plateau in scaling efforts, and prompting renewed innovation in AI architectures. The other is whether further scaling of model size leads to the emergence of missing ingredients such as episodic memory and in-context learning that makes performance even more human-like — or better-than-human.

25-year horizon:

Deep learning's influence is ubiquitous in daily human life

Given current acceleration, at this timescale predictions about AI have become incredibly difficult. If scaling laws hold, then AI is likely to reach superhuman capabilities in all domains. In this scenario, it is also likely to become self-improving, 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, deep learning will still be a powerful tool that is able to match human performance on many tasks, but efforts to build generally intelligent AI will refocus on combing 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.[15,16] More recently, large-language models repurposed to work with multiple data modalities have shown considerable promise. Photorealistic imagery can now be generated from simple text descriptions, the latest AI-powered chatbots can perform complex image analysis, and robots can combine visual input and natural language commands to carry out complex tasks.[17,18,19]

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.[20] 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 barrier.

5-year horizon:

The knowledge industry is entirely disrupted

Multimodal AI works with both text and image data, automating 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 data expand the modalities that AI can work with. This leads to breakthroughs in 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 to work more seamlessly and safely alongside humans, boosting the use of the technology in less structured settings like retail, care and education. However, the expanded modalities also create the possibility for emergent characteristics such as in-context learning and episodic memory to develop, opening up a path to artificial general intelligence.

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 enquiry by allowing the simultaneous analysis of vastly different kinds of data.

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. The sheer volume of data produced by the growing Internet of Things also presents a problem.

Hence, running models embedded on "intelligent devices" will be imperative for many of the most promising AI applications. 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 without sacrificing performance.[21,22]

Training these intelligent devices will also require innovations. Federated learning is a promising approach that distributes training over many smaller devices without pooling data centrally, reducing bandwidth requirements and improving privacy.[23] Reinforcement learning, in which AI learns to perform a task by repeatedly performing actions and seeing if they maximise a carefully chosen reward, is seen as a promising way to train robots and other automated machines. Doing this is in the real world is slow and costly, though, and collecting enough real-world training data is a significant challenge A new paradigm that involves training models in simulations and then porting them over to devices may present a powerful alternative.[24]

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 faster and cheaper 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 man-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, recreating the kind of flexible and efficient intelligence seen in humans 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.[25] 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.

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.[26] 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.[27] And "Bayesian AI" approaches use the statistics of probability to help AI better understand the uncertainty of the real world while achieving continuous learning.[28]

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 cognitive science provide more clues about the missing ingredients behind general intelligence.

10-year horizon:

Emerging scaling laws determine the future of deep learning

Even at this timescale, the horizons are unclear. 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 over unintended consequences of deploying deep learning models. This could result in a shift to hybrid systems that make use of many different AI techniques to boost explainability, efficiency and flexibility. Alternatively, further scaling of model size could lead to the spontaneous emergence of these missing ingredients in deep learning models, causing interest in alternative approaches to wane.

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, 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 causal reasoning.

1.2 Quantum Revolution

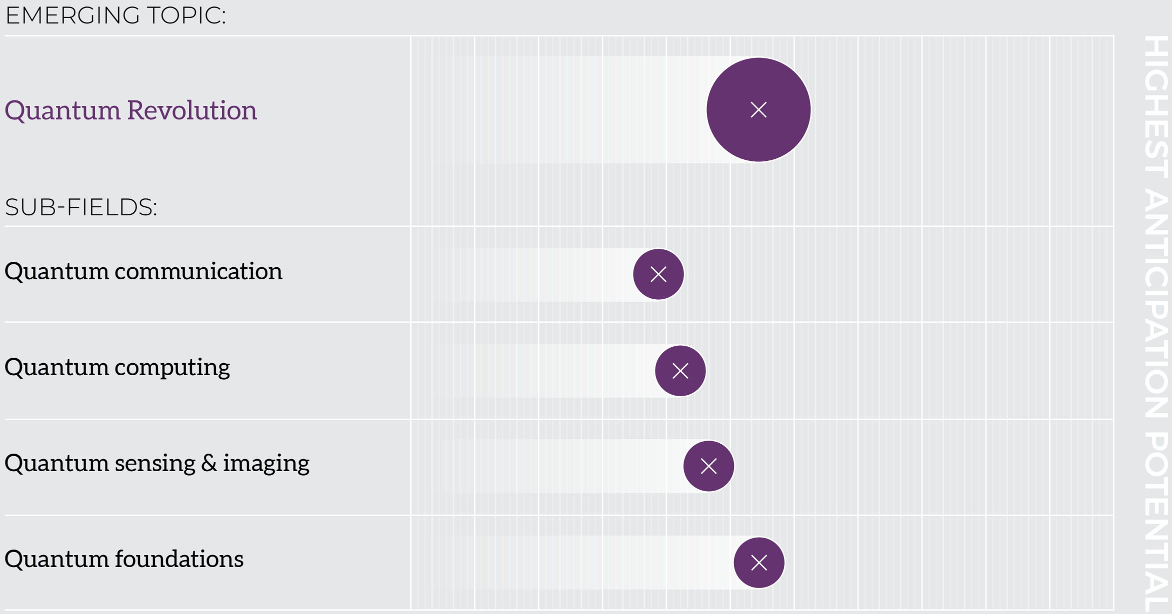
Systems made up of subatomic particles like electrons and photons are subject to physical laws unlike the ones we are familiar with. Quantum technologies make use of two phenomena unique to such quantum systems. One is “superposition”, where a quantum entity’s physical properties remain undefined until they are measured, creating an entirely novel mechanism for encoding information. The other is “entanglement”, where quantum entities have intertwined properties that mean action on one entity instantly affects the outcome of future actions on its entangled twin, even when they are physically separated.

These phenomena allow cryptographic keys to be shared securely over hundreds of kilometres, quantum computers to solve classically intractable problems and quantum sensors to make measurements of unprecedented precision. These technologies are still under development, but already pose challenges: for example, we can confidently anticipate that future quantum computers will be able to crack most of the encryption techniques currently used to secure communications and data. More speculatively, it has been suggested that quantum phenomena might play a role in processes such as the functions of biological systems, which if confirmed would raise the prospect of unanticipated new technologies.

Matthias Troyer

Technical Fellow and Corporate Vice President, Microsoft

Anticipation Potential



SURVEY OBSERVATIONS:

Few emerging disciplines have received more attention in recent years than quantum technologies, with many countries, companies and researchers producing roadmaps of the future of the field. Much of the focus has been on quantum computing so, despite its undeniably disruptive potential and the years it will take to reach maturity, much of the anticipatory work is already underway. In contrast, foundational quantum discoveries with major impact on other fields such as biology or neurosciences have received little attention so far. Major breakthroughs in this area are not expected for many years, making it hard to assess their disruptive potential, but this uncertainty and the field's low visibility suggests it is one worth paying more attention to.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In July 2023, renowned institutions, including CERN and IBM, produced 'Quantum Computing for High-Energy Physics: State of the Art and Challenges: Summary of the QC4HEP Working Group', offering a roadmap on the state of quantum computing within high-energy physics and highlighting the IBM 100 x 100 challenge. In another notable report entitled 'Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage', a Team of Microsoft researchers shed light on the true potential and challenges of achieving quantum advantage, with special attention to areas like material science and chemistry. An international collaboration with researchers from the US, Germany, Canada and Austria published 'Drug design on quantum computers' in January 2023, underscoring the revolutionary prospects and hurdles of employing quantum computers in pharmaceutical research.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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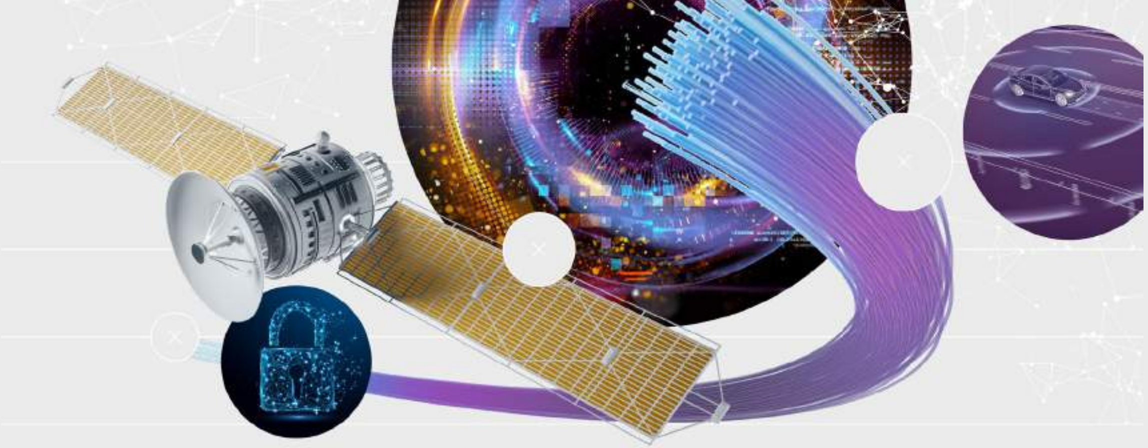


1.2.1 Quantum communication

The unique properties of quantum systems such as individual photons of light allow them to be used in provably secure cryptographic key exchange. This is of great interest to organisations such as healthcare providers, governments and financial institutions. Quantum protocols can now be deployed between dedicated nodes distant up to about 600 km using existing optic fibres — enough to link, for example, a bank headquarters and a data storage warehouse. Academic prototypes are operating at very low key generation rates over satellite links.[5,6]

Already very difficult to break, future implementations will provide unconditional, device-independent quantum cryptography that will be unbreakable both in theory and practice. However, a number of challenges to the widespread rollout of quantum cryptography remain. Among them are cost, bandwidth and distance, integration with standard communication systems and the need to establish certification methods that are easy to apply. A crucial breakthrough will be the development of "quantum repeaters" that can securely amplify the signals to enable their transmission over thousands of kilometres, although workarounds may be possible.[7]

5-year horizon:

Commercial quantum cryptographic channels are established

An increasing number of companies commercialise systems providing secure quantum cryptographic channels over hundreds of kilometres. The first demonstration of quantum repeaters increases the distances for quantum communications. Quantum random number generators are more broadly deployed in personal technology, radically improving security for financial transactions and secure communications.

10-year horizon:

Satellite links and repeaters allow >500 km secure communications

Terrestrial and satellite links are available for quantum cryptographic secure channels over more than 500 km, which compose networks containing dozens of nodes and quantum repeaters. So-called device-independent protocols realise the theoretical promise of unconditional security. Certification techniques based on general tests allow people to trust an encryption system without knowing all the details of its inner workings.[8]

25-year horizon:

A secure intercontinental quantum internet is established

A "quantum internet" is in place with provably secure quantum communication channels running between many nodes, combining terrestrial optic fibres and satellite links to connect several countries, in particular in and between Europe, the US and China. This will be of particular interest for sensitive data concerning e.g. health, finance, legal, whistleblowing, but also possibly for autonomous vehicles. The quantum internet will augment the "conventional internet" for the most privacy- and security-critical applications.

1.2.2 Quantum computing

Two decades of academic research into quantum computing have resulted in significant recent investments in the field from major technology companies such as Microsoft, IBM, Google, Intel, Alibaba, Huawei, Fujitsu and Honeywell. A rapidly growing number of start-ups are also active in the field. Today's most promising machines include IBM's 433 "quantum bit" (qubit) Osprey processor, the largest general purpose quantum computer to date. Demonstrations have shown that some quantum machines are now taking only a few minutes to perform complex calculations that would take days on the most powerful classical computers.[9] Although there are no real-world uses as yet, it is clear that quantum machines are starting to push into problems that are extremely difficult, time intensive and expensive for standard processors.

However, most real-world applications for quantum computers will require "quantum error correction", which necessitates systems with millions of qubits.[10] It is not yet clear whether the various different hardware implementations in development (superconductors, ion traps, silicon-based wafers and photonics to name a few) will all yield useful quantum computers, or whether one type will win out. In addition, very few truly revolutionary algorithms have so far been devised to run on these machines. It is likely that early (and possibly all) implementations of quantum computing will involve hybrid quantum-classical operations.

5-year horizon:

New, useful quantum algorithms accelerate hardware development

More companies commercialise quantum computers. These operate in the "Noisy Intermediate-Scale Quantum" (NISQ) regime, solving only demonstration problems that are of no practical use. Cloud-based access to early quantum computer prototypes draws in talented scientists and software engineers, stimulating the development of new quantum algorithms beyond the 60-odd examples that existed in 2020.

10-year horizon:

Quantum processors find real-world applications

Quantum machines incorporate error correction and simulate quantum systems with a precision unattainable with classical computers, albeit using simplified models rather than accurate microscopic models of materials. New quantum algorithms continue to offer a significant speed-up (exponential or polynomial) over classical methods.

25-year horizon:

Million-qubit computers solve useful, classically intractable problems

Universal quantum computers with millions of qubits run accurate and predictive simulations in chemistry and materials science, accelerating discoveries such as, perhaps, materials that superconduct at room-temperature, catalysts for nitrogen fixation and new pharmaceutical products.

1.2.3 Quantum sensing and imaging

Quantum-enabled measuring and calibration devices are already in advanced stages of development. There are sensors, for example, that use quantum properties to achieve higher spatial resolution and larger bandwidth than conventional tools, and their simultaneous sensing of multiple signals enable new functionalities.[11] For example, "superconducting quantum interference devices" are already being used to measure brain activity in hospital-based magnetoencephalography (MEG) scans.

The scope of future applications for quantum technologies include use as very high precision clocks (for GPS satellites among other applications); magnetic sensors (such as miniaturised handheld NMR scanners for medical imaging, geological surveys and nuclear monitoring)[12]; gravitational detectors (for geological prospecting, mining and autonomous vehicle safety); electromagnetic field sensors (for medical applications, materials development and communication technology), and accelerometers and gyroscopes (for navigation and autonomous transportation).

5-year horizon:

Quantum imaging improves medical diagnostics

A new generation of quantum-enhanced imaging delivers more precise images in materials science and biology, in particular in neuroscience. Quantum inertial sensors complement GPS systems and quantum gravity detectors are deployed for geological surveys and very precise seismological monitoring (including earthquake prediction and nuclear test detection). Quantum clocks are used for improved GPS systems and for time-stamping algorithmic trading transactions. Quantum sensors distiguish between atmospheric isotopes in efforts to monitor climate change.

10-year horizon:

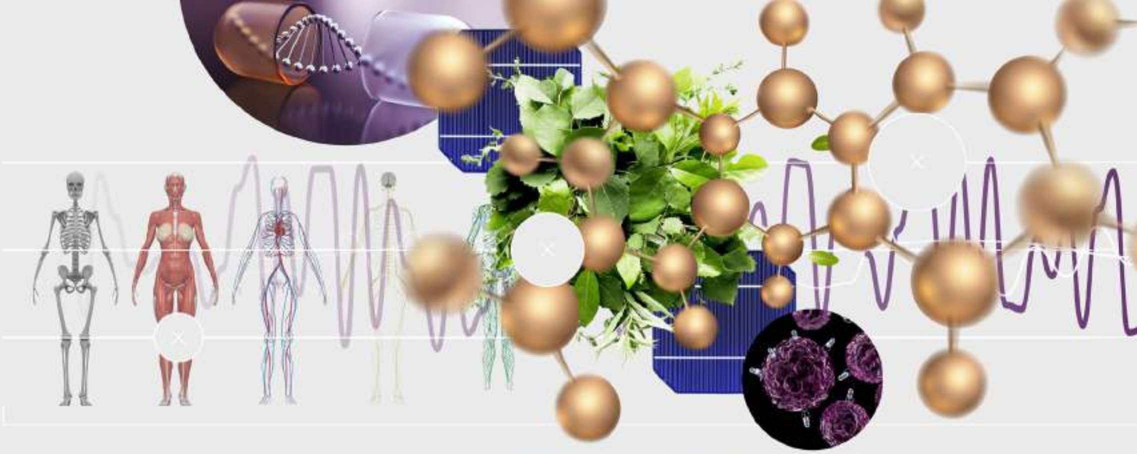
Quantum detectors monitor earthquakes and nuclear tests

Connected via quantum channels, ultra-precise networks of quantum sensors are deployed for a variety of applications: for example, spectrometers for the analysis of gases in atmospheric science and climate change modelling, seismic monitoring and increasing the precision of international unit standards.

25-year horizon:

Handheld quantum sensors detect and diagnose consciousness

Quantum sensors and non-invasive imaging systems are routinely employed in medical diagnostics and healthcare. They are miniaturised and integrated into portable handheld devices and wearable technology. Satellite-borne quantum gradiometers may replace GPS with ultra-precise magnetic field measurements.



1.2.4 Quantum foundations

Quantum theory is still a rapidly evolving field, and academic researchers are investigating a number of speculative ideas that could result in profound and useful discoveries. For example, there is increasing interest in the idea that quantum effects are at work in living organisms and play important roles in their functioning.[13] It may be, for instance, that quantum effects are at work in plant photosynthesis, birds' navigational abilities, and anaesthetics and cognition. This emerging field of "quantum biology" offers the possibility of improved photovoltaics, medications for cognitive health, navigation tools and chemical sensors. It could also benefit investigations in basic science, such as efforts to understand consciousness and the chemical building blocks needed for life to develop.[14]

The famous Heisenberg uncertainty principle has led researchers to suggest re-workings of the concepts of time's flow, the nature of information and the kinds of work that can be carried out by machines. If these ideas persist, they may lead to entirely new technological possibilities operating at the quantum scale.[15]

5-year horizon:

Quantum biology becomes established

Fundamental research continues to investigate quantum effects in biology, which becomes an established field of study.[16] New possible violations of traditional causality continue to invite speculation about application in information processing.

10-year horizon:

Possible medical applications emerge

Investigations of quantum properties of atoms and isotopes might uncover mechanisms of interaction with biological processes, such as in anaesthesia[17] and medication.[18] There will be new ideas for new breakthroughs in sciences that open the path for new applications.

25-year horizon:

Quantum foundations research delivers commercial technologies

Quantum sensor technology might be re-purposed to deliver activation of components of cellular biology for micro-level medical interventions. Investigations in quantum information theory and quantum thermodynamics lead to innovations in nanomachines and biological applications. There will be surprisingly new as-yet unknown applications of quantum technology at that scale.

1.3 Unconventional Computing

The silicon transistor is one of the most fundamental inventions in human history, birthing the Information Age and transforming the lives of billions of humans in just a few decades. But 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, this 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 its 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 underway.

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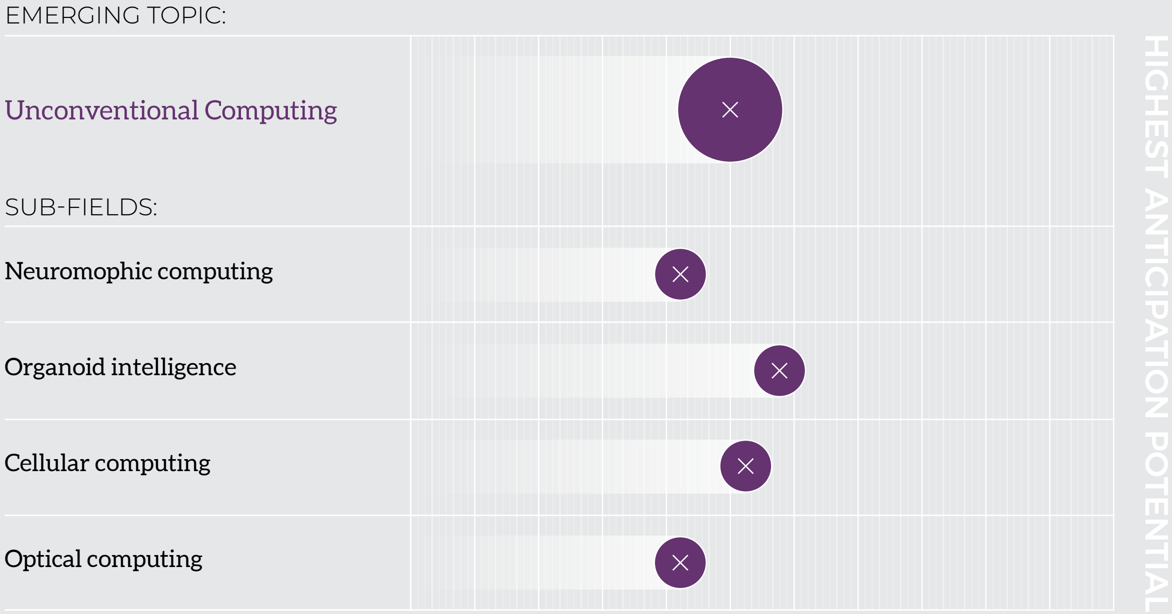
Head of the ASIC Laboratory and the Electronic Vision(s) Group, Heidelberg University

Lena Smirnova
Assistant Professor, Johns Hopkins University, President International MPS Socieety

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

Anticipation Potential



SURVEY OBSERVATIONS:

Drawing inspiration from the brain to inform the design of computing systems involves synthesising expertise from many fields. This convergence is the driving force behind the need for anticipation in this area, as the transformational impact of such a cross-cutting discipline is hard to predict. Tempering this is the fact that respondents predict this field to be less than a decade away from maturity. Other approaches, such as organoid intelligence and cellular computing, are likely to reach maturity closer to twenty years from now and their implications are less discussed, drawing their anticipation scores at higher levels.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In February 2023, an international team published a report entitled 'Organoid Intelligence: the new frontier in biocomputing and intelligence-in-a-dish', offering an overview of the field and suggestions for strategic development and an ethics-centred approach. A collaboration from Jordan, Pakistan and UAE laid out the promise and challenges of cellular computing in 'Research Challenges and Future Facet of Cellular Computing' a few months later, emphasising its potential in medicine, bioengineering and environmental monitoring. In July, US researchers published 'Solving the big computing problems in the twenty-first century', which explored the potential for new computing efforts to assist with problems such as brain-scale modelling and planetary-scale weather modelling.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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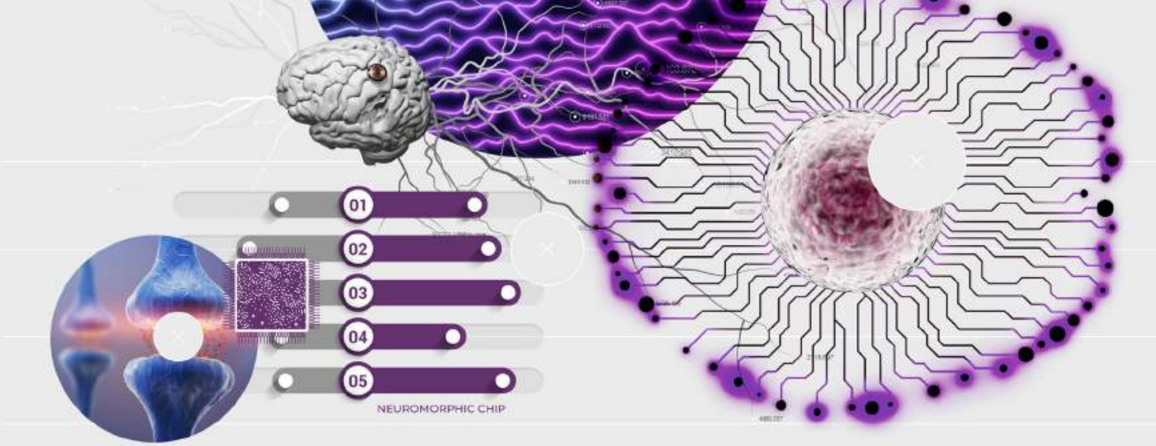


1.3.1 Neuromorphic computing

Neuromorphic computing seeks to implement relevant aspects of structure and function of biological circuits as analogue or digital representations on electronic substrates. The aim is to develop machines that will ultimately display the same capabilities as the human brain by emulating the structures and processes of biological neural networks.[1]

Emulating the brain's behaviour requires us to develop new kinds of computer chips that more faithfully mimic the way neurons work and are arranged.[2] One particular challenge is to replicate how brain cells communicate via spikes of electrical activity. Although there are similarities with AI, the details mean that there are limited opportunities for borrowing insights from that field. 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.

Many efforts at developing neuromorphic computing are underway. Researchers have, for instance, developed "Spiking Neural Networks" (SNNs), in which neurons communicate with each other with spiking, discrete electrical signals. The SpiNNAker project at the University of Manchester arranges general purpose silicon chips in a novel, highly parallel architecture.[3] IBM's TrueNorth chip and Intel's Loihi chip have both been custom-designed to run SNNs.[4,5] Memristors, simple transistor-like components that can retain information how much charge has flowed through them, also hold considerable promise.[6] However, we still don't know what brain (and, possibly, embodiment) components we need to mimic, and in how much detail.

5-year horizon:

Useful neuronal architectures emerge

More sophisticated models of neurons and a deeper understanding of plasticity rules boost the capabilities of neuromorphic architectures. 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:

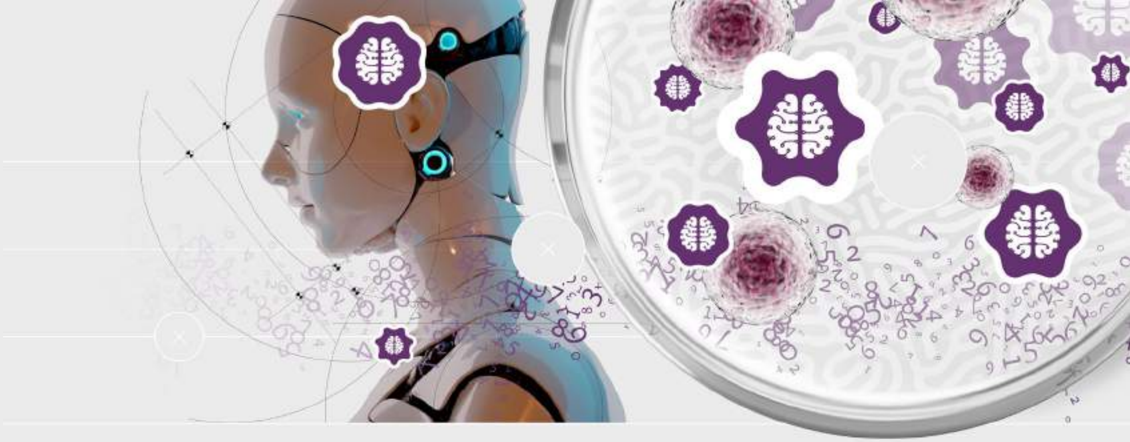
Neuromorphic computing is developed for embodied AI

New memory-based hardware better suited to implementing analogue spiking networks reaches commercial scale. 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, and the approach becomes the dominant computing framework for embodied AI that works with sensory signals and motion control. 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

We have a better understanding of the processes and causal relationships between different levels of the brain, going from molecular to cellular to circuit to structures. We map 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, while still primitive compared to the naturally evolved brain, work in recognisably mammalian ways. Robots powered by neuromorphic computing are widely deployed in the defence and care sectors. AI is pervasive and an integral part of our environment, with the technological basis of AI shifted to neuromorphic technologies.



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.[7] Now, researchers are investigating whether these organoids could be used to create new hybrid computing technologies that combine biological and electronic components.[8]

Early experiments have shown that neural cultures can be taught to play videogames or show features of reservoir computing.[9,10,11] If the technology can be scaled up it could have applications in AI and robotics, 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 sophisticated organoids, interface with them reliably, and understand how they learn and compute.[12] 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.[13]

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. 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:

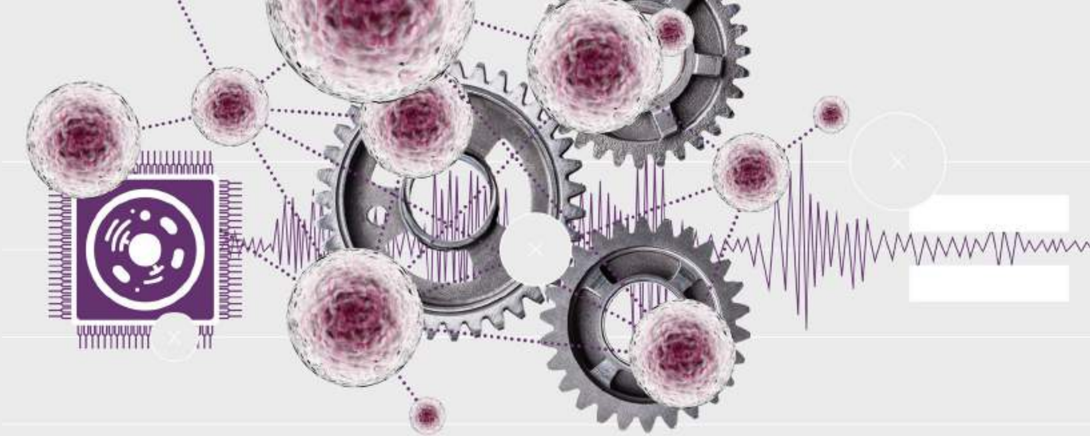
Fundamental science breakthroughs give organoids useful function

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 work practices and the suppression of any development of consciousness and sentience.



1.3.3 Cellular computing

Many biological processes take a molecular input, carry out some process using molecular or cellular "machinery", and output a related molecule or 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 is focussed on using the tools of synthetic biology to build "genetic circuits" equivalent to logic circuits in conventional computers.[14]

Biological computing has great potential beyond mimicking standard computing.[15] A cell's components can be re-configured in response to external stimuli, for instance, 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,[16] and the communication pathways that exist between biological cells allow for new forms of distributed computation.[17,18]

This rich array of possibilities 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, the production of novel materials and medical diagnosis.[19,20] That said, significant improvements in our ability to manipulate and interface with biological processes, and to understand the and measure the state of a cell, will be needed to make this a reality.

5-year horizon:

Parts and processes are standardised

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:

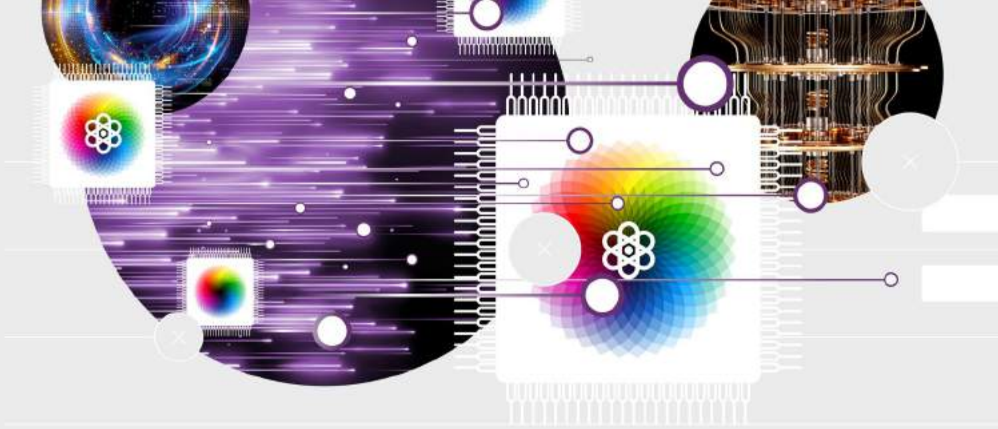
New biocomputing pathways are designed and developed

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. Regulatory progress allows programmed synthetic microbes to bring relief to stressed environments.



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. These particles travel at the speed of light, they are not subject to electrical resistance, and they don't interfere with each other. This allows multiple light signals to travel extremely fast in parallel, massively boosting data flows.

These advantages have been known about for decades, but recent innovations, driven by investments from the telecoms industry, have finally started to make optical computing devices practical. In particular, breakthroughs in silicon photonics are making it possible to build sophisticated optical processors using the same technology as the existing chip industry.[21]

The most promising near-term application appears to be in AI. That is because optical processors are well-suited to carrying out operations known as matrix multiplications; these are fundamental to all deep learning algorithms.[22] 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.[23,24,25,26] There are reasons for caution: catching up with and displacing decades of progress in silicon transistor technology remains an enormous engineering challenge, for instance. In addition, photonic chips normally rely on wavelengths of light measured in micrometres, making it unlikely that 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. 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 to 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 a several important tasks and applications.

1.4 Augmented Reality

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 and more impactful from other XR technologies like virtual reality and telepresence. The technology is already finding applications in education,[2] workplace training,[3] and industry.[4] In combination with data streams from the expanding Internet of Things,[5] 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. These glasses can provide an always-on overlay of digital information, mediated by AI that personalises what is displayed to the user's needs. 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.[6] The blurring of the boundaries between the physical and digital worlds that this entails holds unknown and potentially enormous implications for society.

Alexander Ilic
Executive Director and Co-founder of the ETH AI Center

Anticipation Potential

EMERGING TOPIC:

Augmented Reality

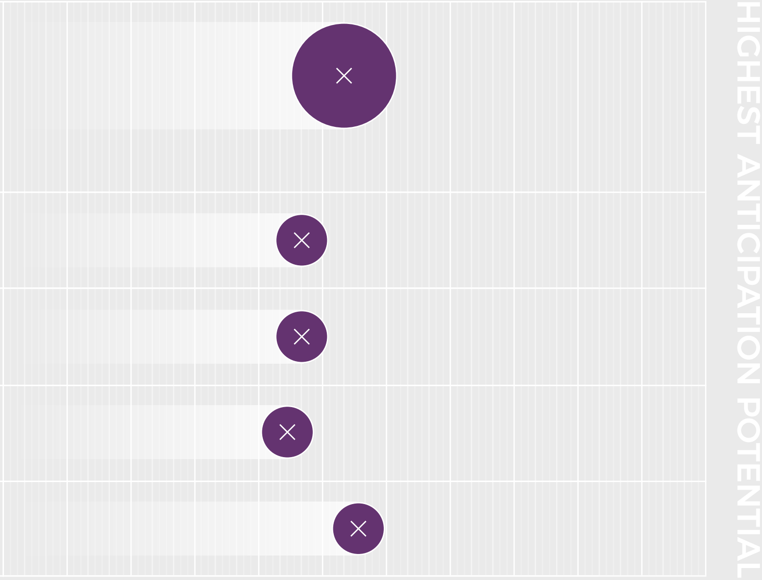
SUB-FIELDS:

Augmented reality hardware

Augmented experiences

AR platforms

Human factors of AR



SURVEY OBSERVATIONS:

Real and virtual worlds are becoming increasingly intertwined as augmented reality (AR) technology advances. Significant work across disciplines is already ongoing, and this convergence is the driving force behind the need for anticipation in this area. The relatively low awareness of the impact AR could have on human psychology and social relations suggests this is an area that requires particular attention.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In February 2023, a team at Cleveland State University published 'Towards an Evolved Immersive Experience: Exploring 5G- and Beyond-Enabled Ultra-Low-Latency Communications for Augmented and Virtual Reality', which investigates the potential of 5G and Beyond (5GB) technology in refining augmented and virtual reality experiences, emphasising the importance of ultra-low-latency. A publication from May 2023, 'The persuasion effects of virtual reality (VR) and augmented reality (AR) video advertisements: A conceptual review', published in the Journal of Business Research, offers a pioneering model to decipher consumer persuasion dynamics in VR and AR advertisements. Lastly, a seminal paper titled 'Extended depth of field in augmented reality', unveiled in a May 2023 Nature article by three South Korean researchers, presents a novel optical structure for 3D displays, aimed at revolutionising the clarity of augmented reality experiences.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r1-4

1.4.1 Augmented reality hardware

AR hardware developments have been spearheaded by advances in microelectronics, sensor technologies and vision equipment, which have also reduced the cost. With 5G availability on mobile phones, AR can be implemented — in limited ways — on portable devices without the need for expensive eyeglasses and Head-Mounted Displays.

However, augmented reality glasses like the Microsoft HoloLens 2, Google Glass Enterprise 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.

For the technology to achieve widespread use, it needs to be indistinguishable from a normal pair of glasses. This will require massive reductions in size, power consumption and cost. Breakthroughs in optics,[12] energy-efficient computing and wireless communication will all be crucial, but the biggest challenge is safely dissipating heat from on-board electronics.[13] Another outstanding problem is finding ways for virtual objects to convincingly occlude real world ones using optical technology.

It may be possible to sidestep some hardware limitations through "foveated rendering"[14] where the eyes are tracked and only the area of focus is rendered in high definition. Spatial audio could alert people to things outside their visual field, and physiological monitoring through EEG and skin conductance could help understand the user's intention or cognitive state to optimise the information displayed. Pairing smart glasses with a companion device, such as a smartphone, could help get around limited processing capacity.

Creating truly immersive augmented reality will also require breakthroughs in haptics technologies. Generalised haptics that can mimic a wide variety of sensations remain elusive, though ultrasonic devices show promise.[15] In the distant future augmented reality may eventually be mediated by smart contact lenses rather than glasses,[16] or even via brain-machine interfaces.

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 smartphone and beamed to glasses over 5G. A breakout product from a leading device company could start to make consumer applications attractive.

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. Smart contact lenses replace smart glasses as the primary AR interface, while advances in brain-machine interfaces start to make it possible to transmit visual and haptic information directly to the brain.

1.4.2 Augmented experiences

Early incarnations of AR are concerned with two fundamental activities: learning about the world and interacting with other people. This includes tasks like overlaying instructions or translations on the real world, or participating in 3D video calls.[17] Near real-time interaction is now possible depending on the amount of processing required, and AR has moved from game-playing and applications requiring lower accuracy to precise engineering and medical fields.

Further down the line, AR glasses will be able to integrate complex virtual objects into real world scenes. However, doing so in an intuitive and seamless way will require significant breakthroughs in 3D scene reconstruction[18] and low latency graphics to improve realism.

A crucial aspect will be innovations in user experience[19] — 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, and that it enhances their cognition without being distracting, obtrusive or addictive.

To make this a reality AR will have to become adaptive, using AI to analyse data from physiological sensors and cameras to understand both the user and their environment.[20] This will require breakthroughs in areas like continual learning — so that AI can update models of the user on-the-fly — and activity recognition, so that AR devices can understand the user's context and anticipate their needs. Core AI functionality like image recognition or translation will be served by large, shared models accessed over the cloud, but AI responsible for learning about the user's preferences will need to run on AR devices in a decentralised fashion.

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. The technology will start to provide everyday users with always-on AI support in their everyday lives. The boundary between AR and VR becomes blurred: breakthroughs in graphics enable complex virtual content, such as realistic shading and dimming by virtual objects on the real-world view, and vice-versa.

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.

1.4.3 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. 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.[21]

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.[22] 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.[23]

An AR platform is no longer for visual display only. Various ICT algorithms and sensor technologies have been integrated to build the basic elements for digital twins, utilising cloud, edge and fog computing, microservice and kubernetes to facilitate speed and ease of communication.

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 wireless delivery of high-fidelity AR experiences to headsets, 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.

1.4.4 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[24] and body dysmorphia caused by image filters[25] could all be turbocharged by AR technology. 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.[26] 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. 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.[27]

Symbiosis between human and machine is the next phase, where complementary and improved working relationships between humans and machines will be strongly fostered. In this scenario, the boundary between physical and digital worlds will become wider and have larger overlaps.

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 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.

1.5

Collective Intelligence

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) aims to understand the dynamics underpinning human collaboration and discover new ways to enhance and guide these processes. The field is founded on the principle that when people come together to solve problems, the sum is greater than its parts.

Collective Intelligence is an emerging field, drawing from a broad range of disciplines including biology, psychology, economics and computer science.[1] The methods of collective intelligence make it possible to look more systematically at how organisations and whole systems think, how they observe, analyse, plan and create, using a mix of human and machine intelligence, as well as pointing to how they can think more successfully.

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

In the last decade, there has been significant growth in the use of technology to enhance the CI of groups both large and small. This ranges from web platforms designed to coordinate large-scale collaboration to the use of artificial intelligence to facilitate group discussions. However, although efforts to harness CI are widespread, the practice is often well ahead of the theory. Significant research is required to improve our understanding of the fundamentals of CI and how to design and apply new tools to enhance it.

Geoff Mulgan

Professor of Collective Intelligence, Public Policy and Social Innovation University College London

Anticipation Potential

EMERGING TOPIC:

Collective Intelligence

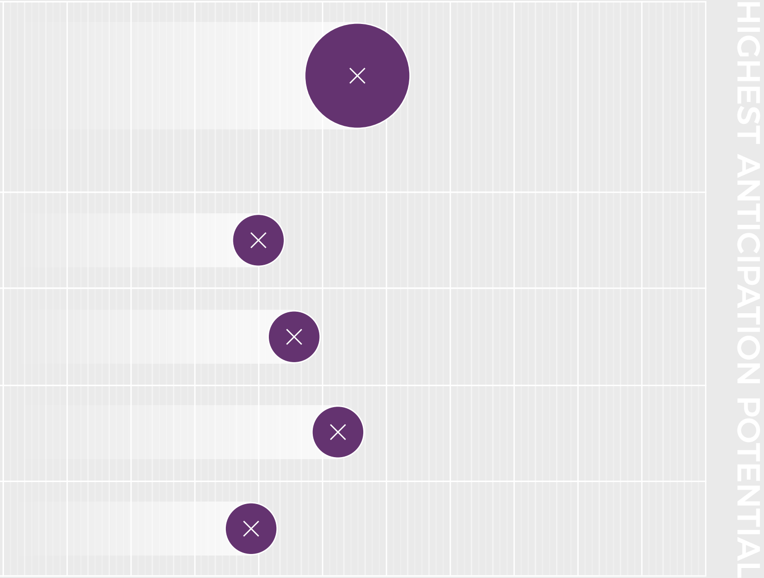
SUB-FIELDS:

Large-scale collaboration

Smarter teams

Collective cognition

Human-computer interaction



SURVEY OBSERVATIONS:

Understanding and enhancing the dynamics underpinning human collaboration is an active area of research. While human-computer interaction and small-scale collaboration are more mature and well-recognised areas of research, they are anticipated to have the largest impact across business and communities, boosting their anticipation scores. Large-scale collaboration and our understanding of how groups “think” as a unit – our collective cognition – are less well developed and could require more attention.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Released in January 2023, ‘Balancing Autonomy and Collaboration in Large-Scale and Disciplinary Diverse Teams for Successful Qualitative Research’ by a team of UK researchers spotlights the art of harmonising individual and collaborative efforts in large, interdisciplinary research. ‘Beyond collective intelligence: Collective adaptation’ was published in February by an international collaboration, and broke new ground by offering a fresh perspective on collective behaviour, emphasising the delicate balance between social strategies and environmental factors, and advocating for a multi-disciplinary lens. ‘Collective Intelligence in Human-AI Teams: A Bayesian Theory of Mind Approach’ was launched in June by Northeastern University researchers, and introduces a Bayesian framework enhancing human-AI team synergy, showcasing remarkable advances in performance prediction.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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1.5.1 Large-scale collaboration

Digital technology now makes it possible to collaborate on scales unimaginable in the past. This has led to a plethora of approaches aimed at harnessing diverse groups to solve practical problems.

Crowdsourcing opinions, information or small chunks of work from large numbers of people is helping tackle challenges as varied as training AI to predicting floods.[8] Citizen science projects engage the general public to help scientists to collect and analyse data, and even to develop new theories. Open innovation platforms like Kaggle and InnoCentive make it possible for companies to outsource engineering challenges to independent experts. And deliberative democracy is being used to involve everyday citizens in political decision-making in countries such as Taiwan.[9]

Technology is already crucial to these projects, but there are growing efforts to augment them with new tools to enhance the CI of large groups. These include better means of gathering and visualising data, collaborative mapping technologies and open source repositories of information and tools. 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] CI may ultimately incorporate both humans and AI agents working together, though this would require major breakthroughs in AI technology.

Decentralisation technologies such as blockchain and quadratic voting are also opening up new avenues for enhancing CI.[11] In particular, decentralised autonomous organisations (DAOs) could help run organisations in a distributed and non-hierarchical fashion.[12] The technology is still in its infancy, but could eventually provide ways to organise anything from local energy systems to finance bodies in more collaborative and inclusive ways.

5-year horizon:

Basic CI becomes everyday tool

CI will become more ingrained in everyday life, with many micro-collective intelligences 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.

10-year horizon:

CI applications grow

Ideas from CI start to be applied to solving big global challenges such as climate change, access to water and pandemic response. Organisations like the Intergovernmental Panel on Climate Change embrace new tools that use a combination of AI and CI to better organise scientific knowledge and bring in perspectives from more diverse groups.

25-year horizon:

Open innovation hits the mainstream

Democratic assemblies around the world embrace the CI tools of deliberative democracy to involve people far beyond the elected representatives in political decision-making. Companies' use of open innovation to solve problems becomes mainstream.

1.5.2 Smarter teams

Researchers are now trying to understand and enhance collaboration within teams, building on previous work in organisational psychology, behavioural economics and group dynamics. This involves solving a number of challenges, including goal alignment, task prioritisation, progress tracking, maintaining attention, distribution of responsibilities and ensuring that deliberation processes are efficient and equitable.

Research into group dynamics is already providing simple but powerful insights into how to improve the CI of teams, such as including intermittent breaks in collaboration and ensuring the right balance of cognitive diversity.[13,14] But it is also laying the foundations for new tools designed to enhance team performance. These include real-time visualisations of how much effort each team member is putting in,[15] information dashboards that provide summaries of people's expertise,[16] and even AI powered chatbots that nudge teams into sharing their expertise.[17]

Researchers are also building AI tools, based on the way swarms work in nature, to help groups make better forecasts, predictions and decisions.[18] In the future, better natural language understanding and sentiment analysis could see AI facilitators morph into AI moderators that can orchestrate group deliberations to boost CI. A nearer-term goal is the use of human collectives, with some AI assistance available, to provide oversight of individual decision-making in areas like criminal justice and medicine.[19]

5-year horizon:

Understanding of organisational structures aids CI

Researchers develop a better understanding of the organisational 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 everyday people with a form of "cognitive autocomplete" via brain interfaces that help them quickly access important information and augment their ability to deliberate.

1.5.3 Collective cognition

The theory underpinning CI research remains fragmented and underdeveloped, which limits our ability to design interventions that can enhance CI. A better understanding of collective cognition — how groups of humans "think" as a unit — will be critical for moving the field forward. This can be split into different aspects such as observation (integrating citizen inputs and other data sources); models (for example, a shared digital model of how a city or organisation works); memory (records of past systems and their performance); creativity (innovation, for example) and empathy (sensing and understanding feelings). This provides a framework for seeing how they can be advanced, with technology advancing some rapidly (eg observation) and others much less so. This approach makes it possible to use CI for diagnosis and problem-solving by bringing together new methods for understanding problems, generating solutions, implementing them and learning from them.

Filling the gaps in our understanding will be a major challenge. Research has shown that collective cognition is not uniform and is shaped by the social structures in which the groups operate,[20] a significant observation since current approaches to studying human interaction struggle to account for social dynamics. While there has been progress on defining and even measuring CI itself,[21] deciding what characterises "intelligent" group behaviour remains subjective.

Increasing use of technology to enhance CI also necessitates the development of new metrics of collective cognition that can be collected unobtrusively and then used by digital platforms or AI to improve group collaboration. 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.[22]

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.

10-year horizon:

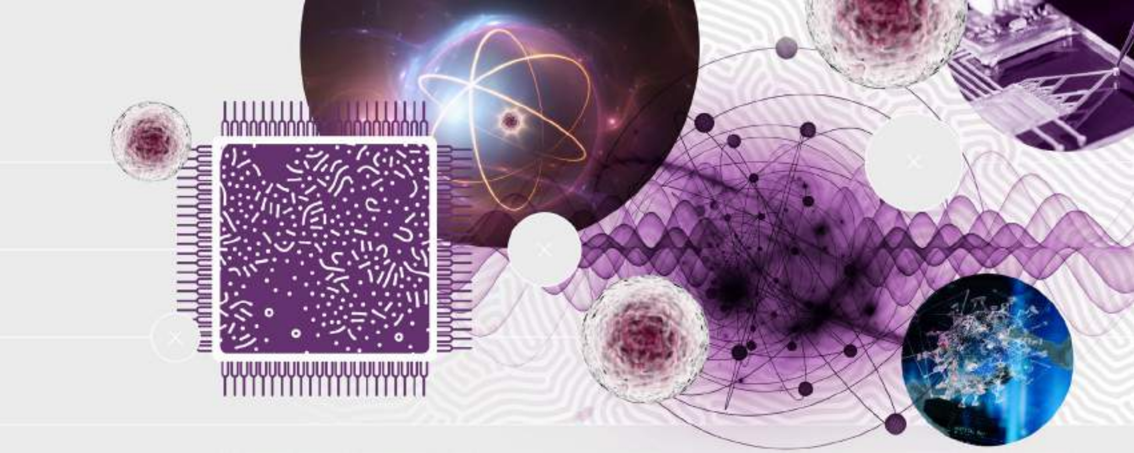
Metrics quantify CI

Data-gathering from online participation in collective activities allows researchers to develop metrics that quantify different aspects of CI. This is used to both develop better models of collective cognition and to act as a crucial input for digital tools designed to improve CI.

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.



1.5.4 Human-computer interaction

Using technology to effectively enhance CI will require breakthroughs in the theory and practice of human-computer interaction. Computer systems designed to facilitate human decision-making have a long history, but many have foundered due to failure to understand how humans use and perceive such technology. If we want to avoid the mistakes of the past, it will be crucial to find ways to link fundamental theories of human behaviour to the design of interactive systems.[23]

The use of AI to facilitate CI presents specific challenges. CI methods can be used to enable more sophisticated learning, for example. By moving beyond the mere analysis of new data to the generation of new categories for that data, we can create a more effective pathway for both understanding and solving problems. Currently, AI does not do these "learning loops" well.

Finding ways for human-computer partnerships to share agency effectively and to delegate control in an optimal manner will be important.[24] Human decision-making is highly context-dependent and that context is not static, so CI technology must be able to adapt on-the-fly to the ever-shifting circumstances in which human groups are operating. It will be crucial for humans to understand what CI technology is doing, and why.

This will require significant breakthroughs. Even such basic tasks as getting machines to understand who is speaking, or what they are saying, are proving difficult: imbuing machines with social intelligence remains a distant goal. Human-AI collaborative teams will also require machines that contain some kind of theory of mind — the ability to model the mental states of others.[25] As technology increasingly mediates group interactions it will also be necessary to find ways to measure how machines are changing human behaviour, to ensure they are enhancing human capabilities rather than causing them to atrophy.

5-year horizon:

Improved interaction boosts effectiveness

Renewed focus on improving how humans interact with CI tools significantly improves their 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 theory of mind, allowing artificial agents to become useful members in AI-human teams. Organisations such as IPCC and UN use human-AI teams to aid cross-cultural negotiations.

Sarah Kenderdine
Professor of Digital Museology EPFL

Invited Contribution: The Technology Opportunity for Digital Humanities and Art

The field of Digital Humanities has its roots in an ambitious goal: to bring computational approaches to the study of heritage and history and to create permanent, high-fidelity records of significant artefacts. Digital imaging and computer vision technologies, for example, have diverse applications — from analysing historical texts through to preserving at-risk archaeological relics and sites whose continued existence can be precarious in an era defined by conflict and natural disasters.

Digitising our cultural heritage in this way could not only protect it in perpetuity and open it up to new scholarship, it could also broaden access and create exciting new pathways for the public to interact with it. That's why, in recent decades, galleries, libraries, archives, and museums (GLAMs) have invested heavily in such projects, building new infrastructures for digital documentation and dendric classification.

Many of these institutions are now sitting on vast repositories of data that encode large swathes of our shared cultural heritage. These powerful archives offer new opportunities for knowledge creation and curation. However, these ventures have raised challenging questions of accessibility for the constituents that these knowledge organisations hope to serve. That is because most of this information is only available in a form that privileges experts, and efforts to open it up to publics require fundamental shifts in curatorial and museographic practices.

This is a missed opportunity, because new technologies mean the wealth of data can now be used to create immersive and engaging digital experiences of our history and culture that could be accessed by a far broader section of society. Digital exhibitions can gather artefacts from all over the world together in one place or allow them to be in multiple places at once. They can also allow people to explore important heritage sites remotely, without the need for environmentally expensive travel.

What's more, virtual replicas can be presented and engaged with in ways that are normally impossible for real objects, allowing GLAMs to create powerful and inspiring ways for the public to interact with their history. Motion capture, virtual production technologies and motion sensing interfaces are also making it possible to record and interact with more intangible elements of our heritage, from the precise movements of a Kung Fu master to the intricate rituals of Confucian courtiers.

But while there have been pioneering efforts to take advantage of these new possibilities, there remain major technical, cultural and institutional barriers that make it challenging to bring these kinds of experiences and these new materialities to life.

One philosophical debate exists between advocates of a "wiki" mindset that say everything should be in the public domain and thus freely shareable, and those who believe in data sovereignty and the idea that key cultural artefacts must be carefully safeguarded. This is particularly pertinent for indigenous or religious communities that believe certain sacred knowledge should not be widely shared. Other challenges are more functional — working out, for example, how such data can be protected and distributed across networks in ways that protect it from exploitation or manipulation more broadly. These issues have raised challenging questions around the ownership of digital artefacts and the ability to manipulate the cultural foundations of our societies

As we move towards an increasingly digital society, high fidelity cultural datasets will become extremely powerful. The challenge facing us is more than just developing engaging experiences for the museum floor; it is also about how to manage the entire value chain of digital assets to make sure they are simultaneously accessible, knowledge-bearing and protected.

It is important to note that the core technologies that make the collection and display of digital cultural data possible are increasingly consolidated in the hands of powerful technology companies. Many of these firms are increasingly heavily invested in the idea of a Metaverse, for example – a 3D online world where they hope many of us will spend large portions of our lives in the future. Replicating key cultural assets in these online worlds will be crucial to the success of these big tech developments, and there are concerted efforts to aggregate as many of these cultural assets as possible, for future exploitation.

Finding ways to protect our heritage as it becomes increasingly digitised will be crucial to prevent its exploitation by the private sector and prevent manipulation by the forces of late capitalism. So far, however, the problem of managing the ownership and control of digital assets that can be easily copied and distributed remains unsolved.

One exciting avenue for tackling these problems lies in blockchain technologies, which can act as a tamper-proof record of ownership for digital assets. Distributed digital ledger tokens (DLTs) and non-fungible tokens (NFTs), in particular, have emerged as a way to assert rights over digital art and culture. While they have so far been used primarily as a vehicle for financial speculation, they could also prove to be powerful tools for the custodians of our cultural heritage, enabling the repatriation of objects and the decolonisation of collections.

Properly managed, these technologies could also open the door to new, more inclusive models of ownership, in which the rights and control of artefacts can be shared among many people simultaneously, or entire communities. Smart contracts embedded in the blockchain could encode how these digital assets can be used and by whom.

However, many museums, libraries and archives are currently ill-equipped to engage with these technologies. There are large and worrying imbalances in both technical knowledge and resources between the heritage sector, the academic and private actors, which limits the ability to both take advantage of this wealth of data and to adequately exploit (but also protect) it.

Leaders across these sectors must take the challenges seriously and start investing in both the talent and infrastructure required to keep up in this fast-moving sphere. As the custodians of our shared heritage, we all have a duty to ensure the digitisation of the humanities is a net positive for society while ensuring the existence of sustainable business models. Robust partnerships between GLAMs, universities and technology sectors are essential to this shared future.

Pushmeet Kohli
Head of Research, Deepmind

Invited Contribution:
AI for Science

Artificial intelligence (AI) is transforming the way scientists conduct research and accelerating progress across a wide range of scientific disciplines. This is because many of today's scientific challenges are highly complex, involving far more data than any individual can process and understand. AI can help us turn this abundance of information into understanding, and deepen the nature of questions researchers can ask.

But progress is never certain. Every technology has the potential for harm, which is why scientists and society need to take short and long term risks seriously to ensure that AI fulfils its potential to advance science and benefit humanity. It is crucial that we all engage with the promises and perils that accompany this new era in scientific discovery.

At DeepMind, we use AI to solve fundamental scientific problems that can help unlock further research and benefit society. This type of foundational impact is exemplified by recent breakthroughs in protein folding. Proteins are the building blocks of life and their structure is fundamental to their function. Many of the world's greatest challenges, like developing treatments for diseases or finding enzymes that break down industrial waste, are fundamentally tied to proteins and the role they play.

However, connecting their chemical makeup — their unique sequence of amino acids — to their three-dimensional shape and ensuing biological function is complicated and time-consuming, sometimes taking years and millions of dollars. One of biology's longstanding "grand challenges", unsolved for nearly 50 years and known as the protein folding problem, was to find a shortcut that predicts a protein's 3D structure from nothing more than its sequence of amino acids.

In 2020, DeepMind's AI system AlphaFold was recognised as a solution to this challenge by the organisers of the Critical Assessment of protein Structure Prediction (CASP) competition. By training AlphaFold on a large database of known protein structures and their associated amino acid sequences, our team developed a model that could predict the shape of a protein, at scale and in minutes, down to atomic accuracy. AlphaFold predictions have already been accessed by more than half a million researchers and used to accelerate progress on important real-world problems ranging from plastic pollution to antibiotic resistance. In partnership with EMBL's European Bioinformatics Institute (EMBL-EBI), we've now made over 200 million of these predicted structures — nearly all catalogued proteins known to science — freely available to the global scientific community, with the potential to increase humanity's understanding of biology by orders of magnitude.

We believe that protein folding is indicative of where AI can have one of the biggest impacts: decoding complex biological systems to advance our understanding of the world around us. In a glimpse of the AI-powered discoveries to come, our team has already used deep learning to predict how non-coding parts of our genome influence which of our genes get switched on and off. This could dramatically improve our understanding of how genotype influences phenotype, with major implications in research and medicine.

We have also seen success in applying AI to quantum chemistry, where it has enhanced our ability to predict how electrons will behave in molecules. This might seem esoteric, but solving this puzzle is the first step towards being able to design novel materials from the bottom up, opening the door to breakthroughs such as new high-temperature superconductors and designed-from-scratch pharmaceuticals. In mathematics, we have seen how machine learning can help mathematicians make progress in answering foundational questions. Collaborating with AI systems that expose patterns that humans have been unable to spot, researchers have been able to develop entirely new mathematical conjectures about symmetries and knots.

The next step in the relationship between AI and science will be to better connect machine learning techniques with scientific processes. The AlphaFold breakthrough came from applying machine learning to pre-existing datasets that had not been collected specifically for that purpose. In some sense, the in vitro and in silico parts of the research roadmap were separated. We are beginning to see those barriers break down, and in a wide range of disciplines, AI will become an integral part of the scientist's toolkit. Computational techniques will then be central to how science is conducted, and learning how to use them effectively will be a vital skill for anyone working in the field.

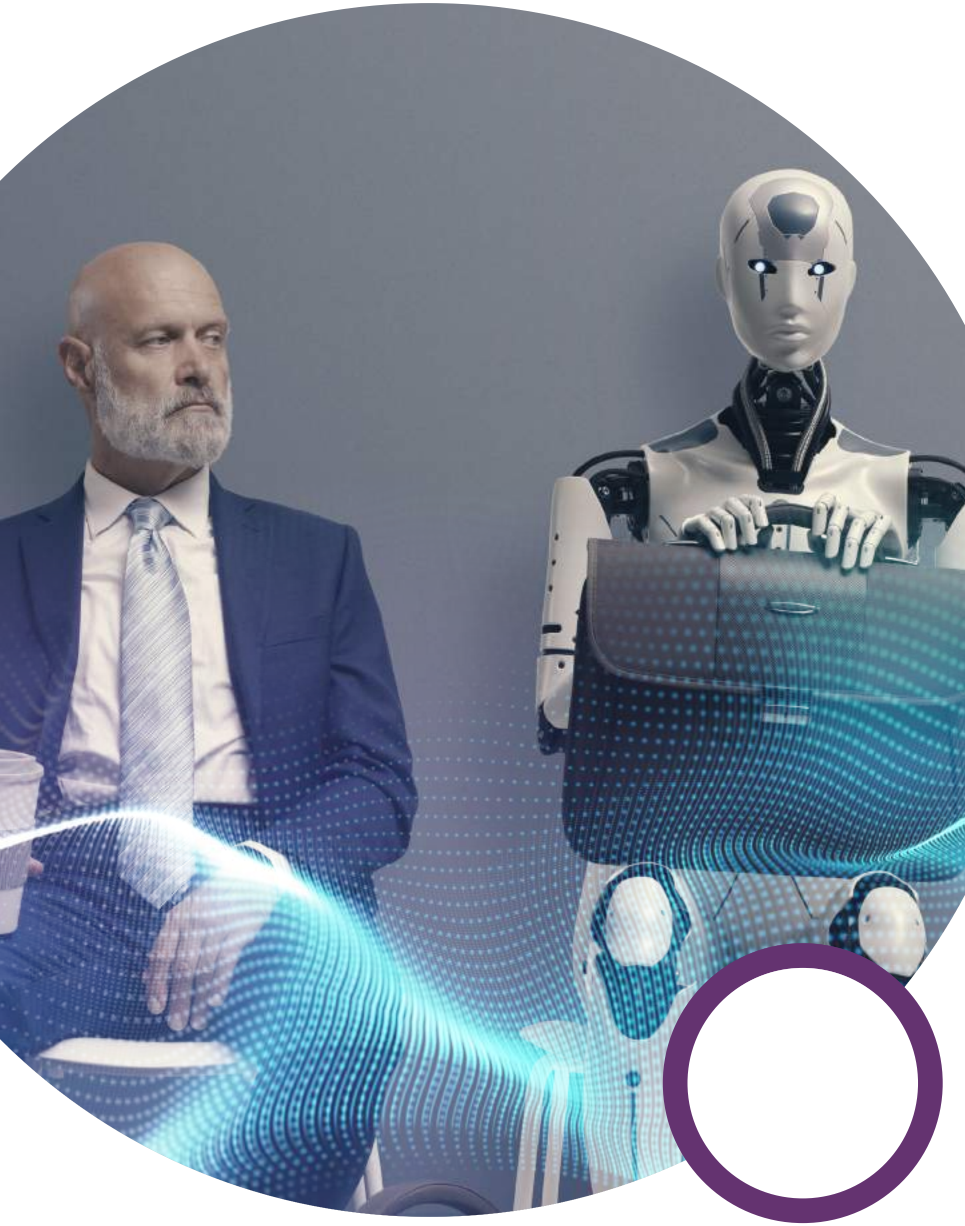
AI is many things, but it is not a panacea. It is critical that we also educate the next generation of researchers about the limitations of these tools. When we talk about artificial intelligence we have to understand where that intelligence comes from. Today's machine learning systems develop intelligence through experience. This experience either comes from training data collected by humans or through experimentation in simulators. If the data is poor quality, or the simulator does not accurately describe the system it is meant to represent, then the AI will be ineffective at achieving its goals.

There is a well-worn but important phrase in computer science: "garbage in, garbage out". Researchers must remain aware that AI cannot be thrown at a scientific problem with the expectation of a solution. We must understand that how we apply these tools matters as much as where we apply them.

Scientists will also need to get to grips with the challenge of "problem specification", which refers to deciding exactly what problem that they want AI to solve for them. To understand why, consider the design of antibiotics. Set a machine learning system the goal of finding a drug that efficiently kills bacteria, and it is likely to come up with something that would also wipe out a patient's microbiome — their body's health-enhancing bacteria. Instead, the AI must be tasked with optimising its search to find a drug that selectively targets specific pathogens.

And while AI can dramatically accelerate progress in research, it is not a substitute for scientists themselves. Researchers that use AI cannot afford to rely blindly on it — especially given that many machine learning systems remain black boxes whose inner workings can be difficult to decipher. Researchers should be aware of the limitations or biases of any AI tools they work with.

Perhaps most challenging of all, we will have to come to terms with what an AI-powered acceleration of scientific progress could mean for society. If AI helps us solve fundamental problems in areas like biology and quantum chemistry, it could put unprecedented capabilities in our hands. That could be good — science can be used to ensure we all live richer, happier lives — but we must always remain aware that this power can have negative consequences too. How do we ensure that the fruits of this new era of scientific progress align with our priorities, values, and goals? This is an important question and one that neither DeepMind nor the scientific community can answer alone. AI will ensure that science transforms society. It is up to all of us to make sure that this transformation is for the better.



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Invited Contribution: Robotics and the Challenge of Embodied Intelligence

The idea that we will soon have robots capable of performing many of the same tasks as humans has become commonplace, thanks to their depiction in films, television and books. However, the design of robots that can sense and process information about their environment, then use this information to make decisions about their own behaviour, remains a major and multi-faceted research and engineering challenge.

Despite recent breakthroughs in Artificial Intelligence (AI), robots' cognitive systems still lack many of the abilities that humans possess when it comes to tasks such as robust perception, adaptive fine motor control, and adaptation to external conditions. For this reason, robots tend to operate most reliably within precisely calibrated and controlled environments or for a predefined set of operations. To perform in the world at large, they will need to reliably sense and plan their actions depending on, and continuously adapting to, the external environment and their internal state. If this can be achieved, they will be able to interact seamlessly with the environment and other agents to accomplish a range of different tasks, much as humans do. This "embodied" intelligence will represent a genuine breakthrough in creating machines that are able to reason, based on their own perceptions, in order to achieve a desired outcome.

Embodied intelligence is based on two distinct principles. The first principle is that **the way a body is built is instrumental to its perception of the external world and to its behaviour and actions**. That is, the way a robot is constructed will govern what it can perceive and what it will do: having two eyes, for example, gives depth perception through stereo vision; having legs connected to the body through hips enables the robot to exploit pendulum dynamics, allowing it to walk more energy-efficiently.

The second principle of embodied intelligence is **the linking of morphology, perception and action**. Current disembodied image recognition systems, based on deep learning, are trained on many online images, typically taken passively by static cameras. These are thus completely uncorrelated with whatever action a robot has done, or needs to take. The problem of perception becomes more difficult still because there is no information about how the object sounds, feels, or changes in appearance when moved. A robot looking at the world, however, can move its sensors and interact with the object to improve what it sees, in the interest of acquiring more information. It might, for example, move it to gain a clearer view, or rotate it to get multiple views; it can also use additional senses, such as touch, to gain further information about the object. It can simultaneously relate its actions to their sensory consequences in order to improve its execution of a specific action or particular function.

Furthermore, the interplay between the morphology of the robot and its behaviour can improve the efficiency of the overall system: for example, foveated vision allows for both high-resolution central vision and a wide field of view, while optimising resources (size, connectivity and data load), provided it is coupled with the intelligence needed to move the eyes towards salient stimuli.

Those are the principles; what about the practice? The datasets currently used for training state of the art AI models are mostly disembodied, and therefore do not allow us to study the role of learning in the interplay between morphology, actions, and perception. Embodiment enhances the possibility of developing intelligent and efficient systems, using less data to learn and supporting continual learning in new environments. So **the first challenge is to understand how to encode intelligence robustly**, enabling data from multiple sources to be processed on multiple timescales to ensure life-long learning, adaptation and memory organisation.

Current AI methods also have immense computational resource requirements, requiring large datasets and lengthy training times, and often also expensive hardware and vast amounts of energy. That means they are not well suited to embodied AI, which will have to deal with multiple different scenarios expediently, without learning from a vast new dataset for each situation. So **the second challenge is to develop embodied AI models that can efficiently adapt and learn** new tasks in ever changing scenarios, using less data, time, computational resources and energy.

Recent meta-learning techniques can improve on the problem and lead to systems that can adapt to novel situations: using "one-shot" or "few-shot" learning, a system can assimilate knowledge and learn a new task from just a few examples. However, this will barely approach the efficiency of biological neural networks shaped by millions of years of evolution. The biological networks are vastly more efficient than conventional computing at perception, hierarchical information extraction, adaptation, continual learning, and memorisation of temporally structured data.

If we can understand how neurobiology evolved, develops, and works, we can use the same principles to give us a head start in developing **neuromorphic computational systems** for robotics that will show robust, reliable and adaptive performance in complex, ever-changing and uncontrolled environments, as well as higher efficiency, lower latency and reduced computational cost. There are multiple "technological" and computational factors that underlie the brain's capabilities, including event-driven encoding, high parallelism, and the capability of neurons to compute and store information in the same place.

Consider the first of these: event-driven encoding. Today's conventional sensors sample and process information at single moments in time, determined by the rhythm of an internal clock, rather than being driven by external events. By contrast, biological systems sense and process changes in sensory data, sampling data as and when these changes occur. For example, if we flick a switch so a light goes off, the retina of the eye is stimulated and information about the change is transferred to the brain, rather than an ongoing succession of reports about the on or off status of the light. This event-driven sensory information is not only very rich, but requires much less computational power than a clock-driven system, and can thus allow the computational sensory system to become much more efficient than conventional AI.

While GPUs support a high degree of parallelism, they are still based on conventional computing infrastructure, whereby memory and processing are physically separated: performing an operation requires the machine to extract the relevant information from its memory, transfer it to the processor, perform the operation, and then transfer the outcome back into memory. This comprises most of the cost of current computation. By bringing these two functions together (while also supporting highly parallel computation) as they are in the brain, neuromorphic computing has the potential to vastly increase the efficiency of the computational process itself.

Neuromorphic technology is moving embodied AI on from a static, frame-based computing system to a dynamic, event-based system able to efficiently process information and adapt to new situations. While event-driven vision sensors have reached the consumer's market, neuromorphic computing platforms are still evolving and mostly used within the research domain. In the next few years, we will see silicon-based platforms in the market. At the same time, evolved systems, with additional computational primitives and memristive devices for co-localisation of memory and computing, will be available to the research community at large. Novel neuromorphic computing devices are in the making, based on flexible organic electronics, organoids, photonics and other innovations.

Progress in neural computation, as well as neuromorphic hardware, will be needed to build neuromorphic systems. Describing a brain's computational process mathematically, to produce a function that can be plugged into a processing system, is challenging, especially since we don't yet fully understand all of biological computing's components and their computational role in a unified conceptual framework. In a biological system, neurons can not only interact with one another, but their computational function is affected by the manner of their interaction. There are different forms of plasticity and computation performed at different temporal and spatial scales.

As an example, while most neuromorphic computing uses point neurons, biological neurons are way more complex: dendrites, the branched, tree-like structures at the end of neurons, gather signals though contacts with other cells in their vicinity and from other brain areas. The signal received depends not only on the type of chemical contact between the cells, but also on exactly where the two branches of the cells interact and the time it takes for these signals to travel through them. More neuroscience research is needed to understand the computational relevance of each component of the biological system; this understanding can then be integrated into neuromorphic computing and in the development of new neuromorphic hardware platforms.

That will make them much more useful in relatively unconstrained real-world situations, as already demonstrated by proof-of-concept systems that can solve specific perception and control tasks, and carry out simple decision-making such as visual and auditory classification, sound source localisation, visual and auditory attention, basic navigation, obstacle avoidance, landmark recognition, trajectory prediction, and so on. In few years, more robustness and adaptation capabilities will be achieved by the integration of new computational methods such as balanced EI networks, dynamic attractors, multisensory integration and lifelong learning. This will later need to be scaled up and integrated with cognitive large scale brain models to solve complex human-like tasks.

There is a long way to go, but neuromorphic computing to create robots with embodied intelligence is essential for machines to display true hallmarks of cognition, and for AI to become meaningfully intelligent. Machines need to be aware of their environment, be self-aware of their own bodies, robustly interpret their own sensory data, and make decisions about the action that will best fulfil their task. Only then will we have robots that are truly fit for the real world.

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Invited Contribution: The Future of History in the Digital Age

We have entered the “age of abundance”: a huge number of historical sources – books, documents, pamphlets and media of all sorts – have by now been digitised, and the amount of digital-born material is growing at an even faster pace. This boom is paired with new forms of access: in principle, digital sources that are made available online can be studied from anywhere in the world, and powerful digital tools allow us to study the big data of the past in a new fashion.

However, digitisation poses challenges too. These new digital sources are no longer “originals” in the classical sense, but information that has been constantly manipulated, recoded, and reframed. Dealing with a retro digitised source on a screen is very different to sitting in an archive and holding an original letter in your hand.

The methodology of source criticism, developed in the 19th century, is a key scientific competency for historians: being able to understand whether a source is original and authentic, or if it has been manipulated, copied or changed in any way. This methodology needs to be updated for the 21st century as “historical data criticism” — but that poses some foundational questions. What constitutes evidence? How can we authenticate both sources that have been retro-digitised and those that were born digital?

Future historians will need new skills and competencies in order to understand how to analyse and interpret digital sources and documents. In the era of deep fakes and fake news, this isn't just an issue for historians; given their expertise in source criticism and critical contextualisation of evidence from the past, historians have a lot to contribute in the emerging field of "digital forensics".

Digital history emerged as a field 30 years ago, closely related to what was then known as computational humanities. Its first phase focused on how new mainframe computers could be used to collect and manage historical data – for example the collection of economic data (sales statistics), environmental data (weather records), and demographic data (marriage and birth rates) over long periods of time. The second phase, starting in the 1990s, was defined by the mass digitisation of analogue sources by cultural heritage institutions such as archives, libraries and museums.

Currently, we are in the field's third phase, which is focussed on the critical reflection of how new digital research infrastructures and tools change, how we think about history and what narratives we produce. In short, how does the digital affect our imagination of the past and thus our conception of history?

This involves an all-encompassing reflection on how the digital interacts with the way we do historical research, including how we search for, manage and curate data; how we analyse data with new text mining tools; and how we use methods of data visualisation for the production of new forms of transmedia storytelling. In addition to source criticism, we need new competencies and skills to critically evaluate how we search, analyse, visualise, and interpret historical data. Understanding how digital infrastructures, data sets and tools are altering our object of study is called digital hermeneutics.

Next to the methodological challenges, the digital revolution has fostered new epistemic values and virtues such as openness, transparency, traceability and sharing, which now sit alongside the traditional epistemic values of objectivity and accuracy. However, divisions and inequities in the infrastructures that determine access to knowledge are being reproduced in the digital realm, with even greater impact. For example, issues such as the overrepresentation of English and European languages in mass digitalisation of cultural heritage collections mean that the rich cultural heritage of countries such as China or Japan or of the many oral knowledge treasures of indigenous cultures around the world is not feeding into the new digital knowledge base that we're building.

This cultural disenfranchisement has been referred to as 'epistemic injustice' by the philosopher Miranda Fricker, and is becoming increasingly relevant when it comes to questions of democratisation and access to historical data, as well as the knowledge and historical narratives that are produced from the data that is available. To combat this risk, we must actively invest in the retro-digitisation of non-European, non-Western cultural heritage, over the long term.

Looking forward, moving into the fourth phase of digital history will require historians to develop a new form of reading of historical sources. Machine-driven reading of vast digital corpora can identify statistically relevant patterns and semantic topics, but this "explorative reading" of a dataset needs to be combined with the "close reading" of individual sources. Combining artificial with human intelligence will be key but requires an understanding of both the strengths and weaknesses of these two forms of rationality and logics of sense-making. Learning to move easily between these two forms of reading will require training a new generation of historians in a new cultural technique of information retrieval and interpretation which I frame as "scalable reading". This is not only true for historians, but also for practitioners of other disciplines in the humanities, social sciences and journalism.

Change, however, requires co-evolution and time. With tools and technologies being invented and deployed at a much faster pace than their critical appropriation, our education systems are struggling to balance these two factors. In addition, technology has opened up the universe of information to everyone, rather than a well-schooled elite. Teaching must therefore focus on developing critical competencies for dealing with a wide range of sources rather than instilling students with deep but specific corpuses of knowledge. However, this will in turn require drastic changes in the curricula and management of academic institutions such as schools and universities — and these are generally very conservative organisations.

A second big challenge for the future of history as a field is to engage in interdisciplinary approaches and to practice history as collaborative and situated form of knowledge production. Digital history can be thought of as a "trading zone" between many disciplines (history, computer & data science, web-design, statistics, library & information science, cultural heritage & archival science, etc.), which asks for systematic co-design of research projects and outputs. Learning each other's "languages" and understanding the different epistemic traditions require long-term investments that are usually not funded by short-term research grants.

Such collaborations also affect questions of authorship and recognition culture. The co-production of historical knowledge in the digital age necessarily involves co-authorship in terms of publications and outputs. Paired with the aim of multi-perspectivity and multi-vocality when it comes to the production of historical narratives, the future of digital history as collaborative practice will hopefully contribute to the democratisation of historical storytelling and the promotion of shared authority.

2

Introduction to Human Augmentation

In 2023, GESDA convened a High-Level Anticipation Workshop on Neuro-augmentation, where leaders in the field discussed the latest trends and breakthroughs with a view to anticipating future developments in the areas of brain hacking, hybrid brains and artificial cognition. The workshop report is included in this edition.

It is clear that recent advances in neuroscience and machine learning have ushered in innovations for **cognitive enhancement**, for example, improving human memory, cognition, and other aspects of consciousness. In the near term, such technologies will treat neurodegenerative disorders and psychiatric conditions that involve significant memory impairments and for which currently no therapies exist. Reading from, and writing to, the brain is becoming increasingly sophisticated — especially as AI research improves our signal-reading capabilities — offering a range of new applications. Human memory augmentation will become increasingly available for enhancement purposes, alongside psychoactive drugs that improve cognitive abilities beyond IQ.

Genome editing is already improving diagnostics and treatments for cancer and potentially many other diseases of ageing. Such research into **human applications of genetic engineering** is also pointing the way to a future in which bodies can be engineered to be free of cancer, HIV and other infectious diseases. Genome editing even promises to make such changes heritable, meaning future generations will not require preventive therapies. Techniques such as epigenome editing and metagenomics are expanding the portfolio of gene editing tools, promising a new flexibility to achievable outcomes.

Beyond dealing with existing problems, scientific and technological tools may redefine the fundamentals of human experience, such as what we mean by "getting old". Research to assess ageing processes, and to find biomarkers and other signifiers of age, is suggesting that what we think of as the markers of inevitable ageing could be eradicated, and the physical changes that we associate with ageing might even be reversible to some degree. A new generation of clinical trials on **healthspan extension** is about to test such ideas.

Lab research using a range of tools such as electromagnetic interventions, molecular psychedelics and pharmaceutical drugs, suggests that it might be possible to expand consciousness beyond the limits imposed by human senses, standard cognitive capacity and injury or disease. Such **consciousness augmentation** could help us improve education, reasoning, memory and the quality of human interactions and give us new ways to diagnose and assist people suffering debilitating disorders of consciousness.

One of the greatest impediments to progress in medicine has to do with a lack of experimental resources. Fully understanding the origin and progress of diseases and the efficacy of drug candidates requires research on living biological tissues. But neither animal models or human cell lines provide a fully realistic model of human biology, which is why the use of organoids — simplified versions of real organs — holds such promise. A range of **organoids** is now in development, mimicking the properties of brains, tumours, kidneys and even embryos. They are being grown and put to work to investigate the fundamental processes of human biology, the pathology of diseases and the potential for novel treatment pathways. When grown from a patient's own cells, organoids can provide a strong suggestion of suitable interventions. Eventually, they may allow the culture of replacement organs for transplantation.

Although innovations in medicine have been radically extending human lifespan for more than a century now, there is still plenty of room for improvement. Cardiovascular and metabolic diseases are largely preventable, but still end a significant number of lives unnecessarily early. However, a range of new treatment options are coming into view, and these **future therapeutics** could have a great deal to offer medical practitioners. Advances in information technology, biotechnology and basic understanding of how human biology operates are enabling use of electrical signals, AI-driven data analysis, cell therapies and even the mechanisms of the immune system to improve the maintenance of good health, diagnosis of disease and the results of medical interventions.

Turning this vision into reality will require careful management. If any of these innovations are to achieve their full potential for improving human well-being and establishing more inclusive societies, they need to be deployed to all of humanity rather than an elite segment who can afford them. Here, we examine the research on human augmentation now underway, and anticipate how, if carefully regulated and deployed, it could be truly transformational.

2023 Villars High Level Anticipation Workshop on Neuro-augmentation

Patrick Aebischer
Vice-Chairman,
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Chair, GESDA Academic Forum,
President ETH Domain

At the inaugural Villars high-level Anticipation Workshop, a carefully chosen group of leaders from across several relevant disciplines met to discuss issues pertinent to the future of "neuro-augmentation". The meeting was organised by the GESDA Academic Forum with the financial contribution of the foundation Defitech. A full list of attendees is in the online version of this report.

The uptake of devices that measure and influence the activity of the brain and nervous system is rapidly growing as they spread from university research out to clinical applications. According to one estimate, the neurotechnology marketplace is worth $14.3 billion US, with that number due to climb beyond $20 billion within four years.[1] Brain-monitoring devices, brain-machine interfaces, and other ways of reading and writing the signals of the nervous system are on the cusp of wide adoption across society. Their ubiquity could change everything from workplace rights to what it means to be human.

The development of neural augmentation science and technologies will pose significant challenges to society and individuals, asking questions about what it means to be human, how our society functions and the processes of science. While such technologies are still under development (and some face significant road blocks), anticipation is an ethical imperative. Issues that arise will include: whether neuro-augmentations will be optional in the workplace; their potential effects on other aspects of our biology and on self-determination; the optimal trade-offs between intrusiveness and usefulness; who will benefit from this push to neuro-augmentation, and what potential ethical and legal consequences will emerge? The technological improvements are happening quickly enough that we may only get one chance to ask these questions.

The gathered experts were uniquely positioned to provide informed insight about the technological and scientific progress that will drive the direction and speed of neuro-augmentation. They outlined the current status of the science and identified areas of immediate, mid-term and far term impact and concern, and how this should drive the focus of diplomatic and ethics intervention. This report is structured as follows:

1. **Reading from and writing to the human brain:** state of the art; predictions and possible applications; current obstacles to progress
2. **Hybrid brain development:** state of the art; predictions and possible applications; current obstacles to progress
3. **Artificial cognition:** software simulation; biomimetic hardware; AI as external cognition; predictions and possible applications; current obstacles to progress
4. **Ethical and governance dimensions:** considerations for the individual; considerations for research animals and other entities; responsible anticipation.

1. Reading from and writing to the human brain

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State of the art

A current standard, FDA-approved implant for reading from the brain is a "Utah" array with around 100 electrodes. These can pick up cortical signals and analyse them in order to decode motor and language functions, such as language production. Patients who are no longer able to speak – whether due to traumatic injury or neurodegenerative disease such as ALS – have participated in several trials of such implanted devices. The technology's capabilities have accelerated due to machine learning. In 2017, language acquisition using this technology was at 8 words per minute using a keyboard-based manual letter selection process. When researchers developed machine learning algorithms that could pick patterns in the brain data from local electric field potentials, it became possible to detect which letter a user was thinking about writing. This raised the rate of writing to 15 words per minute. Now it is possible to detect language formation intent in relevant areas of cortex at a rate of 65 words per minute.[2] In 2021, the FDA approved the "Stentrode", an endovascular implant that can translate brain activity from inside a vein in the motor cortex. In a 1-year safety trial of four people with paralysis,[3] the device enabled thought-mediated control of computer activity, including shopping and sending emails. One patient was able to chat on Twitter.[4] The company behind the Stentrode are still recruiting for more safety trials.

Decoded neural signals have long been used to actuate external robotic limbs and tools, as demonstrated in experiments like BrainGate.[5] More recently, it has become possible to use them to actuate parts of the human body whose control has been lost to spinal injury. Several labs are working on a "neural bypass" that routes the brain's signals around areas of spinal cord damage, activating the remaining undamaged nerve fibres that actuate the limbs. By stimulating nonfunctional but undamaged neurons or nerves that lie beyond the site of damage, signals obtained from invasive electrode arrays (and less penetrating electrodes such as electrocorticography implants beneath the skull) are able to re-activate these nerves using the motor command signals, which has restored the ability to walk and even some proprioception — that is, limb perception and movement.[6,7]

Substantial recordings form single neurons in the brain have also been achieved in clinical settings using platinum-iridium microwires. Most commonly this approach has been employed in epilepsy monitoring units where these microelectrodes can record single neuron activity in patients who can declare their memories and intentions. These studies suggest neuronal signals prior to conscious memory recollection or intention, thus in principle presenting the possibility of decoding cognitive faculties such as memory and will prior to subjects being consciously aware of them. This means not only reading your mind, but reading your mind before it is made up.

Writing to the brain is a much less developed field. It has been possible, with invasive implants, to use Utah arrays to generate patterns of electrical pulses that stimulate a targeted collection of neurons, with the effect of implanting "false" sensations.[8] Other experiments have ostensibly implanted false memories in animal models, or removed specific memories, though whether these experiments will have useful outcomes in humans has been questioned. In humans, the representation of conceptual knowledge in memory and will is encoded in single neurons.[9] Although understanding these codes could help predict and modulate memory and behaviour, the tools capable of activating deliberate intervention may need to penetrate deeper than the cortex, which seems to lie beyond the practical capabilities of the current generation of implants. Many potentially suitable tools, most famously Neuralink, are in development but not yet approved for this purpose.

The neuroprosthetic devices of the future will need to combine reading from and writing to the brain, that is they will need to be closed-loop systems. Such systems are entering clinical use, such as the Responsive Neurostimulation system for epilepsy or adaptive deep brain stimulation for Parkinson's Disease, but these systems still lack specificity and single neuron resolution.

The most technologically mature alternative is optogenetics, which allows the activity of genetically-edited neurons to be switched on and off with light. Over the past two decades, it has become an increasingly important tool for neuroscience, allowing researchers to probe how the brain works, how specific networks or neurons might be controlled to treat disease, and even to control behaviour in animal models. Multiple clinical trials are now ongoing to investigate the treatment of retinal degenerative diseases using optogenetic methods.[10] However, because the retina is manipulable with non-invasive light sources in a way that other neurons are not, and uniquely accessible to gene editing, it is less clear what the next targets within the brain could be. That said, as the cochlea lies in the periphery, optical cochlear implants offer the possibility of optogenetic approaches to hearing restoration.[11]

Another alternative route towards writing to the brain is by exploiting its own plasticity and ability to adjust to new information in 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, over-writing circuits to accommodate the addition.[12] Controlling this digit does not require invasive implants, and can be done intuitively and quickly by recruiting a different or redundant part of the body into service, for example a toe whose movements drive the thumb. This proof of principle — that the brain will quickly adopt a new tool and adapt its body plan accordingly, augmenting its ability to manage its environment — has led to interest from several corporations for further development and adoption in a manual workforce to increase productivity, and from clinicians as an alternative to traditional assistive technologies.

There is strong early evidence for a fourth route to brain modulation. Mouse and observational human studies indicate that epigenetic variations initiated by environmental factors are a powerful modulator of both behaviour and function in the brain.

In some ways this is expected: the brain is constantly changed by its interaction with a changing environment, and brain cells, like all other cells in the body, have a dynamic epigenome influenced by these changes and by experience. There is simply more to the contribution of the epigenome to the brain than is classically thought. While we have long known that epigenetic processes control gene expression during development and determine cell fate, recent research in neuroepigenetics has shown that they also control the genome in the adult brain including in postmitotic cells. The power of the epigenome goes beyond altered gene expression. Epigenetic factors and mechanisms control genome activity and its very architecture. A form of structural memory can be instantiated by epigenetic changes, for example, providing a way to encode specific information into cells.

In some cases, this information is heritable and can be passed across generations when it is present in germ cells. Specific experiences such as stress, poor diet, and exposure to endocrine disruptors, can alter epigenetic factors across the body including in the brain and reproductive cells and can affect brain plasticity, cognitive functions and behaviour and lead to psychiatric disorders and physiological dysfunctions in exposed parents and their offspring.

Research is underway to tease apart the relevant factors and their control over genes or genomic loci that influence brain plasticity and behaviour, but learning to exert some measure of control over this could be important. Taking command of specific epigenetic control mechanisms could help attenuate or prevent cellular dysfunctions and possibly some aspects of disorders from arising, but may also favour desirable behavioural traits. Epigenome editing has the added attraction that, unlike gene editing, it is reversible.

Predictions and applications

In the near-term (5 years), technology for reading and writing the signals of the brain is predicted to become wireless, integrate a higher channel count and become biocompatible. That said, the most mature and impactful near-term technologies will remain non- or minimally invasive (an example being wearable augmentation). One especially promising area for near-term neuro-augmentation is enhancing the depth and quality of sleep with a closed-loop implanted or wearable EEG device that could provide even non-invasive stimulation to push a waking brain back into sleep when needed, or push a sleepy brain into alertness. Sleep may well be a major port of intervention, and change in the architecture of sleep may prove important in enhancing cognitive function such as memory.[13]

In the medium and far term (10 to 25 years), following this trajectory, brain-computer interfaces will provide better readouts of brain states combined with closed-loop neurostimulation, they could lead to restoration of sensation and bowel control. In the cognitive domain they may provide another tool in combating the devastating effects of neurodegenerative conditions such as Alzheimer's and Parkinson's Diseases.

For optogenetics, the first medical use case will be restoration of vision. One of the most promising applications is the treatment of retinal degenerative diseases. Multiple clinical trials are ongoing.

For epigenetics, the promise is big, although extremely speculative. Preliminary studies suggest it might be possible to "rejuvenate" the epigenome – erasing the signals and modifications accumulated over a lifetime – to restore youthful vision.[14] Such therapeutic use cases are still far off. However, within five years, it may be possible to profile the epigenome in individual brain cells in healthy adults and disease.[15] Within 10 years we could have functional and causal links between epigenome and some brain functions. In 25 years, epigenome editing of the brain and the germ line may be possible, providing resilience against disruptive factors in the environment. Editing tools could involve CRISPR systems but, instead of modifying the DNA code, change the epigenome and the way a piece of DNA is regulated. An attractive first target may be post-traumatic stress disorder which has been associated with epigenetic alterations in the brain, and whose manipulation has a favourable risk/reward ratio.

Current obstacles to progress

If we are to develop better electrical implants, the materials used will have to become more biocompatible in order to listen in on more brain data. However, there are other ways existing electronic brain-machine interfaces need to evolve. Wireless data transfer methods will also need to be developed - but there is a fundamental limit to how fast data can be processed in situ, or transferred out of the brain and onto external processors. That is due to thermal issues: beyond a certain rate of data transfer, the heat generated begins to cook the brain tissue. This presents a major hindrance for wireless brain implants as both wireless transmission and on-chip processing require tens of watts, which generates enough heat to burn the surrounding tissues. This reality sits in tension with the fact that, for electrical implants to go outside the lab, devices will need to be wireless.

For the moment, these implants will require surgery because it is currently impossible to replicate the capabilities of implants with non-invasive surface technologies (though progress is being made in this area). The physics of how signals attenuate within brain tissue means that we simply cannot pick up the details of signals emitted deep within the brain from the surface. Edge computing, where data processing occurs on distributed devices close to the user, may help.

For optogenetic approaches, the perennial impediments are gene and light delivery methods. New methods are constantly being proposed.[16] The first success of the technique, for retinal degenerative disease, worked in part because of the accessibility of the light source (at the surface of the eye, there was no need to import light, as it was naturally available). Translation into subsequent successes will depend on new ways to get light into deeper targets in the body, which currently necessitates invasive procedures.

For epigenetics, the roadblock is the lack of clarity as to whether epigenetic profiles from animal models translate to humans. Then there is the question of whether these edits are stable,[17] and the usual questions about gene editing: is the delivery sufficiently targeted, are the editors precise enough?

2. Hybrid brain development

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State of the art

To extend the capability of implanted devices, or to translate their capabilities from the university lab into the clinic, requires a deeper understanding of the brain that explains longstanding open questions of neuroscience such as, for example, how neuronal diversity emerges during early brain development and assemble into complex neuronal networks and circuits to allow the execution of high-order human brain functions, including cognition, sensory perception, and motor control. For obvious ethical reasons, the developing human brain is largely inaccessible for study. Despite animal models having been very useful in providing insights into basic principles regulating the development of the mammalian brain, important interspecies differences make them unsuitable for understanding aspects of human brain development and function that are distinctively human. To accelerate new insights in neuroscience, therefore, researchers are increasingly turning to organoids, chimeras, and transgenic animals.

Organoids

Organoids – miniature and very simplified models of real organs – are tridimensional aggregates derived from stem cells, able to reproduce biological structures similar in architecture and function to the endogenous tissues.

In particular, brain organoids show great promise for the study of human brain development and function; brain organoids have been shown to recapitulate processes of human brain development with high fidelity and reproducibility[18,19] They also exhibit basic features of functional activity resembling those observed in the developing human brain.[20]

Brain organoids provide a unique opportunity to investigate mechanisms beyond neurological diseases. Indeed, organoids have been used to investigate the neurobiological basis of many conditions including lissencephaly, autism spectrum disorder, epilepsy, tuberous sclerosis and Zika virus infection.

Despite the remarkable progress that has been made in the brain organoid field, many challenges remain. Current brain organoid models fail to recapitulate precise anatomical structures, and well-defined circuits are also not formed. They lack experience-dependent stimulation, which is important for in vivo circuit maturation. Finally, most organoid models still lack a complete representation of the cell types found in the developing human brain. Achieving cellular and functional maturation in vitro is one of the major challenges for the organoid field, this is particularly true organoids modelling the human brain that in vivo take decades to develop. Therefore, despite being invaluable models of the developing human brain, current brain organoids cannot fully mimic the complexity of the adult human brain.

Chimeras and chimeric organoids

Building more complex and physiologically relevant organoids will require solving problems like the lack of anatomical organisation and vasculature, and the limited organoid maturation. Current approaches to overcome these limitations include generation of assembloid organoid models, co-culture with missing cell types (such as microglia), and integration of exogenous vasculature

Another potential way to address these limitations, is to transplant human brain organoids into rodent host brains to provide a more physiological environment, including vascularisation, access to appropriate developmental cues, and cell-cell interactions.[21] Doing this using cells from several different individuals implanted into animals could enable full organoid maturation for transplants.

Transgenic animals

Despite the fact that human brain organoids can be used to model and understand the neurobiology behind disorders, these models are unable to replicate complex functions such as emotion and behaviour. But animal models have their limits: neither non-human primates nor mice can recapitulate all aspects of human phenotypes, especially if they involve complex genetics and affect higher-order brain functions, as with neuropsychiatric disorders. However, proof of principle concerning the power of introducing human genes, such as MCPH1, into monkey models have recently emerged.[22] Inactivation of another gene, BMAL1, a gene associated with circadian rhythms and the brain's internal "clock", has resulted in monkeys exhibiting the traits of human-like psychiatric disorders,[23]. Research into the evolution of human intelligence found that monkeys carrying the human gene MCPH1, which is associated with DNA repair, performed better on short-term memory tasks. Such research opens the door to transgenic animal studies to explore specific genes in more human diseases, including distinctive brain diseases.

Predictions and potential applications

In the near-term (5-10 years), more sophisticated brain organoid models will be available. They will include a larger diversity of cell types, vascularisation, and more mature circuits. The development of brain organoids will be faster and enhanced maturation will be achieved. This will allow better modelling of late-onset neurodegenerative diseases, such as Alzheimer's Disease. Importantly, the increased speed of brain organoid generation will offer the opportunity to develop and test drugs on patient-derived organoids to identify customised treatments that consider the specific characteristics of each individual (that is, personalised medicine). One especially promising area will be the possibility to combine multiple donor cells within single organoids to study genetic and environmental perturbations in the context of inter-individual variability. Within 10 years we could expect to gradually move from the use of brain organoids for disease modelling to drug discovery and development. Following the FDA Modernization Act 2.0's incentive on alternative non-animal testing approaches, brain organoids will become more and more implemented in preclinical studies.[24] It will be possible to treat devastating conditions that affect many brain functions, including cognition, resulting in "neuro-augmentation" of patients.

In the medium and far term (10 to 25 years), biological, brain-directed computing (biocomputing) using 2D or 3D cell cultures might be used to overcome limits of current silicon-based computing, including speed and energy and data efficiency. Furthermore, brain organoids might be able to replicate basic molecular and cellular aspects of cognition in vitro, such as learning and memory and help understand disorders associated with cognitive impairment.

For chimeras, the near to medium term (5-10 years) will see advances in throughput and standards, and an extended longevity of implanted organoids, both for monkey organ development in pigs, and eventually for human organ development in pigs.

For transgenic animals, it will be possible to demonstrate that this line of research is useful for neuromodulation or therapy within five years. For example, probing the mechanisms of schizophrenia in a macaque model could result in better drugs or other treatments.

The ability for organoids to manifest "learning in a dish" could provide the basis of future biocomputing.[25] This vision of biocomputing would encompass a complex, networked interface connecting brain organoids to real-world sensors and peripherals. The system could take advantage of biological memory and learning which is now beyond computing systems. Bigger and more complex organoids could also increase the efficiency of computing more generally. Linking brain organoids up to sensory organoids to allow them to perceive the world – a multi-tissue structure called an assembloid – could improve machines' ability to interact with the environment. Near to far term (10-25 years), organoids will recapitulate complete neural circuits, not simply cells that touch each other. This research will begin to underpin mechanistic conduits to human mental traits. In the far term, cells from several different individuals implanted into animals could enable full organoid maturation for transplants.

Current obstacles to progress

Organoid technology is steadily improving, and research is achieving better replication of processes of human brain development and function. However, many challenges remain, including attaining increased cellular complexity.[26] Current brain organoid models still lack a complete representation of the cell types found in the developing human brain. They fail to recapitulate precise anatomical structures, and well-defined circuits are also not formed. Finally, brain organoids lack experience-dependent stimulation, which is important for in vivo circuit maturation.

Achieving cellular and functional maturation in vitro is one of the major challenges for the broad organoid field and is particularly arduous to achieve in organoids modelling the human brain, which in vivo takes decades to develop. Despite being invaluable models of the developing human brain, current brain organoids cannot fully mimic the complexity of the adult human brain.

Biocomputing harnessing brain organoids requires more standardised and sophisticated models with increased cell density. The number of neurons generated in organoids is limited by culture conditions. The lack of vascularisation also contributes to limiting brain organoid growth and neuronal survival over extended times; however, microfluidics work has supported the growth of complex intestine organoids,[27] leading to hope that this approach may work for brain organoids. Instrumental for biocomputing will be to generate brain organoids with reproducible and defined cell types that interact in precise neuronal networks and circuits, like those in vivo.

Organoid production needs to become more scalable. Thousands of identical organoids are needed to allow the application of brain organoids for large-scale drug and toxicology screening. Analysis methods that fit high-throughput screening requirements are also needed.

3. Artificial Cognition

Inputs by

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State of the art

Organoids, chimeras and transgenic animals will generate valuable insight but in order to develop fine-grained models of brain processes, in-silicon representations may be more useful. Such "artificial cognition" — an umbrella term that encompasses simulation of human brains, or AI or hardware that recapitulates biological brain functions — is already generating new insight about neuroscience. Further development could eventually provide high resolution, global scale models, including digital twins of brains, to enable research it is not currently possible to conduct on biological substrates.

Conceptual advances in computer science and neuroscience also form a feedback loop — the more we understand about the brain, the more we can use these insights to improve artificial intelligence,[28] and the more, in turn, these increasingly powerful computers can unlock new insights about the functioning of the human brain and its potential augmentation. Three broad areas emerged from the discussions: software simulations of the brain, biomimetic hardware, and external cognition.

Software simulations of the brain

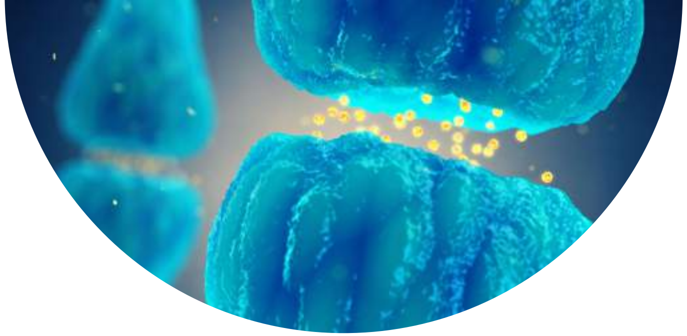
The Blue Brain project, the BRAIN initiative and the China Brain Project have yielded an abundance of data. Blue Brain has created a biologically-realistic rendering after collecting brain data from a wide variety of sources, with fidelity high enough to allow investigation down to the ion channels in individual neurons.

A biological-scale simulation of the brain could lead to "digital twin" sandboxes of real people's brains in which hypotheses about disease progression, as well as simple general insights, could be tested. In-silico perturbation of gene expression could allow you to predict which types of cells will be created, for example.

An alternative approach, which could provide insights without the computational load of a biological-scale model, is to scale down the resolution to a fraction of the brain's 86 billion neurons but retain crucial principles of structure and organisation that reproduce specific functions and behaviour. Even with 6 million neurons, one such model has been able to test hypotheses, perform diverse tasks including classifying handwritten digits, and imitate the way brain cells collect and process information.[29]

Biomimetic hardware

A major theme that emerged at Villars was an increased appreciation in the computational neuroscience and machine learning communities for the true heterogeneity of neuron structure, shape and behaviour. There are 86 billion cells in the brain, and they are not all the same. Hundreds of thousands of brain cell types have been catalogued through single cell sequencing, and deeper sequencing is identifying more classes still. Eventually we may find that each neuron may exist in a class of its own. These are not cosmetic differences: they have major impacts on the way the cells compute.



The significance of neuron morphology has long been understood in the neuroscience community. Santiago Ramon y Cajal, the father of neuroscience, understood at the turn of the 20th century that dendrites are unique from neuron to neuron. More recently, explorations of cell morphology have taken into account the heterogeneity of axons, the information-transmitting, elongated portion of the neuron. In computer science and machine learning communities however, this knowledge has not been integrated – for functional purposes, neurons are represented as being identical to each other. Artificial neural networks tend to use "point-neuron" models that ignore these morphological differences.

Changing this, including considerations of morphology and heterogeneity, will radically improve computational neuroscience and machine learning. Chip design and Spiking Neural Network learning theories are starting to implement so called "multi-compartmental" models which include the neuron's multiple functional parts. This growing appreciation of the role of morphology in computation is already leading to insights. For example, researchers have shown that a single realistic neuron model which takes into account the morphology of real pyramidal neurons is as powerful as a multi-layer deep-network,[30] and that dendrites, another kind of protrusion from the neuron, play particular computational roles of their own[31] – in particular they are being investigated for their role in consciousness.

This shift will have impacts beyond better modelling of real brain dynamics on a traditional computer architecture; it could change the architecture itself, and the efficiency of artificial cognition.

The current practice of relying on traditional graphics processing units to replicate complicated layers of cognition is wildly inefficient. The advent of GPU for Deep Neural Networks quadrupled Google's energy bills; the electricity bill to train GPT-3 was $4.6 million, according to a conservative estimate. By 2025, information and communication technology is on track to consume 20 percent of the world's electricity.

In the far more efficient biological brain, structure is function. In other words, the substrate is not the generic hardware on which the algorithm runs. Instead, the substrate is the algorithm. The project of replicating this is widely known as "neuromorphic computing". First defined in the 1980s by Misha Mahowald, this field is beginning to mature.

External cognition

Though a relatively banal insight, it is worth noting that better AI, even if not bio-inspired, may also qualify as neuro-augmentation; deep learning is already artificial cognition in its own right. From a near to medium term (5-10 years) perspective, the most effective interface between the brain and external cognition will continue to be human vision and digits, which are highly connected to the brain, and have a large bandwidth.

The more intelligent the external devices become, the higher level such communications can be, giving the human brain capacity to perform more complex tasks, or multiple tasks simultaneously.

Predictions and possible applications

Within 5 years, brain simulations will be capable of actuating real-world objects and it will become possible to study and interact with digital twins of simple biological organisms.

In the medium term (10 years), digital twins could let doctors interrogate specific brain functions[32] or disorders, and emerge into clinical practice. We will be able to engineer specific neural circuits.

Within 25 years, it will become possible to engineer a brain with more neurons than exist in the human brain. Blue Brain will be annotated with enough granular biological detail – down to the level of genes – for researchers to be able to test specific hypotheses by making specific changes to the model at the level of genes or ion channels to observe specific phenotypic outcomes.

Obstacles to progress

For any of this to happen, significant hardware and software limitations need to be addressed. This may require a paradigm change for computing. Furthermore, artificial cognition will need to be capable of building a model of the world from which to reason about the world. We know that this is how human intelligence reasons, but neuroscientists still understand little of how humans build their mental models of the world, or how such a model could be instantiated in artificial cognition. Embodiment was agreed to be a crucial factor that could create a sensory interface with the outside world that AI could access to build its model of the world. This embodiment could take the form of robotics, organoid-type biological sensorium, or a high-fidelity simulation of the world for the AI to explore.

On the biomimetic hardware front, neuroscience still has a long way to go before we understand the link between genes and relevant functions and behaviours; genes and cell development; how cells organise themselves into different anatomies. These are major challenges that will hopefully be addressed by high-resolution digital simulation of brains.

4. Ethical and Governance Dimensions

Inputs by

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Broadly three major ethical categories of concern emerged from the Villars discussions: ethical considerations for people who will benefit from neuro-augmentation; ethical considerations for the research animals and other entities which will inform the expected scientific and technological advancements, and responsible anticipation that emerge from the development of these technologies and insights. These are further subdivided where relevant.

Considerations for the individual

Here, workshop participants identified three subcategories of concern: the blurry line between restoration and augmentation, the evolving boundaries of medicalisation, and whether augmentation technology, once unleashed, can remain a choice.

There are three overlapping subgroups of neural augmentation, each of which may require tailored ethical adjudication. One type of neuro-augmentation substitutes lost function to return cognitive capacity to "normal" levels after loss to trauma or disease. Here, an example would be brain-computer interfaces that can decode intended speech and help, for instance, those who have lost verbal communication after a stroke or through ALS. The second type of augmentation supplements normal function, exceeding the capacity we associate with traditional human cognition. An example of this would be cognitive enhancers – whether drugs, surgical procedures or wearable technologies – that allow an individual to improve their memory or concentration, or overcome fatigue in the face of sleep deprivation. The third category of augmentation goes further still, providing capabilities that have not been available to previous humans. Such beyond-human function would include optogenetically-added electroception or the ability to "see" in infrared; living life guided by a high-fidelity digital twin, or the addition of extra body parts such as the Third Thumb.

There are some areas of profound disagreement on what constitutes a disorder. Many people with hearing loss or autism, for example, push back on the idea that their experience of the world is a disease to be cured, and that a society without neuro-divergence is implicitly better.

Where the boundaries between these three subgroups lie is open to debate – a debate that will be essential for shaping future policy and ethical considerations.

Some ethical viewpoints seem to depend on to what end the technology is being deployed, but the one boundary that people seem to intuitively accept is between restoration of a lost function and increasing the capacity that is already considered within the normal range. Here, the intuition is that restoration is not augmentation per se, and that there should be a different set of ethical, regulatory, social, financial (and possibly other) thresholds for acceptance of restoration compared to augmentation.

One early approach to determine the difference between restoration and augmentation is being undertaken at the Chinese Academy of Sciences. The beginnings of a cohort study of individuals labelled "healthy" after undergoing routine physical examinations are also being invited to participate in a small battery of cognitive tests that could provide data to establish average markers of brain health benchmarked against age. In the future, this data could be used to benchmark an individual's cognitive capacity against the average established by their baseline age cohort. Having determined "normal" functioning, it then becomes possible to understand under what circumstances restoration or even early interventions – prior to onset or diagnosis of a "disease" – should be offered.

Advances in organoid and silicon-based modelling and simulation suggest that in the future, it will become possible to intervene when a pre-disease state is detected. For example, early biomarkers or hints in the projectome could warn of impending Alzheimer's before any symptoms emerge, and intervene accordingly. Is intervention at this pre-disease stage classed as restoration or augmentation of function? The distinction may be important for financial matters such as insurance coverage. There are also lessons to be learned from breast cancer screening overdiagnosis, in which false positives were a problem. For neuro-augmentation, diagnosis before physical symptoms manifest would require a highly trusted model as in the case of brain disorders, a prediction of risk not only suggests what disease a person might have, but who they might become.

More straightforwardly, we know that a number of mental functions change with age and accept this as a part of "normal" ageing. But some may question if ageing itself is a disease; would such an intervention constitute restoration or augmentation? This, too, has implications for insurance coverage and the provision of care resources for an ageing population, as well as for defining a societally acceptable way of ageing.

Such questions raise the issue of "medicalisation", where behaviours and conditions are considered issues warranting medical treatment. Brain technologies have the potential to re-define what we consider appropriate treatment. While most participants in the discussion agreed that neuro-augmentation technologies provide an appropriate response to brain injuries and neurodegenerative diseases, they might define tsuch intervention as simply restorative treatment rather than augmentation per se.

With such questions in mind, the choice to augment becomes a loaded issue. It is possible that the availability of augmentation will make sticking with normal brain function seem old-fashioned or even self-destructive. There may be external or even financial pressure to augment: if age-related cognitive decline is seen as optional, those eschewing augmentation may become a financial liability or be considered selfish by family members with a duty of care. Such options may have to be included in workplace legislation; some employers may consider it necessary, in a competitive sector, to have augmented employees, or to base employment contracts on predictions of potential decline in brain function in the same way that professional athletes' contracts are based on fitness assessments and include injury clauses. University students without access to neuro-enhancement may find themselves at a disadvantage in academic assessment and in job-seeking situations. The military has a long history of insisting that its employees use available augmentations, whether technological or pharmaceutical. It would seem naive to think that this will not be extended to medical augmentations, when they become routinely available and widely accessible.

A complicating factor is that neuro-augmentation may have unexpected outcomes. For example, the augmentation of one mental capacity might come at the cost of another, given the brain constraints for plasticity and cognitive load. Research on the Third Thumb, specifically, has raised new questions about this "neural resource allocation problem". A person who controlled the tool for a full workday with their toe found their brain had a hard time quickly readjusting to "normal", including while driving home. It is crucial that, before we adopt such technologies, we consider precisely under what circumstances we want to add more cognitive load, and what the potential consequences might be.

Considerations for research animals and other entities

Robust debate around establishing the line between augmentation and restoration, as discussed above, could establish red lines around which types of animal research to consider ethically acceptable. However, another ethical tension arises with respect to the augmentation of nonhuman primates with human elements. For example, a transgenic nonhuman primate model of Parkinson's disease for a specific intervention seems less objectionable, under this rubric, than a transgenic nonhuman primate model for open ended research or augmentation research that might enhance non-human animal function to be closer to the capacities of humans (i.e. a monkey with human genetic material).

Such research on a transgenic non-human primate, expressing human genes in nonhuman primate brains, may recreate human suffering such as mental illness. Furthermore, it might be possible for an AI construct with a sufficiently complex model of the world to develop emergent properties that resemble consciousness. What do we owe these entities in our care? Will these entities still remain tools for science to use, or will they become collaborators whose rights (including the right to not be made to suffer) must be taken into account? How and under what circumstances would this distinction change research protocols?

Tests may be developed to explore the answer but they may be subject to shifting goalposts. For example, the tendency to see non-human entities as a class worthy of protection hinges on how human-like they are, but those traits tend to be rationalised away if a greater need presents itself. In these debates, one further, crucial question requires attention: even if agreement can be reached over these issues, how can it be enforced?

Responsible anticipation

Science is a human right – everyone has the right to freely share in the advances of science and its benefits. Article 15 of the International Covenant on Economic, Social and Cultural Rights places obligations on governments to encourage, facilitate and not to interfere with an individual's work as a scientist, except as demanded by ethical and legal standards.[33]

Dispute resolution mechanisms

The accelerating pace and democratisation of technological capabilities in neuro-technology and gene editing are set to bring a similar uptick in international disputes, as ethical priors in different countries may not be aligned.

Participants in Villars gave a positive response to a proposal for an "international court of science". Its nonbinding agreements would not be able to regulate ethical red lines. However, such "soft laws" would help to establish norms and facilitate the development of a consensus- and rules-based international order in this area.[34]

2.1 Cognitive Enhancement

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]

Most existing investigations into cognitive enhancement have sought to restore performance 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.

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Anticipation Potential

EMERGING TOPIC:

Cognitive Enhancement

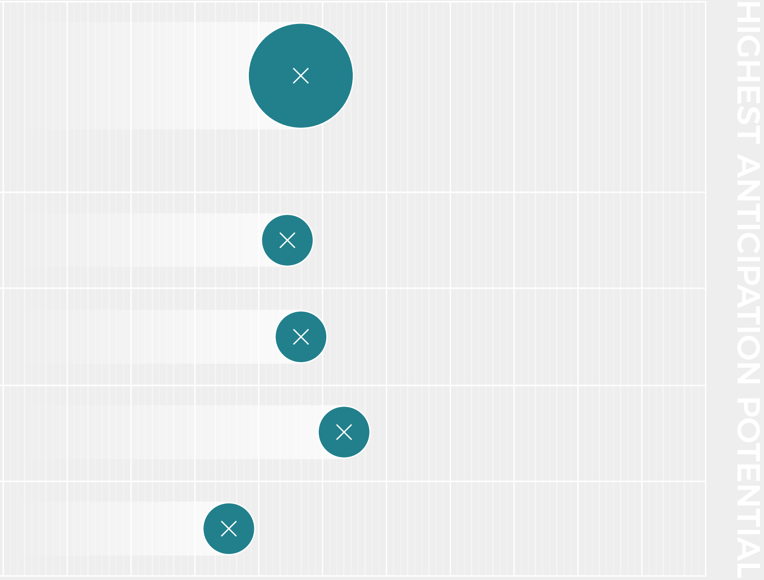
SUB-FIELDS:

Fundamentals of cognition

Brain monitoring

Neuromodulation systems

Exogenous cognition



SURVEY OBSERVATIONS:

Few technologies have such potential to drastically reshape our societies as cognitive enhancement. Bringing this technology to fruition will require advances in a wide range of scientific fields, with this convergence driving the need for anticipation in this area. Brain monitoring technology and neuromodulation delivery systems are closer to maturity than the other approaches, resulting in lower Anticipation Scores. Exogenous cognition should be a particular focus, as a technology with late maturity, strong disruptiveness potential but seldomly discussed.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In May 2023 a Swiss-French collaboration unveiled an exceptional advancement in the digital brain-spine interface. Their Nature publication, 'Walking naturally after spinal cord injury using a brain–spine interface', described a groundbreaking technology that allowed an individual with tetraplegia to regain walking abilities. There was, in addition, an unexpected outcome: enhanced neurological recovery beyond system use. In August 2023, two teams based in the US published 'A high-performance neuroprosthesis for speech decoding and avatar control and a high-performance speech neuroprosthesis', detailing breakthrough brain-computer interfaces which offer a potential communication solution for those with severe facial paralysis.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r2-1

2.1.1 Fundamentals of cognition

Cognition comprises, among other features, 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 normal 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 twins improve enhancement outcomes

Digital twin models of brains like the Blue Brain Project allow us to make specific tweaks to models to predict specific enhancement outcomes. Similarly, a combination of genetic engineering and implants will allow widespread enhancement of intelligence in healthy individuals.

2.1.2 Brain monitoring

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] This approach already decoded word formation at an unprecedented rate of 62 words per minute.[12]

The rise of predictive large language models means semantic decoding becomes possible even without brain implants; one has decoded continuous language from fMRI.[13] This progress suggests that even non-invasive brain recording devices could eventually improve enough to be wearable, reliable and affordable, paving the way for non-medical uses such as employee monitoring.

5-year horizon:

More transparent brains

Reference brain simulations allow testing of interventions on cognition in silico. AI continues to shatter records in parsing meaning from the brain's electrical signals. Brain state trackers will become more ubiquitous in the workplace.

10-year horizon:

Open brain data stimulates research

Digital twins of brain tissue provide sandbox systems that show which interventions alter cognition, and provide functional and causal links between the epigenome and some brain functions. Miniaturisation makes portable brain monitoring devices commonplace.

25-year horizon:

Remotely-operated monitors are implanted in the brain

Optogenetics and gene therapy advance to the point where devices can be implanted into the brain and operated remotely to monitor brain activity at high resolution. Cheap, portable non-invasive imaging technologies are used in a greater variety of real-world situations. Many of these, such as lie detection by law enforcement, provoke significant controversy.

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.[14,15] 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.[16] Other penetrating electrical brain implants are mooted to provide prosthetic memories for people with traumatic brain injuries.[17]

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.[18] Better materials[19] and implantation devices and methods are also in the works; Neuralink, for instance, recently announced that it has earned FDA approval to trial its implants in humans.[20]

5-year horizon:

Brain stimulation devices proliferate

Next-generation implants like Neuralink 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[21] and Neuropixels.[22] 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 diseases including depression. It becomes possible to identify areas of the brain where electrical stimulation gives healthy people a boost in memory capacity. Epigenome editing alters brain function, helping damp the effects of trauma, for example.

25-year horizon:

The era of high-precision genetic brain enhancement arrives

Optogenetics allows manipulation of specific networks and types of human memory with high resolution and precision. AI enables tailored epigenome editing in the brain to remove barriers to optimal cognition. Genetic technologies begin to improve memory and other cognitive functions and reduce the cognitive decline associated with ageing.

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.[23]

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" – an additional, 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.[24]

5-year horizon:

Novel brain circuits are put to work

Artificial cognition informs new kinds of circuits and architectures; those brain circuits begin to be deployed in real-world devices. Companies adopt the third thumb for efficiency gain in the workforce.

10-year horizon:

Brain implants enhance cognition through exogenous AI

Penetrating electrical brain implants improve the human mind by connecting it to artificial intelligence. 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, and better models of cognition, gene editing is possible for specific genes associated with memory and other cognitive functions, reducing the decline associated with ageing. Researchers begin to understand how human brains build internal models of the world, and use these insights to enhance the performance of these models. Medium-scale digital twins are developed for personalised medicine that can pre-test any neurological intervention. It becomes possible to engineer a biologically realistic brain simulation with more neurons than exist in the human brain.

2.2 Human Applications of Genetic Engineering

The relatively recent invention of CRISPR — an editor that can snip DNA to alter its sequence — has racked up a raft of gene editing successes against a variety of diseases, including cancer,[1,2,3] eye diseases, and blood diseases.[4,5] The field is now poised to bring unprecedented disruption in medicine, as well as new possibilities for human enhancement. 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.[6] However, much of the groundwork being done today is with a different vision: to deliver the genome editor into the patient's body, where it will find the right cells and perform its task.[1]

Gene editing is not without complications: it has a history of high-profile failures and procedural mis-steps among its users. That said, a new generation of safer editing techniques and more targeted payload delivery — along with novel ideas about how to manipulate the genome indirectly — shows clear promise. The next generation of gene editors are now being developed to be more precise and less toxic, thereby creating fewer side effects, unintentional alterations and immune reactions. Also under development are more targeted ways to deliver the editor into tissues that are hard to reach, including novel methods that emerged during the fight against Covid-19.

In recent years, new questions have emerged about alternative ways the genome can be tailored and manipulated. Especially intriguing has been the notion of epigenome editing, which can exert powerful effects that are reversible and tuneable. This requires a better understanding of the links between gene networks and disorders, but the field of metagenomics has been advancing steadily, and looks like it could deliver on this.

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Anticipation Potential

EMERGING TOPIC:

Human Applications of Genetic Engineering

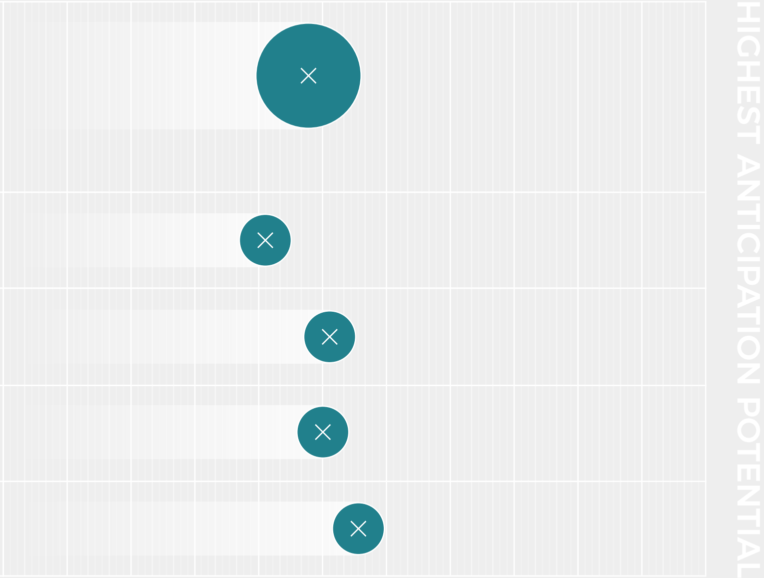
SUB-FIELDS:

Diagnostics

Next generation editors and delivery

Engineered organisms and AI-based tools

Alternatives to direct gene editing



SURVEY OBSERVATIONS:

Breakthroughs in our ability to manipulate the human genome are likely to come in three different waves that will require different responses. Genetic diagnostics have already received significant attention and are expected to have broad applications within the next seven years, with deployments already in the pipeline. Next generation editors and artificial intelligence assisted genetic engineering, on the other hand, are not expected to go mainstream for at least a decade. Finally, alternatives to direct gene editing, such as manipulating the epigenome or the microbiome, are expected to reach maturity after 15 years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In March 2023, a 'Statement from the Organising Committee of the Third International Summit on Human Genome Editing' emphasised the thrilling advancements and ethical considerations surrounding somatic genome editing, calling for global cooperation and judicious oversight in the face of this rapidly evolving field. In the same month, a Japanese research effort published 'Generation of functional oocytes from male mice in vitro' , which delved into groundbreaking techniques that convert XY chromosomes to XX in mouse stem cells. This discovery heralds a new horizon for treating infertility linked to chromosomal anomalies and unveils the promising potential of bipaternal reproduction. In June, MIT researchers published 'Fanzor is a eukaryotic programmable RNA-guided endonuclease', a counterpart to prokaryotic CRISPR-Cas systems. Fanzor amplifies our understanding of RNA-guided endonucleases across life's domains and paves the way for revolutionary human genome engineering applications.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r2-2

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.[7] For example, the CRISPR-Cas system is enabling the fast detection of pathogens; Cas12a has detected Hepatitis B in less than 30 minutes.[8] More typically, sequencing is now possible in days to weeks.[9] Costs are also falling.[10]

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 closer to the clinic.[11]

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 or $200 a genome.[12] Therapeutic investment explodes. Genome targeting for pathogen diagnosis comes to point of care settings, including pharmacogenomics when drugs are prescribed.

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 the choices of partners based on genetic compatibility, as well as retirement plans and insurance.

25-year horizon:

Gene reading and editing 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, and has been successful in trials treating blood diseases, cancers, and eye diseases.[13] It is not clear that these successes will transfer to other tissues, however; muscular diseases, for example, are system-wide, so treatment might require potentially problematic high doses of the editor in order to reach all the relevant tissues.

Alternative genome editing systems, such as zinc finger nuclease (ZFN) systems and transcription activator-like effector nuclease (TALEN) systems, are being explored (although they suffer from some of the same issues),[14] and CRISPR can be augmented with other helpers including transposons.[15,16] Higher-precision editing is possible using base editing and prime editing, two recently developed approaches.[17]

Today, viral delivery is the method of choice into living matter. Of the nearly 300 clinical trials underway worldwide with viral-vector-based gene therapies, about half use modified adeno-associated viruses (AAVs). These can target a wide range of tissues, but AAVs can be too small to deliver the needed quantity of editing payload. This necessitates using huge amounts, which can trigger dangerous immune responses; efforts are underway to re-engineer AAV to be bigger and/or evade immune response.

Nonviral delivery has become an increasingly viable alternative, thanks to rapid progress in the use of lipid, polymer, extracellular vesicles, and inorganic nanoparticle-based delivery systems.[18] Physical methods, including electroporation (where an electrical pulse is used to create temporary pores in cell membranes), are promising but not yet scalable.

5-year horizon:

Ex vivo and in vivo therapies advance

Several large-scale stage-III clinical trials for ex vivo therapies take place, with a number of therapeutics approved and commercially licensed.[19,20] Early-stage clinical trials of in vivo editing techniques, targeting easily accessible tissues such as the eye, or the liver, show results. In vivo therapies move to experimental clinics. CRISPR corrects for mitochondrial genetic disease in IVF procedures. Next-generation genome editors appear on the stage.

10-year horizon:

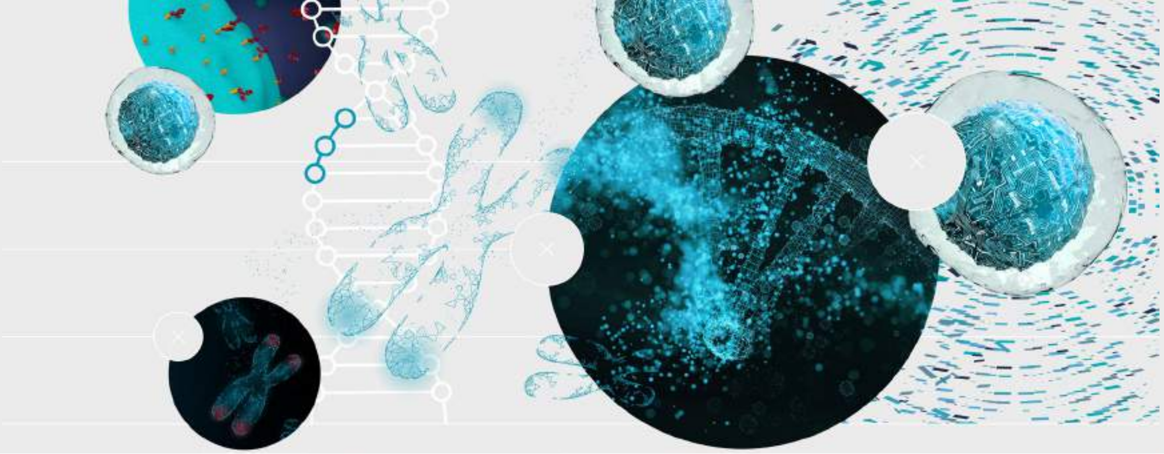
Safer germline editing blurs boundaries between therapy and prevention

Researchers engineer delivery techniques to address size and immune response: engineered AAV vectors deliver working genes to cells more efficiently, reducing the need for large doses, reducing cost. Haemophilia and macular degeneration are successfully treated with gene therapy.[21] Trials commence using next-generation base and prime editors for polygenic diseases including heart disease and obesity. Heritable gene editing begins to gain limited acceptance, although not everywhere, as a consequence of successful somatic techniques and preclinical safety data.

25-year horizon:

Polygenic editing erodes boundaries between therapy and enhancement

In vitro derived gametes can be edited safely before fertilisation and implantation. Many forms of gene editing are mainstream. It becomes possible to engineer resistance to radiation, chemical warfare, agents 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

Synthetic organisms and AI will help advance genome editing for human applications in several crucial ways. For starters, synthetic organisms will provide improved ways to deliver the editing payload to the cell and experimental organisms that provide a better proxy for human testing.[22]

AI can design editors for maximum efficiency.[23] It will also be crucial for automated analysis of human tissue. 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.[24] Machine learning may also be able to help identify novel biological candidate systems to manipulate DNA; it would be useful to find molecules that offer decreased immunogenicity, for instance. 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.[25,26]

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 editor. 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 human 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 endocrine system. With prime and base editing, plus tisssues 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 engineered gene circuits.

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. 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.[27]

Another emerging option is precision microbiome editing:[28] recent insights make it clear that these microorganisms play key roles in diseases. Current tools are blunt and ineffective, but it should be possible to exert precise control over the microbiome using CRISPR and metagenomics.[29] Electrogenetic systems — electrochemical or electrical interfaces — can also activate or repress gene expression in tuneable ways.[30] Pre-clinical studies show this method can control glycemic levels in diabetic mice.[31] The key to future progress is metagenomics, which can provide a complete profile of all the diverse organisms in a given microbiome and is becoming more affordable.[32]

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. Electrogenetics tools are put to work in editing eukaryotic systems, using redox-sensing transcription factors that have been identified in plants, and animals. 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 and electrogenetics helps people temporarily mute some genes or express others, making for temporary alterations including military night vision, radiation, viral and chemical resistance. 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

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, research findings have begun to suggest that there are also specific, underlying biological pathways that unite the diseases associated with ageing. And so, rather than accept the ageing process as a natural process 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.[1]

Even while basic questions around such fundamental processes are being explored, however, 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 specific disease outcomes and ageing biomarkers. However, many analyses 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.

A fundamental shift is underway. 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 low quality of 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 remain high until death.[2]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Anticipation Potential

EMERGING TOPIC:

Healthspan Extension

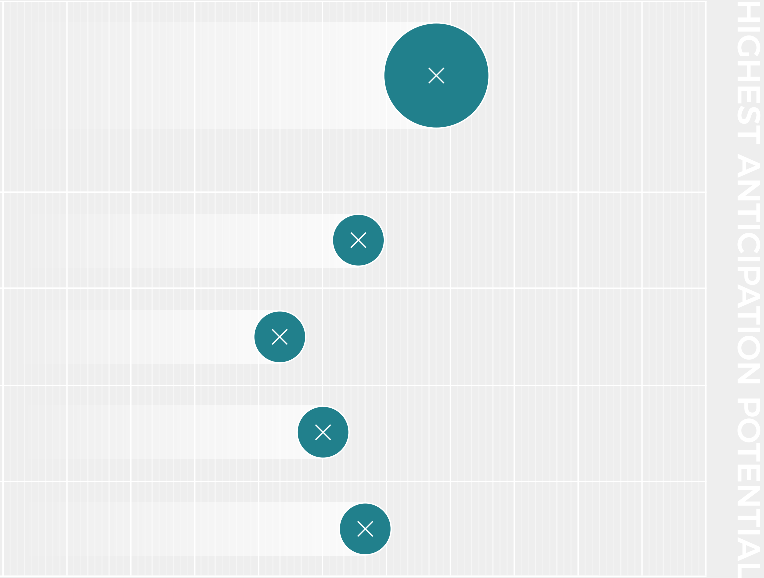
SUB-FIELDS:

Fundamental geroscience

Diagnostics, hallmarks and biomarkers

Healthspan therapies and interventions

Lifespan extension and rejuvenation



SURVEY OBSERVATIONS:

Much of the work focused on keeping people healthy into older age builds on decades of research in medicine and the life sciences. As a result, respondents predicted that future breakthroughs in this area are likely to rely on highly-interdisciplinary research that combines advances from across fields, with a broad impact on people, society and the planet. Research on diagnostics, hallmarks of ageing and biomarkers is likely to reach maturity in the near future. Understanding the fundamental mechanisms of ageing and translating this into methods to slow and even reverse ageing are considerably further off — 12 and 15 years respectively — but have the potential to be highly transformative and will require significant planning to manage their effects.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Unveiled in January 2023, 'Cell-cell metabolite exchange creates a pro-survival metabolic environment that extends lifespan' presents a profound discovery by an international research team working in the field of yeast ageing. Researchers discerned cross-generational metabolic interactions where young cells export vital metabolites consumed by aging counterparts, fostering significant lifespan extensions and underscoring the symbiotic relationship between metabolism and aging.

A pivotal piece of research was published in August by a team from the United States. 'Increased hyaluronan by naked mole-rat Has2 improves healthspan in mice' expounds on the profound impacts of transferring the naked mole-rat's hyaluronic acid-producing gene into mice. These transgenic mice exhibited reduced cancer rates, diminished inflammation, and prolonged lives, charting promising routes for leveraging high-molecular-mass hyaluronic acid to boost lifespan and health. Also in August, a paper entitled 'Platelet factors attenduate inflammation and rescue cognition in ageing' highlighted the role of Platelet factor 4 (PF4) in reversing age-related cognitive decline in mice. The protein, previously recognised for wound healing, demonstrated potential in enhancing cognitive abilities, reducing inflammation in the hippocampus, and promoting synaptic plasticity, suggesting possible applications for conditions like Alzheimer's.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r2-3

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 age cohorts. 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, accumulation of mutations in the DNA and change in the genome organisation, age-related 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, twelve 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 functional decline, and how these in turn are connected into the central system that regulates the ageing process.

5-year horizon:

Identify specific levers in ageing

The field identifies more genes involved in ageing and validates them in an array of animal models 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 and create reliable biomarkers of biological age for evaluating the effectiveness of anti-aging interventions.

10-year horizon:

Ageing is understood as a disease process

The idea that ageing is a disease gains traction. An increase in data combined with machine learning algorithms help to identify many of the 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 a scientifically grounded 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. These 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] and saliva and stool-sourced microbiome analysis — 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.[11,12]

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 underway 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.[13] Machine learning will be used to search hundreds of datasets and previous trials to identify other useful factors and patterns.[14] Population-level work is aiming to expose the relationships between these clocks and disease risk.[15]

5-year horizon:

Validation and standardisation of biomarkers takes off

Measurements of omics reveal the influence of other drugs including SGL2 inhibitors and senolytics. Clinical trials validate measures of premature ageing, while multiple companies’ methods converge on standardised, validated diagnostics of real age, such as the presence of molecules in blood that correlate with impaired functions.[16] It becomes possible to identify unhealthy ageing with greater precision. Biological ages of individual organs begin to predict disease risk in those areas.[17]

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

Healthspan extension can already be achieved through several approaches, including specific diets, calorie restriction and exercise[18,19] 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 reduce respiratory changes in older humans.[20,21,22,23] Two such drugs under investigation are the immunosuppressant rapamycin,[24] 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 to the purportedly healthy non-diabetic controls against whom they were compared.[25]

Trials of metformin and rapamycin[26] suggest that these small molecule drugs can change the biology of ageing in tissues to a younger profile. Another approach is senolytics, which target senescent cells before they can damage tissues. Gene therapy and stem cells are other possible approaches to rejuvenating old organs.

5-year horizon:

Anti-ageing drugs and regimens begin clinical trials

Tests begin to validate anti-ageing drugs and regimens, and clinical trials to delay age progression proliferate. AI, baked into a myriad of wearable devices, apps and trackers, allows people to personalise exercise and diet interventions to maximise their healthspan. Results emerge from first trials of cell and gene therapy to slow ageing in dogs. 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.

10-year horizon:

Clinical trials clarify promising drugs

Health plans begin to prescribe validated age-delaying therapies. Promising genetic and pharmacological interventions in animals, and longevity adaptation identified in long-lived animals including naked mole rats, bowhead whales and bats, are 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, preventive 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,[27] but the question of what determines maximum human lifespan, and why it differs from other species, remains. Bowhead whales can live to 200, for example. Naked mole rats can live more than 40 years, more than ten times the lifespan of rodents of similar size. They have "healthspan" too, it seems: 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.[28] Pathways have been identified that are associated with longevity across animal species: for example, animal species with longer lifespan have more efficient DNA repair and more active Sirtuin 6.[29] These pathways can be activated in humans to slow the rate of aging.

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.[30] Animal experiments have identified age-associated biomarkers which can be delayed, stopped and even in some cases reversed.[31] Stem cells can be reset to age 0 - these have been used to regenerate a crushed optic nerve in rats.[32] Gene therapy has reprogrammed epigenetic information to reverse glaucoma in a mouse model.[33] 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.[34] 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),[35] and gene therapy,[36,37] 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

Scientists investigate why different species age differently and identify the pathways involved. The degree of conservation between ageing hallmarks among different species is established.

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. Interventions that improve 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 determines whether this method plausibly rewinds ageing in humans.

2.4 Consciousness Augmentation

Science offers no standard, widely agreed definition of consciousness. Currently, there is also no agreed theory of consciousness, and it is unlikely that there will be one for the next quarter-century. Our best theories, Integrated Information Theory and Global Neuronal Workspace Theory, have recently been assessed in an Adversarial Collaboration test: though successful in some areas, they faced "substantially challenging" outcomes in others.[1]

This means that much-discussed issues such as machine consciousness and animal consciousness also remain unresolved. 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, 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.

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 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, autonomy of the self and what it means to be human.[2]

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Anticipation Potential

EMERGING TOPIC:

Consciousness Augmentation

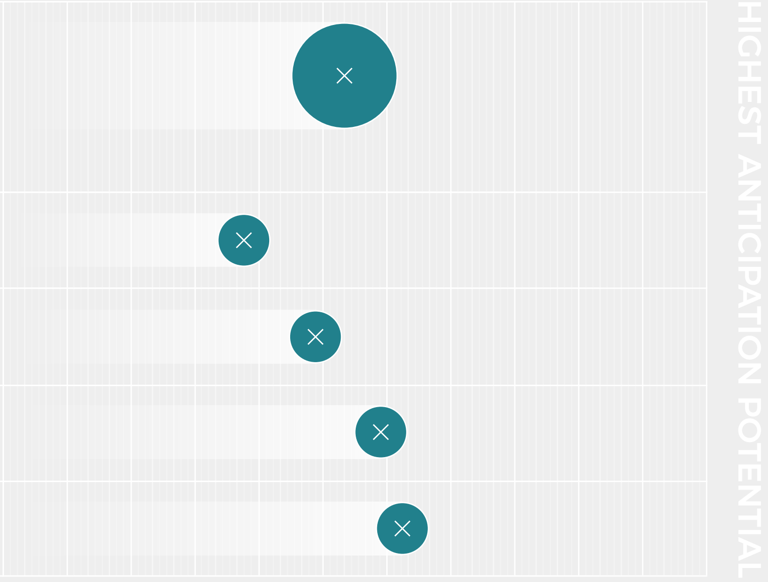
SUB-FIELDS:

Consciousness assessment

Cognitive capacity enhancement

Consciousness-augmenting interventions

Beyond-human consciousness



SURVEY OBSERVATIONS:

Understanding and assessing consciousness is an endeavour that is still a decade away. As a results, efforts to augment human consciousness are likely to reach maturity beyond the next 15 years, while going beyond human consciousness is unlikely to happen before 20 years. The field's reliance on interdisciplinary research drives some of the anticipation score.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In January, a broad international collaboration published 'Consciousness beyond the human case, delving deep into the realm of AI consciousness'. Echoing long-standing debates from animal behaviour studies, the paper draws attention to the multi-layered intricacies of consciousness and sentience and poses compelling questions on whether AI can attain high-order cognitive functions devoid of foundational emotions. The authors call for a greater emphasis on consciousness-centric research in AI development. In June a research team at the Johns Hopkins University published 'Psychedelics reopen the social reward learning critical period', shining a light on the transformative potential of psychedelics in rewiring critical learning phases related to social rewards in mice. The study, which reveals alterations in the brain's oxytocin pathways, underscores the potential therapeutic applications of psychedelics in neuropsychiatric disorders. Also notable in June was an article titled 'A 25-Year-Old Bet about Consciousness Has Finally Been Settled'. This recounts the settling of a bet about the scientific understanding of consciousness made between neuroscientist Christof Koch and philosopher David Chalmers in 1998.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r2-4

2.4.1 Consciousness assessment

There is increasing recognition that a significant amount of brain processing is done under the level of consciousness. This has implications — both practical and ethical — about where intervention might be possible, and how we assess levels of consciousness.

Although there is no granular understanding of which circuits are implicated in consciousness, a diagnostic tool based on EEG has been able to differentiate between a vegetative state and a minimally conscious state.[2] EEG can identify candidates for brain-machine interface placement despite minimal responsiveness.[3] Other technologies may detect and assess early memory loss in Alzheimer's, helping guide treatment and care.[4] Deep learning is now enabling faster progress in these types of assessments,[5] even distinguishing between different kinds of states in a patient under anaesthesia.[6]

Such work could help with fundamental science, identifying areas of interest for probing the neural correlates of consciousness. Chinese Academy of Sciences researchers, for instance, are looking at neural circuits associated with specific aspects of consciousness — notably self-awareness — in macaque brains.[7] An understanding of the circuit basis of consciousness could help quantify specific aspects lacking, and thereby point to the best intervention in consciousness disorders.[8] Furthermore, such investigations and analyses may help us to find a generalisable definition of consciousness.[9]

5-year horizon:

We become more adept at diagnosing consciousness

Brain state diagnostics improve, and machine learning overcomes individual patient variability to assist in prognosis and guide rehabilitation. The neural circuit implicated in the mirror test — a key aspect of how we define consciousness — is found in macaques. Specific tests reliably detect early onset of diseases that disrupt consciousness.

10-year horizon:

Consciousness assessment follows internationally-agreed guidelines

An agreed set of international guidelines (effectively a standard scale) standardises assessment of consciousness. Network-based models of arousal and awareness, the two measurable components of consciousness, lead to development of a unifying conceptual framework for therapeutic mechanisms of action — validated electrophysiologic and imaging tools that map brain network connectivity. 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.

25-year horizon:

Consciousness can be evaluated

Scientifically validated assessment of presence and quality of consciousness in humans, animals and machines begins. An agreed theory of consciousness takes shape. Brain-machine interfaces open up seamless communications with apparently unconscious people, even restoring natural consciousness in some cases.

2.4.2 Cognitive capacity enhancement

The 20th century saw a measurable and significant increase in the average human intellect.[10] While systemic efforts like education played a role, about 50 per cent of this rise was due to epigenetic modifications like improved nutrition, better medicine and reduced stress exposure.[11] Further enhancement of cognition is a major project for the 21st century, to be realised by more of the same, plus pharmaceutical interventions and machine interfaces. These are likely to significantly boost educational achievement, creating the opportunity for a far wider swathe of humanity to live more fulfilling lives. It is possible, however, that such enhancements in cognitive function may not suffice to help us meet the challenges of the 21st century – we may need to take a broader approach to augmenting our consciousness.

Much of the human conscious experience is shaped by cultural immersion, including exposure to tools like mathematics and language, which underpin the ability to grasp abstract concepts and create complex models of the world. In order to expand cognition, learning can be expanded to encompass a much broader range of exposures than happens today, especially since neuroscience and cognitive science have delivered new insights into how human brains learn. Furthermore, virtual environments have already been shown to boost empathy[12] and memory retention[13] in the classroom; augmented reality can create simulated sensory worlds[14] and AI can help overcome cognitive biases.[15]

5-year horizon:

Learning environments are enriched

Immersive systems have vastly greater capabilities than just sound, vision and limited haptics, creating enriched virtual environments for learning with greater empathy and salience. We share our cognitive load with systems that enhance general consciousness, attention and recall. AI prompts us to behave and think more rationally. Trials on different kinds of VR discern the difference between cognitive and emotional empathy, and work better at eliciting the latter.

10-year horizon:

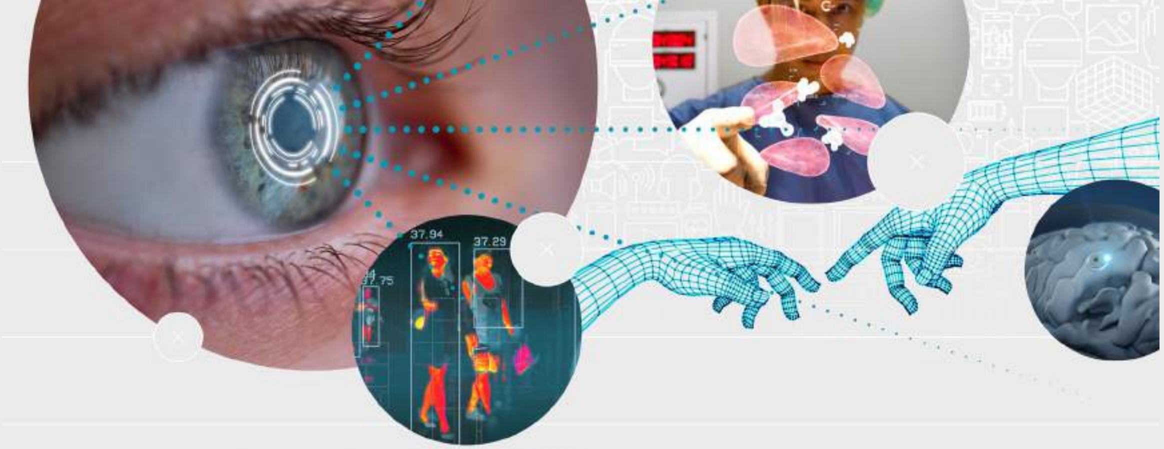
The re-engineering of education begins

Neuromodulation technologies enhance cognitive functions like learning, memory, attention and decision making. A newer understanding of how the brain learns helps people learn differently, faster, and more effectively. Educational achievement rises in a wide range of societies.

25-year horizon:

Hybrid consciousness enhances cognition

Neuro-inspired AI systems that help design curricula are imbued with algorithms that operate on an improved understanding of how humans learn, creating a virtuous loop. High fidelity computer models of the brain provide insights into decision-making and its specific neural correlates. From AI that is able to generate internal models of the world, it becomes possible to understand how human consciousness generates its own models.



2.4.3 Consciousness-augmenting interventions

We can alter consciousness by several methods: pharmacological, electromagnetic and regenerative. Nootropic drugs are proliferating, albeit without adequate tracking.[16] There has been some significant progress in the use of psychedelics and psycho-active drugs to augment and alter consciousness, which may prove useful in medical contexts. Psilocybin and MDMA are being used to treat post-traumatic stress disorder and depression in Australia, for example.[17] It is already possible to restore sensory input when it has been damaged by trauma or is congenitally missing: cochlear implants, retinal implants, and gene therapy have all been used to partially restore the input portfolio of conscious experience.

Therapeutic neuromodulation (precisely targeted non-invasive technology like tDCS) has successfully brought minimally conscious patients back towards higher consciousness.[18] "Closed-loop" neuromodulation is able to act on, and sense, brain state based on feedback.[19,20] If deployed in line with a set of internationally validated guidelines to diagnose the presence or absence of consciousness, a combination of these technologies can be standardised to wake people from comas.

Brain-machine interfaces can help to augment human consciousness in three different ways.[21] First, by augmenting the sensory inputs (already happening through gene therapy, cochlear and retinal implants). Second, by interfacing with a different type of body: robotic appendages with different, non-human degrees of freedom are already at work in factories and in surgical suites, and make their operators navigate the world with a different body plan thereby altering their mental model of the world. Third, by interfacing with AI: this can mitigate standard cognitive biases and improve on standard human consciousness.

5-year horizon:

Embodied machines go mainstream

Immersive virtual reality systems have vastly greater capabilities than today's confinement to sound, vision and limited haptics. There is greater adoption of robotic embodiment 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. BCIs move beyond siloed research labs toward new and more diverse use cases. Small trials of people with specific disorders of consciousness receive brain stimulation to enhance their conscious state.

10-year horizon:

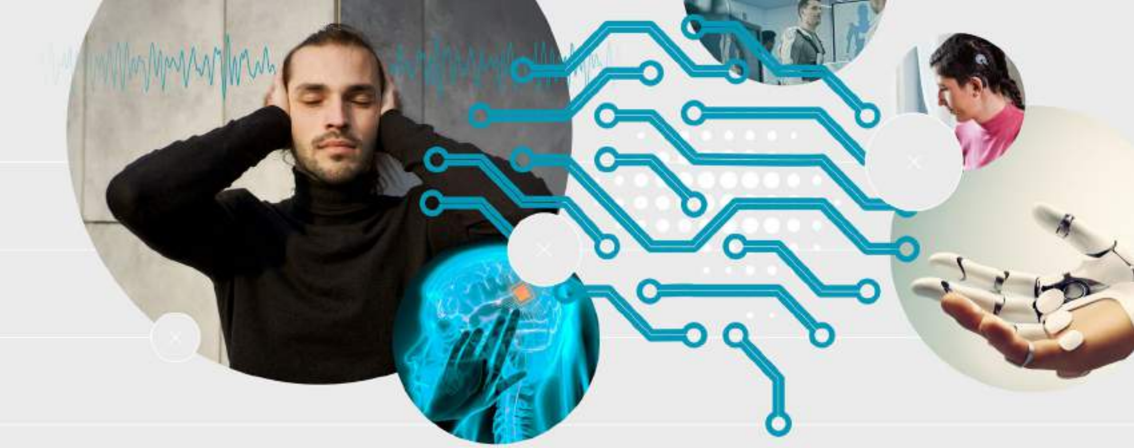
The first human-machine interfaces begin to see roll-out

The wider availability of more general-purpose daily use robotic devices means that some models begin to explore the advantages of invasive interfaces. Medium scale trials commence on non-invasive neurostimulation like tDCS or focused ultrasound to alter people's conscious state. Improved understanding of how neural circuits within distributed brain networks process information underpins better strategies for targeted electromagnetic intervention (including optimal stimulation targets). Clinical trials start on consciousness-restoration therapies tailored to individual genomic, proteomic, and metabolomic profiles.

25-year horizon:

Neural interface for consciousness sharing

The market grows for implantable BMI that is useful in everyday life. Brain implants coupled to AI systems accelerate the development of new human-machine shared consciousness useful in therapeutic settings (e.g. for neuroprosthetics) but also for those wanting to augment evolved human abilities.



2.4.4 Beyond-human consciousness

Work is underway to determine the extent to which machines and animals can have or develop consciousness,[22,23] and to understand whether organoids and other synthetic biological organisms are capable of developing a kind of consciousness.[24]

In humans it may be possible to augment normal consciousness using drugs, technology or genetic interventions. We have already given some animals extra senses — bestowing a snake's ability to see in the infrared on a rat using optogenetics, for example.[25] Some researchers have used wearable technologies or implants to give themselves magnetic senses[26] or the ability to feel sound.[27]

Newly developed brain-to-brain interfaces — currently possible invasively in animals[28] and noninvasively in humans[29] — may allow for direct communication between two brains without involving the peripheral nervous system, instantiating distributed intelligence and consciousness.[30]

5-year horizon:

Humans begin to adopt augmentations

Mouse models elucidate the neural model of drug efficacy, pointing to the design of more precisely-targeted therapeutic interventions. Virtual reality (VR) and augmented reality (AR) offer visual overlays representing other people's heart rate and blood pressure, letting us "see" their inner emotional state. Brain interfaces allow for technologically mediated direct communication between two brains without involving the peripheral nervous system bringing us a step closer to a "social network of brains."

10-year horizon:

Engineered body enhancements become commercially 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 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 meta-humans arrives

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 our experiences.

2.5 Organoids

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. 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.

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, advances in enabling technologies will soon allow them to become far more complex, with greater standardisation of procedures facilitating easily replicated results. 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.[6] 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.[7]

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Anticipation Potential

EMERGING TOPIC:

Organoids

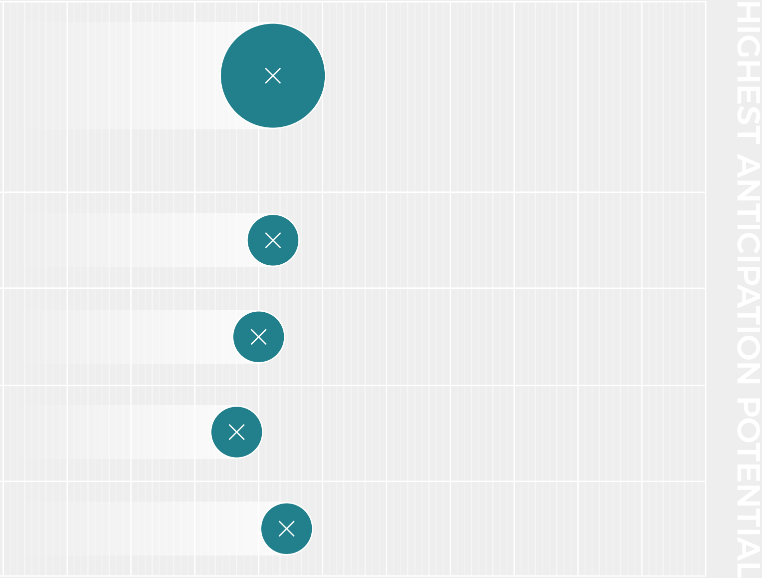
SUB-FIELDS:

Foundational research

Hybrid organoids

Translation and personalised organoids

Enabling technologies



SURVEY OBSERVATIONS:

Lab-grown replicas of human organs promise to serve as a better proxy for the study of tissue function and disease than either cell lines or animal models. Research on organoids is already well underway, explaining the lower anticipation scores in this area. While awareness of this field is relatively high, research into hybrid organoids is less-well discussed. Of the subtopics analysed, the standardisation and commercialisation of these technologies is deemed the most in need of anticipation, thanks to the impact it could have on businesses and communities.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In June 2023, a team from the Universities of Cambridge and Washington (WA) published 'Pluripotent stem cell-derived model of the post-implantation human embryo'. In the same month, a Nature "news explainer", 'Most advanced synthetic human embryos yet spark controversy', bears witness to remarkable progress in embryo growth made by two groups. In August, an international research team published a strategic ethical roadmap for addressing the complexities of in vitro human embryology. 'An ethical framework for human embryology with embryo models' offers a way forward in an arena marked by ethical and legal ambiguities.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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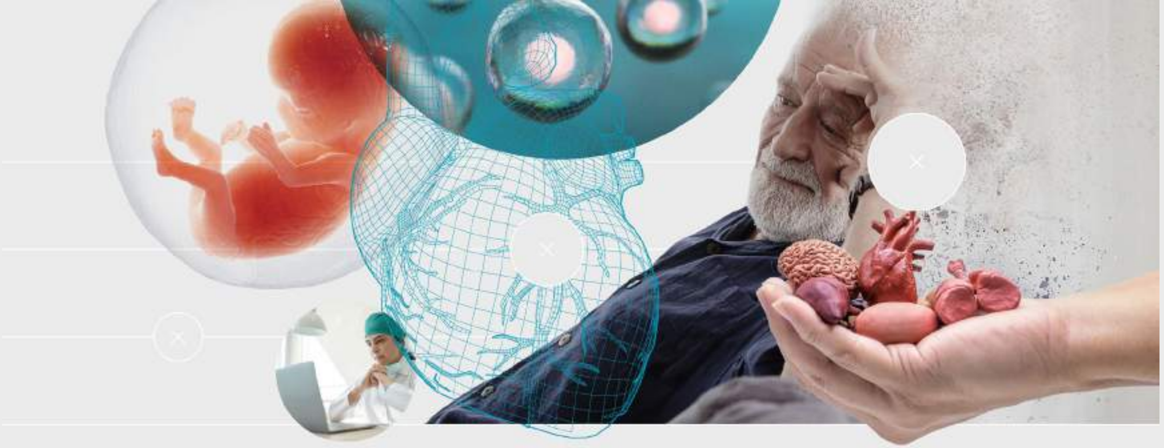


2.5.1 Foundational research

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 other primates,[13] including Neanderthals.[14] Organoids are also being used to investigate novel viruses and emerging diseases.[15]

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).[16] Brain organoids are already being used in the study of neurodegenerative disorders such as Alzheimer's[17] and neurological disorders such as epilepsy.[18]

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[19] — allows the study of inter-organ interactions. Large database(s) 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 will have organoid banks the way cell and tissue banks exist today, used by academia and industry to understand diseases and their variability across different individuals. We increasingly understand of the developmental processes involved with morphogenesis for complex structures. An understanding of the biochemical pathways of ageing allow us 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. Finally, the combination of paleogenomics, genome editing and organoid technology leads to novel insights on human evolution.

25-year horizon:

Whole human on a chip appears

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.

2.5.2 Hybrid organoids

Researchers are pairing human organoids both with other species and with robotics. "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.[20] Interspecies organoids (from mice) are used to accelerate development of human cells in embryoids. Whole organs have been derived with mouse-rat interspecies systems.

Brain organoids have also been paired with silicon technology, driving a robot to investigate how innate learning networks form.[21] Such machine-organoid connections could yield novel computational learning approaches for hybrid wetware/hardware AI.[22] A model of human cortical development could underpin novel computational learning approaches.[23] There is also some hope that hybrid organoids will assist in understanding extinction processes and facilitating de-extinction efforts.[24]

5-year horizon:

Borrowed cellular qualities emerge

Researchers grow tissues that regenerate themselves, thanks to capacity harnessed from other species or re-activated 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: research with brain organoids teaches 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 Translation and 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.[25] Patient-derived tumoroids are a more precise way for clinicians to screen drugs to determine the most efficacious treatment.[26] 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.[27]

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:

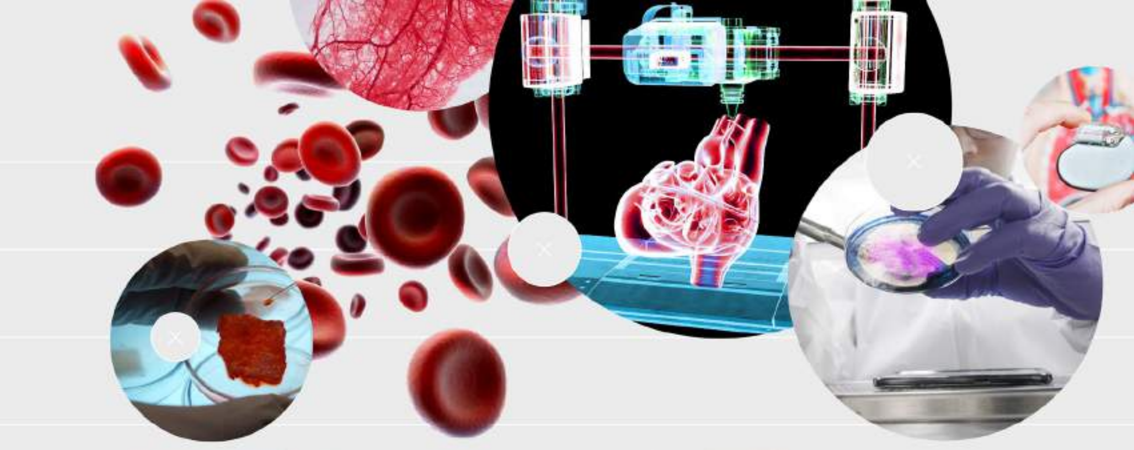
AI predicts drug responses

AI-assisted predictions can be made about individual response to some drugs. 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

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 like 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 very heterogeneous organoids, and so standardisation of tools and protocols, and automated production will be among the most important drivers of advancements 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.

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.

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, which would 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. 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 is scaled

The transition from cell culture to bioreactors allows scalability of complex organoids. Vascularisation begins to become more successful. "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 learned from large scale bio-manufacturing, at scales large enough to be useful for food production. As a consequence, food (for humans and other species) will become more nutritious, cheaper and can be personalised.

2.6 Future Therapeutics

In wealthy countries, one third of the population between ages 40 and 75 currently die due to preventable diseases including cardiovascular and metabolic disease, and cancer. If the right medical information were available to act upon at the right time, it would be possible to predict and prevent many of these deaths. There are four broadly defined domains in which promising trials could transition drugs and devices into the clinic over the next five to 25 years: electrical therapies, data-led therapies, cell-based therapies, and targeted immune-therapies.

These future therapeutics collectively represent the next wave of innovation in healthcare; some are already entering the market. Their growing success is down to a number of changes in the philosophy and practice of medicine. First, there has been a gradual move towards seeing medicine's goal as actively maintaining good health, rather than just fixing things when the body goes wrong. Second, a growing number of medical domains have begun to appreciate the complex properties of the body's own immune system, and to work with them. A third factor is the availability of increasingly sophisticated diagnostic and monitoring tools, which give previously inaccessible insights into the structure and function of the body's biology.

Within 25 years, the convergence of advances in these domains will, it is hoped, turn medicine from a restorative into a preservative model.

Simon P. Hoerstrup

Chair and Director of the Institute for Regenerative Medicine (University Zurich) and Founding Co-Director of the Wyss Zurich (University Zurich & ETH Zurich)

Anticipation Potential

EMERGING TOPIC:

Future Therapeutics

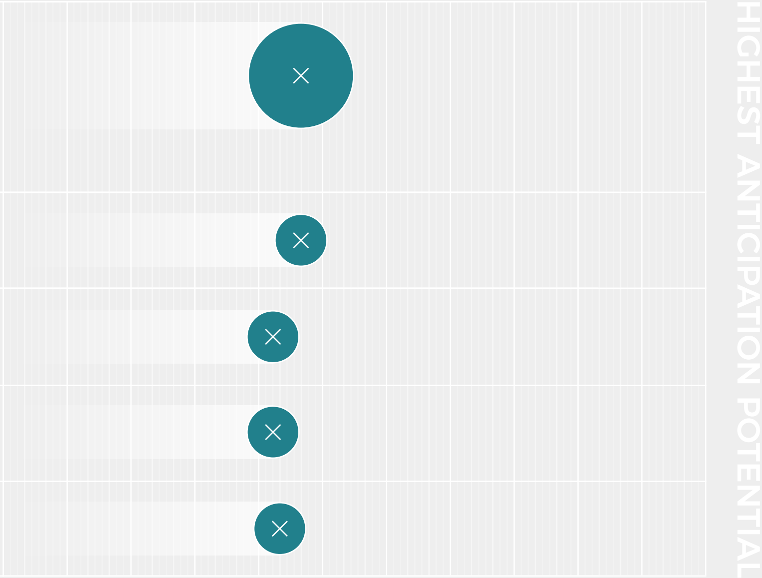
SUB-FIELDS:

Electrical therapies

Data-led therapies

Cell, gene, biomimetic and nucleic acid therapies

Immunome-based therapies



SURVEY OBSERVATIONS:

Bringing the next wave of innovative therapies to market is a highly active area of research, with immunotherapies and cell or gene-based therapies already available for some diseases. This activity has driven down the anticipation scores, as experts predict immunonome-based therapies and data-led therapies will reach maturity within the next 10 years. Electrical therapies were identified as a potential area of focus in future therapeutics, as the field is less mature and has received less attention so far.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In May, a team from Italy highlighted the intersection of genetic engineering and stem cell biology in 'Genetic engineering meets hematopoietic stem cell biology for next-generation gene therapy'. This insightful piece sheds light on advancements in HSPC-GT, underscoring the potential of transformative treatments on the horizon. In August, researchers from MIT introduced a game-changing method in their paper 'Cell type-specific delivery by modular envelope design'. They present DIRECTED, a method streamlining the process of targeted cell delivery, marking a milestone for precision in genetic therapy. August saw a reflective piece from Antonio Regalado titled 'After 25 years of hype, embryonic stem cells are still waiting for their moment'. This article offers a comprehensive look into the long journey of embryonic stem cells, highlighting challenges, recent advancements, and the hopeful future of stem cell-based treatments.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r2-6

2.6.1 Electrical therapies

The nervous system runs on electrical signals, and these can be manipulated to help with mental health problems, movement disorders, autoimmune diseases and diseases of ageing. While gross application of electricity has long been used in medicine, subtler and more targeted ways to change the body's natural electrical signals are now emerging.

Deep brain stimulation was initially developed to treat movement disorders but for the past two decades it has been in trials to target treatment-resistant mental health disorders, including depression and obsessive-compulsive disorders.[9] Promising trials are underway. Current therapies are invasive and have limited functionality, but ongoing trials are testing new materials and closed-loop designs for implants that will ensure better monitoring, wider adoption and biocompatibility.[10] Brain signals can also be manipulated non-invasively, and altering the frequencies of brain oscillations has been shown to affect cognition, memory recall and behaviour. Recently there have been early indications that it may mitigate the symptoms of Alzheimers disease.[11]

Another promising target for electrical therapies is the vagus nerve, a thick cable of parasympathetic nerve fibres that innervates many vital organs. Vagus Nerve Stimulation (VNS), both using invasive electrodes and non-invasive wearable devices, is now the subject of intense interest across many trials, with hopes of proving a wide range of therapeutic effects including on diabetes, depression, and autoimmune conditions like Crohn's disease.[12]

Electrical therapies are even emerging as potential components of regenerative medicine. It has become evident that electrical signalling plays a role in non-neural systems, and early successes in pre-clinical models suggest that stimulation could help scarless healing.[13] Some drugs can be repurposed to affect electrical aspects of the wound healing and regeneration response: in frog trials the drugs were able to fully regenerate an amputated limb.[14]

5-year horizon:

Closed loop systems and better implants

Closed loop designs help deep brain stimulation devices to give more precise control over brain circuits involved in depression and OCD. The evolution of implant materials continues, with new biocompatible materials entering (and completing) clinical trials for chronic nervous system implantation. Vagus nerve stimulation devices are FDA approved for medical uses, while non-invasive VNS apps, targeted at non-medical needs, are commercialised on the supplement market.

10-year horizon:

Implants become ubiquitous

New designs of brain implants which should do less damage when being implanted, such as neurograins and neuropixels, move through more clinical trials. The devices lead to improved understanding of neural pathways. Stentrodes (implantable electrodes) become commercially available.

25-year horizon:

The line between implants and biology is erased

Electrical stimulation is sufficiently parametrised that it is used to provide scarless healing and electrical control of regeneration response in the clinic. Better materials allow biomimetics to exist permanently in the nervous system to regulate its functions. Implants transition from central, single electrodes to nano-sensors and nano-stimulators distributed throughout the body.

2.6.2 Data-led therapies

Artificial intelligence is poised to become a major ally in the fight against disease. Ever-growing volumes of medical data are already being generated in clinical practice and in research, and the trend is set to continue. This vast store of information contains the seeds of future insights and treatments.

However, this will require far more meaningful and reliable patient data than is currently available. Patient involvement can be increased and improved through digital tools that range from simple smartphone apps to wearables that harvest data from users' bodies, and require prescription or physician referral. Many include sensors, gamification and connection to the care team for more effective and frequent self-reporting.[15]

Such devices are rapidly evolving into commercial products. These "digiceuticals" are predicted to become ubiquitous because they offer two major benefits. Most immediately, they increase patient adherence to therapies and medicines, and allow more frequent monitoring, which improves outcomes. The second benefit is that they enable more precise, high-resolution, high-quality data collection and integration.[16] This can identify patterns relevant for both the individual and patient populations.

The enormous volume of data generated by digiceuticals will make it necessary to use AI to identify patterns and generate useful insights.[17] For example, machine learning could expose meaningful correlations between disease symptoms and cures, as well as between genomes, other -omic layers and vulnerabilities to particular diseases.[18] This will also assist clinicians in decision-making, in the form of "augmented intelligence".[19] Augmenting human decision-making through the use of AI data analysis, sometimes referred to as "clinomics", offers a potential step change in maintaining a population's health.

5-year horizon:

Digital therapeutics comes of age

Health insurance begins to cover more digital therapeutics. Stroke rehabilitation software takes advantage of brain plasticity. VR and AR tools become a mainstay of health apps. Health care AI systems increasingly provide predictive analytics, precision medicine, diagnostic imaging of diseases, and clinical decision support.

10-year horizon:

Digiceuticals become mainstream

App-based digital therapies enjoy further success and ever-wider use. Ingestible or injectable sensors, such as ultrasound systems that are able to detect proteolytic activity (enzymes that are changed by disease), are used alongside the apps. Smart homes tie in with clinics and apps: toilets with integrated sensors, for example, will couple with ingested bioelectronics to transmit basic health data directly to digital apps. The convergence of biomedical data and the ability to analyse, share and reuse it allows AI to comb through multiple databases in order to assist diagnosis, drug discovery and the development of new therapies — some of which are personalised to take account of likely responses to drugs.[20]

25-year horizon:

Digital twins assist maintenance of health

Data-gathering nanosystems roam the body, detecting and diagnosing multiple disease states ever earlier in the process. Ingested or implanted tools to flag up potentially harmful changes in biology or behaviour are ubiquitous. Digital twins incorporate experimental results.

2.6.3 Cell, gene, biomimetic and nucleic acid therapies

Cell, gene, biomimetic and nucleic acid therapies work with the basic units of the human body to achieve medical results, rather than acting on a whole body or organ. In the first instance, this is done by replacing unhealthy or dysfunctional elements. So, for example, cell therapies bring healthy cells into a patient's body as replacements for missing or unhealthy cells; they are already licensed for the treatment of certain types of leukaemia and lymphoma. Similarly, gene therapies are intended to restore functionality, often by introducing healthy genes; after some missteps this is now breaking into mainstream medicine. Elsewhere, techniques derived from optogenetics have reversed retinitis pigmentosa and sickle cell disease,[21] suggesting potential for a cure.

More fundamental still are therapies which "reprogramme" or "educate" the body's immune defences. mRNA's ability to teach the body how to make specific proteins can help the immune system prevent or treat many diseases: trials are now in progress against malaria, rabies, cancer and influenza, and there are promising early results when it comes to personalised pancreatic cancer vaccines.[22] Beyond vaccines, mRNA could also be used in novel therapies for cystic fibrosis, heart disease and rare genetic conditions.

Small-molecule drugs could be the basis of antiviral therapies against Covid.[23] While the efficacy of repurposed existing drugs has been up for debate[24], new mechanisms are being identified for preclinical trials[25], and these could augment a vaccine strategy and help prepare for future pandemics.

Meanwhile, nano-engineered molecules that are mimics (but not always exact copies) of existing drugs are providing a useful way around the limitations of naturally occurring compounds.[26] Used in medicine, the highly interdisciplinary field of biomimetics will bring down costs, speed up development, and make the medicines more globally available.

5-year horizon:

Novel therapeutic techniques acquire greater visibility

Researchers develop a better understanding of the wide variety of whole-body responses to drugs. Trials of mRNA-based cancer vaccines, currently underway or planned, begin to show consistent results. Researchers develop therapeutic agents that bring about "targeted protein degradation" – destroying faulty proteins using the cell's own machinery. It becomes possible to generate different cell lines in the field of immunotherapy, and to modify T-cells, and this becomes standard medical practice. Regenerative medicine approaches such as cell therapies and biomimetic implants are in first clinical trials and begin to appear in clinical use but are not yet standard therapy.

10-year horizon:

Increasing convergence and transparency

Small-molecule therapies, which can be stored and transported more easily than biologics, become generic, making them much cheaper. Smart homes deliver results of automated sampling directly to family physicians, and biocompatible devices replace and/or support biological function. Clinical and research data is drawn from repositories that combine data from a wide cross-section of disciplines; this data, through AI-assisted insight, helps to turn cancer into a chronic disease. Sensors and actuators interrogate cells at the subcellular level, either through direct application or remote sensing.

25-year horizon:

Health care is prevention

Cell therapy becomes a major topic in immune disorders, regenerative medicine and blood disorders. It becomes possible to restructure the genome to maintain optimal health. Fully living organs are created from autologous cells. Living therapeutics stay in the body permanently, and in vivo sensors comprehensively monitor the entire physiological state of a wound or injury — from gene and protein expression to mechanical properties — to ensure optimal healing. This will work in tandem with regenerative medicine systems that can alter cellular states in injured tissue to make it heal with standard tissue rather than scar tissue. The pivot from reactive to preventive health management is complete.

2.6.4 Immunome-based therapies

Over the past two decades there has been a dramatic transformation of our understanding of the immune system's relevance to every major aspect of medicine. It is important not just in infection and vaccinations but aspects that were previously considered unrelated, including cancer, foetal development, ageing and mental health. Targeting T-cells has proven clinically powerful in treating cancer.[27] There is also compelling evidence that targeting the immune system may work on depression.[28]

Furthermore, many immune events leave lasting marks, as cells express particular antibodies and T cell receptor genes with an increased frequency.[29] This "immunome" is a personalised record of a person's immune status; reading and mapping these rearrangements in an individual who has been exposed to disease, vaccination, cancer and other "foreign" material is likely to become clinically useful in the near future. It could facilitate medical diagnosis and treatment. Progress in digital technologies and artificial intelligence will allow us to model parts of the immunome and its complex interactions. Access to data, coordination and data-sharing at a global scale remains a challenge.

In principle, this makes it possible to compile a record of an individual's immune responses, which can help in clinical decision-making. With enough examples, it should be possible to create population-level diagnostic tests for disease. A better understanding of the immunome will also help us to work with it, rather than against it, when designing the next generation of implants, including neural prosthetics, replacement organs and nano-drug delivery systems. In the longer term, through modelisation, a personalised immunome could be established, leading to new boundaries in personalised medicine.

5-year horizon:

The immunome is characterised

Engineers design new biomaterials that can interface with the nervous system without inflammation. New combinations of immune-system modulating drugs enter cancer trials, with greater precision that reduces the problem of drug toxicity. Researchers develop machine learning algorithms to amalgamate data that will help inform initial models of the human immunome.

10-year horizon:

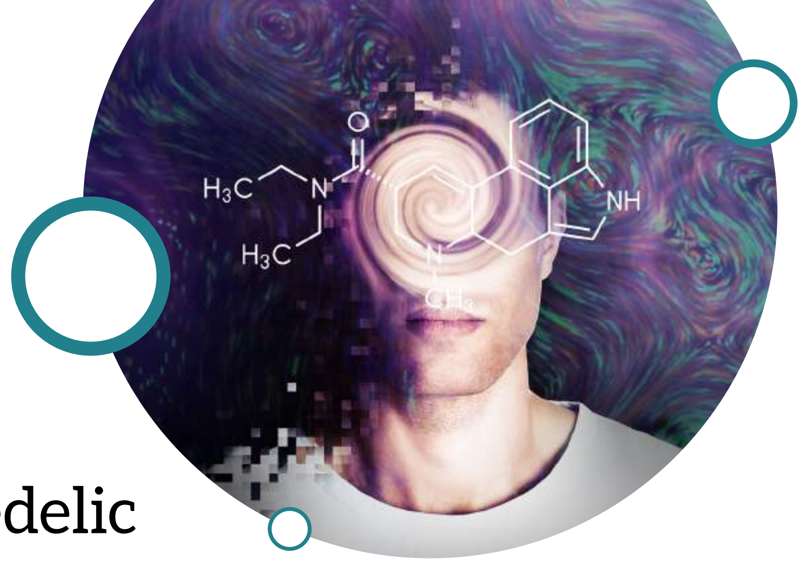
Manipulating the immune system becomes possible

Researchers begin to unpick the intricacies of how wound healing and regeneration work. Most kinds of cancer become a chronic disease. Preliminary models emerge of the human immune system as the network of genes, proteins and cells that are its components. The first in-silico vaccine and immunotherapy trials take place. AI-assisted longitudinal studies of individual immune systems create new understanding of mechanisms of the immunome.

25-year horizon:

The era of personalised immuno-medicine begins

Granular understanding of the immune system, coupled with the ability to control it, makes it possible to prevent the onset of autoimmune disorders. Deeper understanding of tissue regeneration makes it possible to coax the body to regrow whole organs and limbs. Personalised vaccination programmes or drug delivery tailored on a particular immunome becomes possible, enhancing vaccine efficiency. Better understanding of inflammation and immune system activation in pregnancy reduces premature births. Immune senescence becomes a treatable condition.



David Nutt
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Founder and President, Instituto Phaneros, Brazil

Invited Contribution: The Future of Psychedelic Medicine

This year marks the eightieth anniversary of the first time a human ingested LSD. Albert Hoffman's first trip, in April 1943, began a period of experimentation and discovery in both academic and counter-cultural circles. The word "psychedelic" was coined by the psychiatrist Humphry Osmond about a decade later, and research into these chemicals' potential therapeutic use continued for the next several decades — as did their recreational use. But this first psychedelic "revolution" came to a halt in the early 1970s, when a censorious attitude to recreational drugs led to many becoming controlled substances, with the result that serious scientific research into their applications became extremely difficult to conduct.

Now the psychedelic revolution is starting up again. A decade ago the authors conducted the first neuroimaging examination of LSD's effects in the brains of healthy volunteers. Since the publication of this landmark study,[1] the field has expanded from a few labs examining an exotic topic in neuroscience into an extensive network of academic laboratories and dedicated university centres in prestigious institutions. This work is being conducted around the world but is concentrated within the UK, USA, Switzerland, Spain and Brazil. In June 2023, the largest ever conference on the topic, Psychedelic Science 2023, took place in Denver, Colorado, USA, with about 500 speakers and 12 thousand participants from many countries.

Given that most psychedelic substances remain controlled, some might find these developments surprising, and perhaps concerning. But consider the need. Mental health is considered by the World Health Organization to be our biggest challenge. But most countries invest less than they should in the field, and the unmet need is huge. Psychedelics are powerful agents which target specific receptors in the human neocortex and can dramatically affect cognitive functions and emotions for a period of a few minutes to many hours. This makes their use quite distinct from almost any medication in current use in psychiatry.

Research with psychedelics has therefore mostly focused on their psychiatric applications. Although such research has been ignored by funding agencies for a long time, it has continued to evolve for decades through the visionary actions of philanthropic donors. At the beginning of the 2020s this evolved into a growing drug development marketplace, with a few specialized investment funds and hundreds of startups, plus a few public companies pursuing regulatory approval of a variety of compounds, mostly in Europe and the USA.

This activity has led to the so-called “classic psychedelics” (LSD, psilocybin, DMT and mescaline) and a series of closely related chemical analogues (MDMA, ibogaine and 5-MeO-DMT, among many others) being examined in pre-clinical and clinical studies. Results so far have been very encouraging, with few serious adverse events and promising efficacy data for PTSD, depression, substance use disorders and many other conditions.

However, there continues to be stigma around this research, given the many pejorative connotations of “psychedelic”. Psychedelics remain associated in the public eye with illicit drug use and are widely perceived as risky and harmful. That is a policy misclassification with little basis in the scientific evidence to date, which spans a wide range of study designs and approaches, ranging from anthropology to medicine, toxicology and sociology. The classic psychedelics are in fact known to present very little toxicity to the human organism, being safe for use under medical and/or psychotherapeutic supervision. Furthermore, they are not strongly linked with abusive patterns of consumption and do not lead to drug dependence. There is, however, the potential for abuse in terms of excessive frequency and/or dosage — a risk factor which must be taken into consideration, just as for many other pharmaceuticals.

Most studies are done under carefully controlled clinical settings, with professional supervision during the entire duration of the effects. The treatment progresses in cycles, with each cycle typically beginning with a preparatory psychotherapy session, followed by a medication session. This is when a psychedelic substance is administered to the patient, continuously accompanied by specifically trained professionals, generally lying down with eyes closed, perhaps listening to instrumental music, for long periods of time. Talk therapy may be included at various points. After each psychedelic session, more psychotherapy sessions, this time without administration of any substance, are conducted to close each cycle. Protocols differ in many aspects, but this basic and cyclic structure is an important commonality.

While a range of different approaches have already been assessed, there remains much that requires further investigation to safely and responsibly move forward. Psychedelics, by their nature, induce altered states of consciousness, which can for many participants, become some of the most meaningful experiences of their lives. That raises ethical questions deserving of the most serious consideration. Guiding patients through the process also requires specialist training; scaling this training up to the levels needed to meet demand requires educating many thousands of practitioners in the coming years. And commercialisation of these substances may be challenging in a healthcare marketplace which is ill-prepared for the overall structure and intensive care required for a safe and effective course of treatment.

While the formalisation of psychedelic medicine continues, we must also recognise that the properties of many such compounds have been known for millennia and are still utilised by indigenous peoples, the most well-known examples being ayahuasca, peyote and mushrooms. Further insights are likely to be found by working with these peoples and discoveries to be made in ethical and fair collaboration. There are thus concerns to be addressed around intellectual property, which is currently booming, and social justice. If the nascent industry of psychedelic compounds and treatments is to grow ethically, it must take up the challenge of developing models which are inclusive of tangible and intangible indigenous knowledge. This may also create an opportunity to prevent mental health issues, by respecting indigenous sovereignty, biodiversity and land rights, all of which are currently threatened by climate change.

For our societies to fully benefit from the exciting advances now being made in psychedelic medicine, policymakers and stakeholders need to pay attention and dedicate appropriate levels of resources to this important field. Unsubstantiated obstacles to research with currently controlled substances should be loosened. And diverse and inclusive special groups must be convened to discuss how these therapies can be deployed in ways that respect the United Nations’ “right to enjoy the benefits of scientific progress and its application” (REBSP), as well as treaties such as the Convention on Biological Diversity (CBD) and the Nagoya Protocol.

These are all urgent and fundamental to safeguard the ethical and responsible maturing of this field. The specific combination of psychedelic drug with therapy, which does not easily fit into current prescription and dispensing of psychiatrics medications for daily use at home, merits particular attention. Indeed, there may be profit incentives for pursuing such models which are likely to be risky and harmful for many. Therefore, in addition to rigorous scientific research, respect and reparation with indigenous peoples, we need democratic and diplomatic action to safely adjust our healthcare infrastructure, education and practice in order to implement these new treatments in the 21st century. This time, we hope the psychedelic promise will not be allowed to fail.

3

Introduction to Eco-Regeneration & Geoengineering

There can be no doubt that the current state of the planet presents one of the most pressing issues ever faced by humanity. Concerns about warming, pollution and biodiversity are only compounded by the forecast rise in human population, which is expected to reach nearly 10 billion by 2050. Advances in science and technology will be vital for monitoring and mitigating problematic trends, and for establishing new ways for humanity to live on a changing planet.

As a result, **decarbonisation** programmes matter more than ever. From the development of negative emissions technologies that extract CO2 from the atmosphere, to the rapid development and scaling up of renewable energy sources and manipulation and control of energy demand, the decarbonisation of the planet has a ready roadmap. Plans are being developed to combat hard-to-abate emissions, such as those from shipping and heavy industry. But much more work is needed to bring some of the envisaged technologies to fruition.

Also urgent is the development of techniques for **Earth systems modelling,** an effort to map out and make sense of the many complex interactions and feedbacks that underlie the biological, ecological, atmospheric and geological processes supporting life on this planet. As this field's data-gathering and computer modelling matures, we will have ever-more tools in place to limit the negative impacts of human activities, and to gain warning of significant future events.

It is already clear that our **future food systems** will have to be resilient, with inbuilt ability and incentive to innovate. The development of future-proof agriculture techniques, the pioneering of alternative protein sources and the application of cutting-edge gene-editing and biotech can begin to transform our food production to make it more sustainable and nutritious.

Beyond the immediate environment of our planet lies a vast unexplored set of possibilities. Nations and corporations are only just beginning to explore the potential of space resources, whether that is through asteroid mining, programmes for long-term human habitation beyond Earth, or just the search for alien life and further knowledge about the universe, its laws and its contents, all of which might change our understanding of ourselves.

We also need to understand our oceans better, and to help repair their ecosystems where possible. Pathways are opening up that will make this happen. We can deploy the emerging technology of autonomous sensors to gather relevant data, for example, and continue to explore the vast biodiversity of the ocean and the myriad cold-adapted organisms rapidly disappearing from the planet's retreating glaciers. Despite challenges from ever-increasing pressure to exploit the ocean's resources, our growing understanding of their complex, interdependent networks is helping us to achieve proper **ocean stewardship**.

Countering the effects of climate change has proved challenging, both in terms of developing strategies, and in reaching agreements on how they should be implemented. One of the strategies under consideration is **solar radiation modification**, where a range of actions might help us to counter the thermal effects of the anthropogenic greenhouse gases accumulating in our atmosphere. Whether by brightening clouds, increasing the reflectivity of the

Earth's surface, constructing mirrors that sit in low earth orbit or other means, reducing the amount of solar radiation that reaches Earth would help keep temperatures under control. However, important and difficult questions about the control, ownership, deployment and effectiveness of such tools remain, and whether humanity should invest in further research is debated.

Although humanity has made great progress in reducing the impact of **infectious disease**, there is still plenty to do. The COVID-19 pandemic made it clear that new diseases are emerging all the time, and that our interconnectedness provides ample opportunity for them to spread quickly, with devastating results. The problem of vector-borne diseases such as malaria remains unsolved, highlighting the importance of seeing disease as emerging from human actions in, and interactions with, our environment. Medical technologies such as vaccines are only part of the solution; we also need to use multidisciplinary research to garner a deeper understanding of the ways in which infectious diseases arise and emerge.

Each of these programmes of research offers 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.

3.1 Decarbonisation

Greenhouse gas emissions in 2022 were the largest in history: humanity released 36.1 gigatonnes of carbon dioxide (GtCO2), 1.5 per cent more than in 2021.[1] The major emissions sources are:

- **Energy supply: 34%**
- **Industry: 24%**
- **Agriculture, forestry and other land use: 22%**
- **Transport: 15%**
- **Buildings: 6%.**

In 2022, levels of CO2 in the atmosphere reached 417 parts per million, about 50 per cent higher than pre-industrial levels.[2] Thanks to this atmospheric carbon, Earth has already warmed 1.1°C compared to the late 19th century.[3] There is now a 66 per cent chance that the annual global temperature will be more than 1.5°C above pre-industrial levels for aleast one year between 2023 and 2027.[4] To give a 50 per cent chance of limiting global warming to 1.5°C, we can emit no more than 380 GtCO2: if we continue emitting at 2022 rates, we will use up this carbon budget in nine years.[5]

In the 2015 Paris Agreement,[6] 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." 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.

Existing policies are not sufficient to achieve this and are likely to lead to 2.8°C of heating by the end of the century.[7] However, the national pledges made at COP26 in Glasgow would, if fully implemented, limit warming to less than 2°C (but not to 1.5°C).[8] 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.

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Associate Professor in Chemical Engineering,
Director of the Center for Negative Carbon Emissions
Arizona State University

Anticipation Potential

EMERGING TOPIC:

Decarbonisation

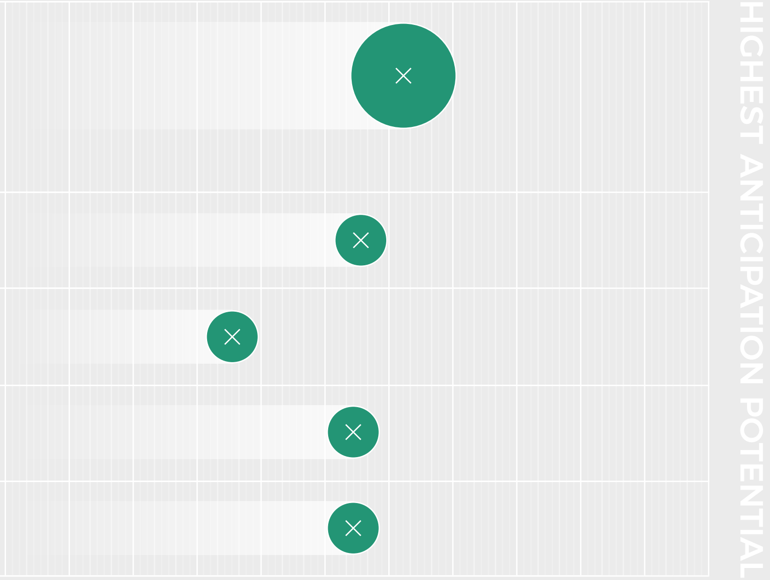
SUB-FIELDS:

Negative emissions technologies

Renewable energy

Hard-to-abate emissions

Energy demand



SURVEY OBSERVATIONS:

The drive to reduce the amount of CO_2 in the atmosphere has been a global priority for a number of decades and a received a boost in investment recently. Moving away from polluting fossil fuels and transitioning into renewable energy systems has been a major focus of this effort, which is why the topic was judged to have low anticipatory need. In contrast, large-scale deployment of negative emission technologies and tackling hard-to-abate emissions are close to 15 years away and have received less attention so far, suggesting a greater need for foresight in this area. Respondents judged the impact of all the topics studied as extremely high.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

From March, 'Why residual emissions matter right now' by an international collaboration critically examines residual emissions in strategies submitted to the UNFCCC. The research calls for consistency and clarity, pointing out potential pitfalls in forecasting and fossil fuel consumption's future. 'Application of energy storage in integrated energy systems — a solution to fluctuation and uncertainty of renewable energy', published in August 2022 by Chinese researchers, navigates the realm of energy storage. Through a comprehensive review, it explores the role of various storage technologies in optimising the utilisation of renewable energy. In September 2022, a collaboration between US, China, and UK researchers published 'Breaking the hard-to-abate bottleneck in China's path to carbon neutrality with clean hydrogen'. This study accentuates the revolutionary role of clean hydrogen in addressing persistent carbon emission challenges, projecting its substantial potential in China's heavy industries and transportation sector by 2060, marking a promising stride towards achieving carbon neutrality in traditionally difficult sectors.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r3-1

3.1.1 Negative emissions technologies

An important element in the global strategy for 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 GtCO2 between now and 2100 – equivalent to 15 years of 2017 greenhouse gas emissions.[9] 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 come under the heading of Natural Climate Solutions. For example, 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. Taken as a whole, natural climate solutions could mop up at most 23.8 Gt GtCO2 per year[10]

In contrast, other NETs are highly artificial. "Enhanced weathering", for instance, entails crushing minerals like olivine into powder, which reacts with CO2 and water to form a new mineral that can be used or buried. Lime can be thrown into the ocean to react with dissolved CO2 to produce calcium carbonate that sinks to the seabed. Alternatively, some regions of the ocean could be fertilised with iron particles, which drive the growth of phytoplankton that draw in CO2. There is also Direct Air Capture (DAC), in which machines are constructed that contain chemical "sponges", which draw CO2 out of the air. In carbon capture and storage (CCS), this CO2 is sequestrated in underground repositories such as aquifers or depleted oil and gas reservoirs. In carbon capture and use (CCU), the carbon is used for enhanced oil recovery or re-purposed through conversion into forms such as fuels, fertilisers or construction materials.[11] Because the carbon remains in use, CCU does not necessarily reduce emissions.

All these technologies face problems of scale and cost. Furthermore, for the most part, their effects (desired or otherwise) are not constrained by territorial boundaries, and raise the potential for inter-nation conflict.

5-year horizon:

Research innovation assists carbon capture and use technologies

Investment in new direct air capture (DAC) technologies re-invigorates academic research in the field. AI-based chemical innovations begin to find applications for re-purposing captured carbon.

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

3.1.2 Renewable energy

As of 2019, about 11 per cent of our overall energy came from renewables.[12] Renewables make up a larger share of the electricity supply: in 2021, 28.7 per cent of electricity came from renewable sources.[13] This represents rapid growth: as recently as 2010, solar and wind made up just 1.7 per cent of global energy supplies.[14]

Much of the growth in renewables can be attributed to rapidly falling costs. Solar and wind are now routinely cheaper than fossil fuels such as coal.[15] This has occurred despite the 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.[16]

There has been considerable disagreement about the role that can be played by hydrogen.[17] 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.

In the longer term, nuclear fission and fusion may also have a role to play. Nevertheless, commercial-scale fusion plants are still likely to be decades away.[18] Small-scale nuclear fission reactors are also under development, although their chances of commercial success remain similarly difficult to predict.[19]

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.[20] 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.[21]

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.

3.1.3 Hard-to-abate emissions

Some sectors of the economy are extremely difficult to decarbonise. A significant fraction of our carbon emissions comes from hard-to-abate sources such as agriculture, forestry and other land use. Part of the solution will be on the demand side: switching to more sustainable diets that feature less red meat will cut emissions, partly by reducing tropical deforestation. Reducing food waste will help, as will progress in developing cultivated meat. There are also improvements to be made on farms, particularly in the management of soils, which are a major source of carbon emissions. Innovations in methane-inhibiting feedstocks, selective cattle breeding for low methane production[22] and anaerobic manure processing[23] are also set to help.

It is also possible to improve industrial processes to reduce overall emissions. In steel manufacture, carbon is typically used to chemically transform iron ore into iron, but newer “direct reduction” processes use hydrogen instead.[24] There is also the potential to use “oxyfuel” — air with most of the nitrogen removed — in order to create emissions that are less dilute and thus easier to capture. This is an attractive option for cement production, a significant source of carbon emissions.[25]

Aviation remains an unsolved challenge, because powered flight requires fuels with a high energy-to-mass ratio, and batteries cannot yet match that of kerosene. Solar-powered planes cannot yet carry large numbers of passengers. Some companies are experimenting with replacing fractions of their jet fuel with biofuels or chemically-engineered synthetic fuels. However, these initiatives are not yet market-ready.

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. 25 per cent of people adopt vegetarian diets.[26] Low- or zero-carbon aviation fuels become available.[27]

3.1.4 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.[28] 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.[29]

Operation of buildings, which consumes 30 per cent of the energy generated globally,[30] is ripe for innovation. 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.[31] 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.

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:

Buildings 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.

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.[32] Electric cars outsell petrol cars globally. New low-temperature industrial processes reduce the energy demand of heavy industries.

3.2 Earth Systems Modelling

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 of significant interactions between elements of the Earth system — oceans, atmosphere, land, Arctic and Antarctic ice (the cryosphere) and biosphere — has proved correct.

Researchers seeking to understand climate change have thus been required to incorporate ever more components of the Earth system into their models. By including explicit models of the cryosphere, for example, 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, that 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 a significant increase 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.

Gavin Schmidt
Director Goddard Institute for Space Studies, NASA

EMERGING TOPIC:

Earth Systems Modelling

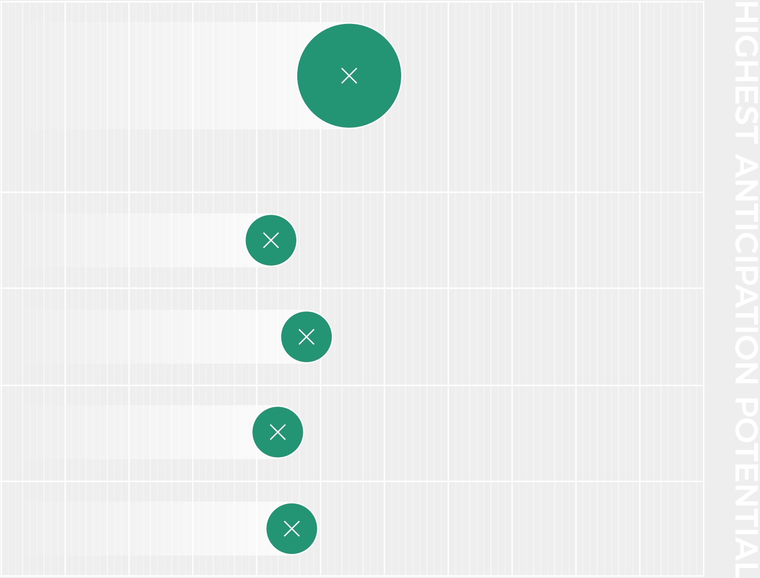
SUB-FIELDS:

Modelling of feedbacks in the Earth system

Tipping element modelling and forecasting

Interactions between Earth systems

Model intercomparison



SURVEY OBSERVATIONS:

Advances in the four topics are likely to reach maturity in 10 years from now. The fact that they draw on highly interdisciplinary research boosts their Anticipation Scores. The modelling and forecasting of tipping points was seen as most transformational, resulting in a higher score for the topic compare to the three other ones. In contrast, standardisation and comparison efforts — while judged important — are less likely to be disruptive for society.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In January 2023, an international collaboration published 'Teleconnections among tipping elements in the Earth system', delving deep into the Earth's interconnected ecological zones. By identifying strong linkages between pivotal components like the Amazon Rainforest Area and the Tibetan Plateau, the study emphasises the potential domino effect of environmental disturbances, accentuating the urgency of decoding these ties to anticipate and navigate future climate alterations. In a similar vein, a group of researchers published 'Many risky feedback loops amplify the need for climate action' in February, an important attempt to highlight feedback loops that are not fully accounted for in climate models. 'Predicting climatic tipping points', also published in February by a collaboration between German and Indian researchers, unravels alarming climatic thresholds by deploying an innovative model. The revelations underscore the impending peril of unchecked greenhouse emissions and the pressing need for timely interventions.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r3-2

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 carbon dioxide triggers also causes allows for more water vapour in the atmosphere, and water vapour is 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 the data suggest 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 the 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 improve 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 that 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 a forest to a 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 calibration with observational data.

5-year horizon:

Permafrost influence is better understood

Research in modelling achieves clarification of whether the permafrost is truly a tipping 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 fresh-water 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:

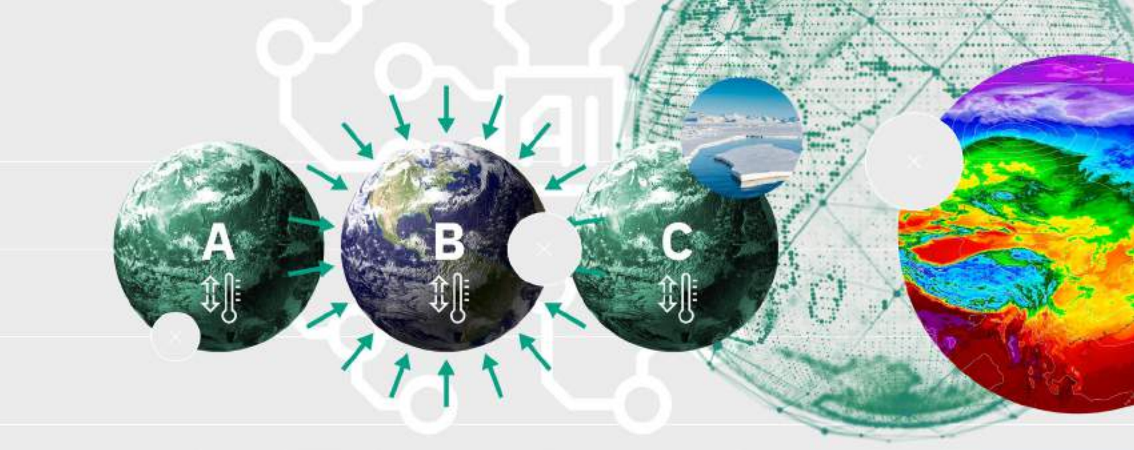
An array of sensing technologies feed into modelling of system exchanges

Improvements in LIDAR, satellite-based sensing and infra-red 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 of 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 already 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 (PCMDI) co-ordinated at Lawrence Livermore National Laboratory have made headway here.[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 remains difficult.

An ongoing challenge for Earth system modellers is to understand in which circumstances the Earth system is stable and/or 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) 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. All these uncertainties would be reduced by improved gathering of observational data, better anchoring the models in reality.

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

Food is fundamental to our existence, and the challenge before us is to build a resilient, sustainable system able to produce and distribute sufficient nutrition for a growing global population.

There is reason for optimism, however. Over the last century, developments such as the Haber-Bosch nitrogen fixation process, advances in fertilisers, mechanisation and innovative breeding techniques have significantly improved agricultural yield. Developments in gene manipulation technologies have already transformed many aspects of agriculture, and the stage is set for rapid advances in this arena.

There are new issues to resolve. The daily consumption of calories is increasing globally, and a growing middle class — especially in developing countries — is increasing demand for animal protein, which is perceived as being of higher quality. However, there is also a growing awareness that we can find protein alternatives and reduce our consumption of meat to curb the greenhouse emissions of livestock. A growing range of alternative proteins have a role to play here, from plant-based sources to cell-cultured beef.

Resolving issues with food waste will also help. Currently, around 40 per cent of globally produced food is wasted. This is enough to support a significant amount of the global population if we manage to prevent the loss and maintain this in the food chain through novel, innovative processes.

We can also improve global health through food. Changes in food consumption have driven obesity and diabetes to the level of a global pandemic. This can be turned around by moving from producing calories to producing valuable, healthy food using food as an important factor to maintain and improve health. For a significant proportion of the global population, basic access to nutrition is the priority. But for many lucky enough to live in wealthier nations, the emphasis will move towards personalised nutrition fuelled by advances in consumer technology.

Ralph Graichen

"Director of Food and Nutrition and Consumer Care and Associate Professor, Agency for Science Technology and Research Singapore"

Anticipation Potential

EMERGING TOPIC:

Future Food Systems

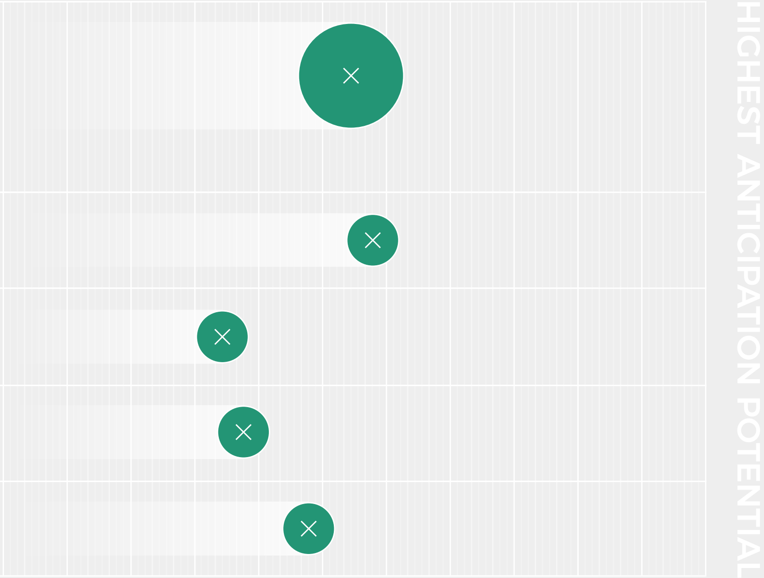
SUB-FIELDS:

Ecosystem-level GM

Alternative proteins

Resilient farming

Personalised nutrition



SURVEY OBSERVATIONS:

Re-imagining the future of our food systems will involve complex and interrelated developments in a host of disciplines and will be built on centuries worth of agricultural knowledge. Nowhere is this more obvious than with resilient farming, where respondents highlighted the high level of convergence between fields required to achieve breakthroughs. Nonetheless, the area highlighted as requiring the greatest anticipatory focus was ecosystem-level genetic modification, due largely to low awareness of its potential and the long road to the technology's maturity, with significant progress and deployment more than 15 years away.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Published in January 2023, 'The use of silkworm pupae (Bombyx mori) meal as an alternative protein source for poultry', by a team of researchers from Egypt, India and Saudi Arabia illuminates the horizon of sustainable poultry nutrition. The research unravels the game-changing potential of silkworm pupae meal, highlighting its nutritious properties that greatly benefit poultry performance. In May, two Chinese researchers highlighted the intersection of agro-ecological sustainability and the transformative power of modern genetic techniques in 'Advancing agro-ecological sustainability through emerging genetic approaches in crop improvement for plants'. The paper underscores the necessity for robust regulatory systems and increased global investments, especially in developing nations, to leverage these genetic breakthroughs for sustainable agriculture. 'Priority areas for investment in more sustainable and climate-resilient livestock systems' was published in June by an international research effort. It bridges adaptation and mitigation goals, shining a light on priority zones across 132 LMICs, spotlighting countries such as India, Brazil, China, Pakistan, and Sudan as prime candidates for investment in a sustainable livestock transformation.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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3.3.1 Ecosystem-level genetic modification

Ecosystem-level genetic modification is about using gene editing and manipulation technologies not only to enhance crops and plants but also to target a range of ecosystem constituents, including weeds, pathogens, pests and food crops. Such technologies, many nascent, include gene drives to eliminate pest populations, the development of RNA-based pesticides (which sidestep the problem of resistance development)[5], and genetic manipulation of soil microbes to optimise crop yields.

Such technologies have the potential to significantly increase food production — especially with the growing importance of indoor and vertical farming — but there are issues to resolve. Much more research is needed to ascertain how the different component of an ecosystem react to even small biological manipulations, for instance. There are also legal issues: the European Court of Justice has ruled that modern gene editing is to be considered the same as genetic modification for the purposes of European Union law, and therefore subject to the same strict rules — organisms developed in this way are largely banned in the EU market.[6] It is likely, though, that it is only a matter of time before genetics-based interventions will be deployed at scale; the US Department of Agriculture does not regulate crops produced using gene editing, as long as those genetic changes could also have been produced using conventional breeding techniques.[7]

5-year horizon:

Genetic modification remains controversial

Debates continue over what genetic modification (GM) methods and products are, or should be, acceptable in markets around the world. Technological capability grows steadily, with scientific advances continuing to outstrip the public debate.

10-year horizon:

Crops begin to receive viral boosts

Agricultural crop performance is boosted by transient genetic reprogramming of plants, for example by using RNA sprays that virally alter crop traits without requiring the genetic modification of the plant's genome.[8] This makes them somewhat more palatable to wary consumers and regulators. Different genetic traits will be promoted, depending on the cultivation method: salt resistance and drought resistance will be important for outdoor cultivation, for instance; nutritional content and shortened growth cycle for indoor cultivation. Molecular sensors in plants become more widely used.

25-year horizon:

The GM toolbox matures

A wide range of GM approaches become available, including novel, genetically active pesticides, gene-drive organisms and genetic engineering of crop plants accelerated by machine learning algorithms. Deployment of GM organisms and technology is differentially constrained around the world, depending on national and international regulations and agribusiness interests.

3.3.2 Alternative proteins

Although protein is almost never the sole source of nutrients in a diet, the impact of farming non-sustainable and ethically questionable protein sources is one that must be addressed. For reasons that range from health concerns to worries over animal welfare and the environmental impact of animal husbandry, the uptake of alternative proteins is already growing, particularly in wealthier countries with mature markets and an emphasis on consumer choice.[9]

These proteins come in many forms, with ingredients sourced from algae, plants (such as pulses, soy and pea), fungi (mycoprotein), insects (such as crickets), or cell-cultured meat typically designed to mimic chicken or beef. Plant-based options are currently the most accepted by consumers[10], but there are other options — including proteins from outside the food chain. Cultured meat remains a young field, with relatively expensive products. However, ongoing investments, improvements and scale-up of the technology will create greater value and impact in the coming decades.

Concerns remain, however, that the organisations pioneering cultured meat may develop monopolies in the market.[11] In addition, if cultured meat production were to scale up enormously, there are unanswered questions about unanticipated environmental impacts. For more established plant-based protein alternatives, the challenges of sustainable farming — minimising fertiliser and pesticide use, protecting soil — are better understood.

5-year horizon:

Alternative proteins become ubiquitous

Alternative proteins are grown more efficiently and become more enticing to consumers as taste profiles are refined. Concerns are increasingly raised about emerging monopolies in cultured meat. Nutritional value and sustainability impacts of alternative proteins are better understood. Hybrid products — a mix of cellular agriculture and plant-based produces — begin to bridge the price-point gap.

10-year horizon:

Markets respond to price-point crossover

Alternative protein, which continues to improve rapidly in quality, falls below $5 per kilogram, becoming cheaper than meat. It now commands 5-10 per cent of the global meat market by volume, compared with less than 1 per cent in 2021. Some specific ingredients, such as milk proteins for dairy-based products, are produced through fermentation, which provides a more acceptable sustainability footprint.

25-year horizon:

High meat consumption is considered antisocial

After decades, the message that tackling dangerous climate warming is virtually impossible without a large drop in meat consumption begins to make meat-eating a morally questionable practice in many richer societies. Novel food categories are well-established, replacing many of the traditional food items.

3.3.3 Resilient farming

If we are to boost crop yields in sustainable ways, alter the geography of our food growing and distribution networks to respond to our growing urbanisation, and reduce our dependence on environmentally damaging fertilisers, 21st-century society will need to make radical changes to its food production ecosystem. These changes are beginning to emerge.

Advances in genetics are creating crops increasingly able to meet our needs. They can tolerate the higher temperatures and lower water availability associated with climate change, resist diseases and pests, increase the efficiency of their nitrate use, and reduce their need for fertilisers. Genetic tweaks also reduce their intolerance of shade, allowing crops to be planted at greater densities. With a global population set to hit 10 billion by 2050, such advances will be essential, especially since that 10 billion people need to be fed from 0.5 billion hectares of land. This requires an increase in food production per hectare of almost 60 per cent in less than 30 years. Compounding the problem, around 66 per cent of the global population will live in an urban environment, which brings its own challenges on supply chain management and loss of produce on the path from harvest to consumer. Currently this can be as high as 40 per cent in developing countries.

On the positive side, the widening use of sensor technology, drones and data gathering in farming, combined with advanced automation and machine learning, is enabling farmers to operate more independently, cutting wage bills, fertiliser costs and time spent checking fields and livestock.[12,13]

With increasing migration into cities, indoor vertical farming in urban areas will provide opportunities to repurpose obsolete infrastructure to create high-density production facilities close to where the food is needed, reducing transit costs, packaging requirements and spoilage.

5-year horizon:

Precision farming begins to change industry economics

Precision farming systems exploit information and communications technology to evaluate the key aspects of the farming environment and crop characteristics. With these in place, farmers use automated systems to maximise yields.

10-year horizon:

New techniques are deployed in the urbanising world

Advances in agricultural sciences allow use of intensive, efficient vertical farming methods to grow staple crops in urban environments, with up to 30 per cent of the food required for an urban population being produced in the urban environment. The resulting minimal food miles significantly reduce spoilage, transportation and packaging.

25-year horizon:

Soils become a critical issue

Despite warnings from agronomists across the globe, a significant proportion of Earth's soils are critically degraded: far more than the 2021 figures of 33 per cent — when 50 per cent less food was required. Soil degradation may yet be reversed through the widespread embracing of the principles and practices of agroecology — sustainable farming that works in closer harmony with nature.[14]

3.3.4 Personalised nutrition

An individual's genetic code affects how their body reacts to and metabolises specific food types. By aligning their nutritional intake in accordance with their genetics, for example, a person may reduce their risk of certain diseases, such as coronary heart disease.[15] At the moment, such strategies are only rarely based on genetic information. In fact, "personalised nutrition" is an umbrella term for multiple approaches, including nutritional genomics, precision nutrition and many more. Nonetheless, it remains true that nutritional advice, products and services tailored to an individual can be more effective in promoting health, longevity and work (and, in particular, sporting) performance than generic, one-size-fits-all approaches to nutrition.[16]

In addition to genome-based information, biochemical analyses such as blood or stool tests carried out by specialists and healthcare providers can offer high specificity of an individual's nutritional profile, their gut microbiome and the resulting optimal nutrition. However, mainstream approaches to personalised nutrition will hinge on the increasing availability and sophistication of smartphone-linked self-monitoring technologies.

5-year horizon:

AI provides insights into diet-related health

Nutrition for Precision Health, a $156 million, 5-year study by the US National Institutes of Health, concludes, providing powerful new insights into links between diet, genes and behaviour. The research also delivers AI algorithms to predict individual responses to foods and dietary patterns, and better understanding and management of diet-responsive noncommunicable diseases such as obesity and diabetes.

10-year horizon:

Wearable technology assists food choices

Wearable and non-invasive electrochemical sensors, able to track the physiological changes that occur when the wearer consumes food or supplements, become mainstream.[17] Links between these real-time data sources and cloud computing brings personalised nutrition into wider reach in the smartphone era. Prevention of noncommunicable diseases through control of food and nutrition accounts for extensive savings in healthcare spending in developed and developing countries.

25-year horizon:

The era of high-fidelity precision nutrition begins

People living in economically prosperous nations begin to use AI-enabled, high-fidelity precision nutrition, where implanted, wireless sensors inform consumers in real time what happens to their physiology when they eat particular foods, enabling a shift to more intelligent consumption decisions.

3.4 Space Resources

The ability to study Earth from space has changed our understanding of the planet and the way humans are altering it. This will become increasingly important in the years ahead as we attempt to limit global warming and better understand and simulate the weather. At the same time, remote sensing and signals satellites will continue to provide an indispensable strategic resource for navigation, for trade and for military operations.[1] Innovation will play a key role in the next generation of these satellites, with private companies leapfrogging and complementing the ability of state-run constellations.[2] As low-Earth orbits become more crowded, orbital management and the removal of debris will become a major ongoing focus of attention.[3]

Many nations and entrepreneurs are eyeing space as a commercially exploitable resource: there is no shortage of solar energy to harvest; space tourism is an emerging business; the Moon has resources of helium-3, a potential fusion fuel, and water, which can also be converted into fuel; passing asteroids are potentially lucrative sources of minerals and rare metals and Mars has some of the building blocks necessary to support a human presence, such as water ice.

Important questions remain over the legal rights we have to exploit areas beyond Earth, how we should govern our behaviour in space and to what extent we should preserve what we find for the future. These questions are already being tackled in countries like the United States, which in 2015 became the first country to entitle property rights for resources extracted beyond Earth[4], and Luxembourg, which is creating a legal framework for space mining so that businesses can be confident of their rights to the resources they extract.[5] In 2020, the European Space Agency established the European Space Resources Innovation Centre in Luxembourg, as a centre of excellence related to the exploitation of space-based resources.[6]

Adriana Marais

Director at the Foundation for Space Development Africa, Founder of Proudly Human

Anticipation Potential

EMERGING TOPIC:

Space Resources

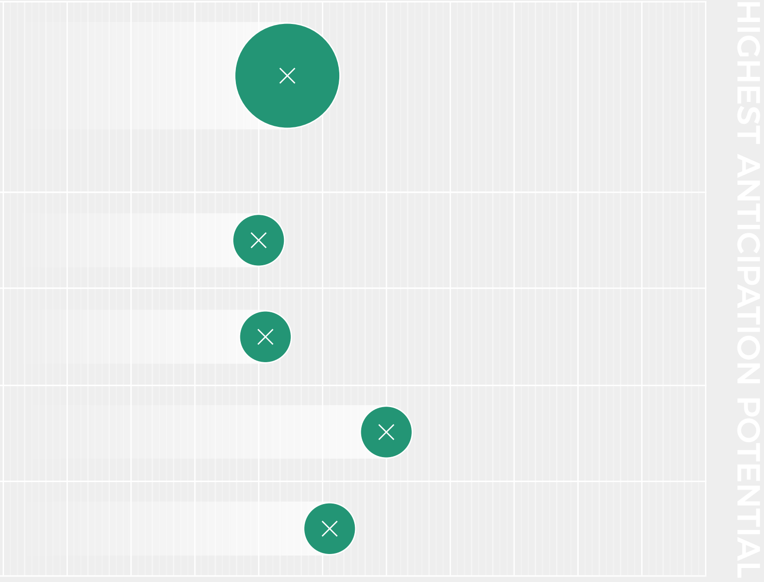
SUB-FIELDS:

Earth orbit

The Moon

Asteroid belt

Mars



SURVEY OBSERVATIONS:

Space represents a new frontier for humanity, with almost limitless resources if we can learn how to exploit them. But the consensus among respondents was that it is likely to be two decades before we see significant breakthroughs beyond Earth orbit and the Moon. This is down to the cost and complexity of spaceflight and the legal and geopolitical concerns raised by the use of space resources, issues that all increase the need for anticipatory planning. Another notable trend is the variability in awareness, with investigations into asteroid belts largely neglected, pushing up its anticipatory need.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In March 2023, a visionary piece originating from a broad international collaboration, titled 'Toward sustainable space exploration: a roadmap for harnessing the power of microorganisms', broke new ground. The article unfolds a strategy to employ microbial biotechnologies for a sustainable approach to space exploration, promising applications both in space and in support of the UN's Sustainable Development Goals on Earth. 'A sample return renaissance', published in April, explores the rationale behind renewed enthusiasm around extraterrestrial sample collection Chronicling both past achievements and recent successes like Hayabusa2 and Chang'e-5, the article offers a glimpse into the anticipated influx of space samples in the upcoming decade. In August, India cemented its space prowess with a landing on the lunar south pole, reported in Nature's news section as 'India lands on the Moon! Scientists celebrate as Chandrayaan-3 touches down'.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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3.4.1 Earth orbit

Since the launch of the first artificial satellite by the Soviet Union in 1957, there are now over 7,000 individual satellites in orbit around Earth[13]. Decreasing launch costs have enabled a variety of industries to benefit from satellite technologies to drive innovation and efficiency in their products and services. Satellite data improves prediction of and recovery from hazards and disasters around the world, as well as providing important insights into ecosystems, the effects of climate change and more, enabling smarter and more sustainable policy choices.

In 2020, almost 1,300 satellites were launched, the most ever in a year. By the end of April in 2021, 66 per cent of 2020's total had already been launched.[14] Satellites have functional lifetimes of around 5-15 years; thereafter they are debris. Existing space treaties do not address space debris explicitly; there is neither a legal obligation to remove the debris, nor to bear the cost for its removal.[15]

Beyond the commercial satellite industry, another Earth orbit resource is energy from the Sun. While both China and Japan have explored the possibility of harvesting solar power in low-Earth orbit and beaming it back to Earth as a microwave or laser beam[16], there's little indication that the lossy and risky business of space-based solar power will ever be cost-effective compared with energy generation on Earth.

Last but not least, the era of commercialisation of Earth orbit by space tourism has arrived. SpaceX became the first private company to take people into orbit, and now routinely delivers astronauts to the International Space Station. Blue Origin and Virgin Galactic are on the verge of operating commercial space enterprises focused on tourism. For these and other operators, reducing the cost of access to space is still a main goal. Safety is critical too. Nevertheless, people who have visited space are set to become increasingly common.[17]

5-year horizon:

Big data flows

A new generation of remote sensing satellites provide autonomous, real-time monitoring of Earth's polar regions in unprecedented detail leading to significantly improved climate models. Big data from remote sensing Copernicus Sentinel satellites begin to offer a fine-grained understanding of how our oceans, winds and biosphere are changing.[18] Private communications constellations provide broadband capability across the world, allowing more widespread and capable observation across the planet. The growth of space tourism accelerates the formation of international forums in which clear legal frameworks for this activity are discussed.

10-year horizon:

Space debris

Vast numbers of satellites launched in the 2020s are now defunct, while new fleets are launched continuously. Communication, navigation, surveillance, research and exploration, and indeed the entire global digital economy, is threatened by increasing prevalence of collisions in Earth orbit. Efforts are made towards a collaborative and international approach to space, however self-interest and short-term, profit-driven decision making abounds. The need for international agreement on standards for managing orbital behaviour is urgent.

25-year horizon:

Commercial versus environmental

Massive data streams from orbiting constellations provide real-time tracking of weather, traffic and emissions along with continuous observations of the amount of energy the Earth absorbs from the Sun versus how much it radiates. China begins building zero carbon, solar energy-harvesting stations in low-Earth orbit.[19] A progressive increase of orbiting object numbers occurs, with collisions becoming the primary debris source[20], accelerating the Kessler effect,[21] a theoretical scenario in which the density of space debris in low-Earth orbit can cause collision cascades, rendering space activities and the use of satellites in specific orbits near impossible for generations to come.

3.4.2 The Moon

Human presence in space is currently limited to low-Earth orbit, but plans are afoot to send crews back to the Moon, perhaps as soon as within the next 5 years. China has agreed with Russia to investigate building a research station in lunar orbit or on the surface of the Moon. NASA had planned to put the first woman and the next man on the Moon in 2024, however a 2021 report from the Office of the NASA Inspector-General indicated potential delays.[22] 2025 is now the new earliest date. Currently, the use of lunar resources towards a human presence on the Moon is a key driver for many resource extraction proposals.

The Moon contains resources like volatiles, minerals and rare metals that could potentially benefit Earth. A specific example is helium-3, a clean nuclear fusion fuel thought to occur in far greater abundance on the Moon than on Earth. However, for the time being, the feasibility of nuclear fusion power generation remains uncertain.[23]

There is evidence of water ice in the permanently shadowed craters on the Moon's surface. Water supports life, in liquid form as well as owing to its oxygen content, and can also be turned into rocket fuel, in the form of hydrogen and oxygen gas. In the past couple of years, launch costs have been reduced by more than an order of magnitude. SpaceX's Falcon 9 payload cost is less than $3,000 per kilogram.[24] The value of extracting water on the Moon will be determined in relation to such costs.

Private companies are also developing capabilities to take people to the Moon. NASA awarded a 2.9 billion contract to SpaceX for the human landing system for the Artemis program planned for 2024,[25] not without objection from competitor Blue Origin. This raises important questions about how potential private visits to the lunar surface should be governed, whether they should be subject to any kinds of restrictions, and how these could be enforced.

5-year horizon:

Humans return the Moon

NASA may achieve its stated goal of landing the first woman and the first person of colour on the Moon.[26] These become iconic and inspirational role models for the diverse future of space travel. Increasing numbers of public and private organisations announce plans for crewed and uncrewed missions to the Moon. Private crewed Moon flyby missions accelerate the formation of international forums in which clear legal frameworks for lunar tourism are discussed. The Chinese Chang'e-7 south pole lander finds water ice, a significant potential resource for the lunar base it plans with Russia.

10-year horizon:

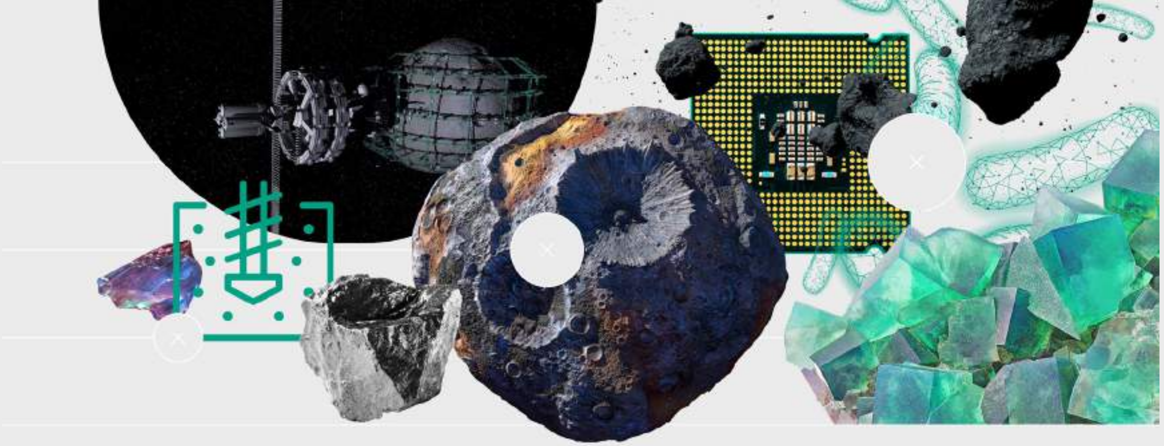
The Moon economy

By 2030, the increase in Earth's population to 8.6 billion and increasing rates of urbanisation will have implications for the demand for resources.[27] Environmental, social and governance factors,[28] along with depletion in terms of diminishing economic returns,[29] results in shortages in metal and mineral supplies, disrupting technology supply chains on Earth. There is a surge in private companies heading to the Moon to extract resources for terrestrial use.

25-year horizon:

Reconsidering Moon mining

Multiple landings and launches from the lunar surface over the years create clouds of rocket exhaust and lunar dust that only slowly disperse,[30] raising the possibility of irreversible alteration of the Moon's environment and tighter restrictions for lunar missions.[31,32]



3.4.3 Asteroid belt

While asteroid resources including minerals, metals and water will be useful for off-world activities, there is also a case for their utilisation on Earth.

Up until less than a century ago, society utilised just a few materials widely, including wood, brick, iron, copper, gold, silver, and a few plastics.[33] Today, a modern computer chip employs more than 60 different elements.[34] Some asteroids are thought to contain significant deposits of rare metals and minerals, and are therefore a potential target for mining. In fact, the presence of metals on the Earth's surface where we can extract them is thought to be the result of asteroid impacts in the first place.[35]

A study from 2012 estimated that moving a 7-meter diameter near-Earth asteroid into low-Earth orbit would cost about $2.6 billion and take 6-10 years.[36] A rare-earth-metal mine has almost comparable set-up costs of around $1 billion.[37] This study, however, was not extended to potential profitability of such retrieval. We know from meteorites that some asteroids are richer in platinum than any mine on Earth.[38] However, the large and long-term investments required for the demonstration of asteroid resource extraction have forced space mining companies to adjust their short-term ambitions, for now. [39,40] Nonetheless, the interest in this area raises the need to tackle important questions about how these resources ought to be governed under international law.

The characterisation of asteroids is interesting for other important reasons. One is mitigating potentially devastating hazards: an asteroid impact is the most widely accepted theory for the mass extinction at the end of the Mesozoic Era.[41] Another is enhancing scientific knowledge: asteroids contain unique information from the origins of the Solar System. And as our understanding of organisms able to survive extreme environments, so-called extremophiles, grows, so does the momentum of the theory that life may have emerged on Earth as the result of the arrival of a microbe-containing meteorite that impacted the surface.[42]

5-year horizon:

Solar System sampling missions arrive home

Successful sample-return missions from the asteroid 101955 Bennu (NASA's OSIRIS-Rex), from the Moon (China's Chang'e 6) and from the Martian moon Phobos (Japan's MMX) spark more ambitious studies of asteroids as potential sources of precious metals and in-orbit supplies.

10-year horizon:

Asteroid prospectors get to work

With continued reduction in costs of launch, as well as shortages in metal and mineral supplies that could emerge as early as ten years' time,[43] there's an increase in the number of organisations involved in local characterisation of asteroids, either by flyby or contact.[44 45]

25-year horizon:

Planetary protection becomes important

The Planetary Protection Policy[46] reflects both the unknown nature of the space environment and the desire of the scientific community to preserve the pristine nature of celestial bodies for future investigations. Mass species extinction on Earth and irreversible disruption of the Moon environment are both attributed to rampant commercialisation. The Policy is extended to restrict commercial resource extraction on planets and moons. Asteroid resources are utilisable within Policy guidelines. The abundance of metals, minerals and water in the asteroid belt means that the creation of technologies and communities anywhere in the Solar System is possible.

3.4.4 Mars

Since the first successful flyby in 1965, the space agencies that have successfully made it to Mars are: NASA, the former Soviet Union space program, the European Space Agency, the Indian Space Research Organisation, and most recently, the United Arab Emirates Space Agency and the China National Space Administration.[47]

A human presence on neighbouring planet Mars is an entry-level requirement to becoming a spacefaring society.

Two decades of human habitation of the International Space Station have led to impressive developments in the basic technological requirements for life beyond Earth: pressurised habitats; solar technology; water filtration systems; LED lighting to grow food; as well as communications systems. Thanks to detailed knowledge of conditions on the surface of Mars from over a half-century of remote exploration, we have far more detailed knowledge of what to expect there than early explorers had setting out to cross oceans, or even the Apollo astronauts when landing on the Moon.

In 2017, the United Arab Emirates announced a 100-year plan to build a city on Mars by 2117.[48] The UAE's first mission to Mars, the Hope orbital probe, is currently in orbit around the planet. SpaceX is on a slightly tighter schedule with founder Elon Musk's aim of a city of one million on Mars by 2050.[49] For that purpose, SpaceX is developing the Starship, a fully reusable transportation system designed to carry both crew and cargo to and from Earth orbit, the Moon, Mars and beyond.

SpaceX founder and CEO Elon Musk said that he's "highly confident" SpaceX will launch people toward the Red Planet in 2026,[50] with the Starship ready to for its first uncrewed mission to Mars in 2024.[51]

The US has been talking about sending crews to Mars for decades,[52] now aiming for sometime in the 2030s,[52] while China has announced plans to put humans on Mars by 2034.[53]

5-year horizon:

Mars begins to feel closer

More organisations send technology missions to Mars, which feels ever closer with all the high definition footage of the surface that we are able to interact with online, and increasingly also in virtual reality.

10-year horizon:

Mars mission plans raise ethical concerns

SpaceX sends the first crews to Mars on the Starship. Base infrastructure construction begins. National and private missions to Mars with ambitious timelines race to overcome significant technical challenges, such as protecting the crew from radiation during the journey. While SpaceX's Starship is a reusable vehicle for return trips, some organisations plan one-way missions to reduce cost and complexity, triggering widespread debate about the ethics of space exploration. Chinese and NASA/ESA missions separately collect samples from Mars and return them to Earth.

25-year horizon:

Human presence on Mars

Human population exceeds $9.5 billion and the destabilisation of Earth's life-support system continues. The pursuit of continued economic growth results in further disruption of habitats, eradication of species and pollution of water, soil and air. Plans are made to expand a range of permanent bases (including those of China, the US and also private infrastructure)
for more people to live and work on the surface of Mars. Unless major shifts in our current trajectory are made, humans heading to Mars on the 25 year horizon may be less motivated by exploration than by desperation, as with many intercontinental migrations on Earth in the past millennium.

3.5 Ocean Stewardship

The ocean is central to the existence of life on Earth. However, human activity is putting increasing strain on the ocean, directly through activities such as overfishing and pollution, and indirectly through the emission of greenhouse gases and associated anthropogenic climate change.

While the intensity and scale of ocean uses has reached unprecedented levels and traditional ocean industries have been joined by emerging and new sectors,[1] the tools and resources available to us to scientifically explore this dynamic environment are also unprecedented. Ongoing science, monitoring technology and innovations in bio-prospecting mean that we are gathering unprecedented amounts of ocean data that can be put to a wide variety of uses, from supporting conservation policy to developing exciting new biotechnology applications ranging from the development of pharmaceuticals to the creation of novel bioremediants and enzymes.

Yet despite tremendous technological advances and achievements, the ocean science and innovation landscape is highly uneven. Few countries have the capacity to observe how ocean temperatures, currents, oxygenation, sea life, and ocean plastic vary across depths and over time. At a global level, large gaps exist in understanding around these issues, and technological and resource allocation limitations are substantial hurdles. Likewise, the connection between people and the ocean — whether in small communities or megacities — is rapidly changing in many places, and is a key component of understanding changing perceptions of ocean stewardship. What is known about changes in ocean conditions and humanity's relationship with the ocean underscores an urgent need for new paradigms of ocean stewardship alongside efforts to achieve a truly equitable and sustainable "blue economy" for the future.[2,3]

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Researcher, Stockholm Resilience Centre

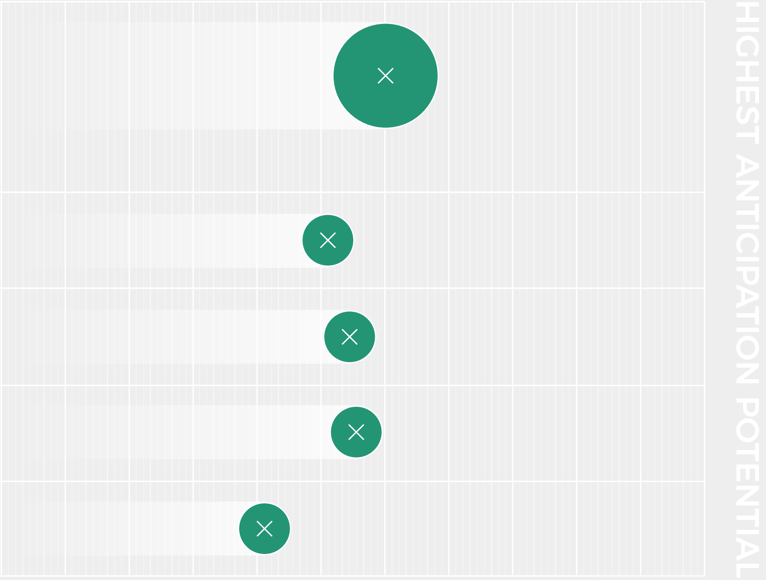
Anticipation Potential

EMERGING TOPIC:

Ocean Stewardship

SUB-FIELDS:

- Harnessing ocean biodiversity
- Transition ecosystems
- Repairing the ocean
- Improved ocean observation



SURVEY OBSERVATIONS:

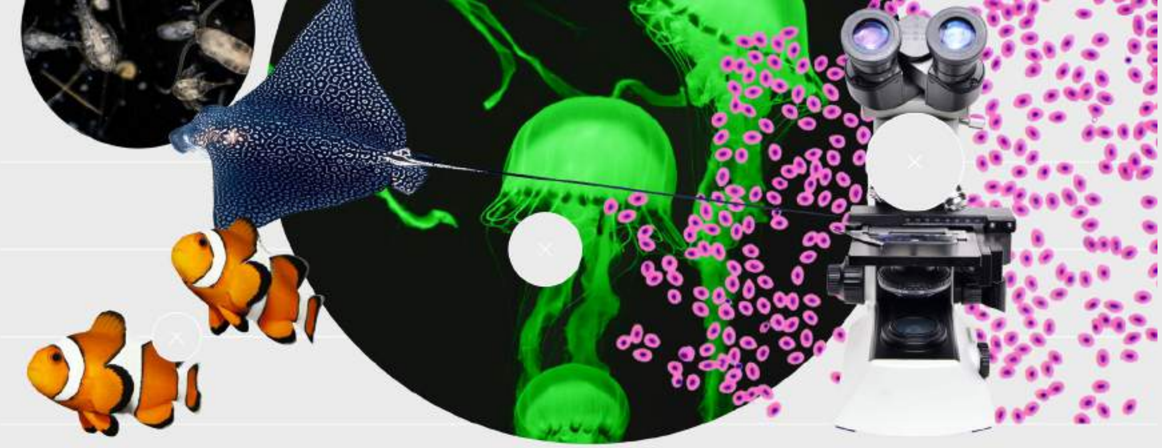
The oceans cover more than 70 per cent of the Earth's surface and are central to the existence of life on Earth. While efforts are well underway to improve ocean observation, with impact expected in the next decade, we are almost two decades away from technology that could help repair the ocean. While awareness of the need to repair our oceans is already high, the need for multidisciplinary research efforts, the relative infancy of the field and the potential impact of technologies means this topic warrants significant attention in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In October 2022, Spanish and Italian researchers published 'Business for ocean sustainability: Early responses of ocean governance in the private sector'. The paper drew attention to the need for private sectors to match their oceanic impact awareness with actionable solutions, pushing for a sustainable blue economy transformation. In February 2023, an enlightening paper from a collaboration of Italian, French and US researchers titled 'Ocean Circulation from Space' showcased the transformative potential of nadir radar altimeter missions. This research, which maps out dynamic ocean topography and currents from space, stresses the upcoming era of global wide-swath altimetry and emphasises the urgency for exploration in uncharted coastal and high-latitude regions. In July, a trailblazing work from the United States detailed the promising applications of synthetic biology in 'Harnessing synthetic biology to enhance ocean health'. The article proposes innovative strategies for combatting challenges like plastic pollution, coral bleaching, and harmful algal blooms, underscoring its potential for oceanic preservation.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r3-5



3.5.1 Harnessing ocean biodiversity

Marine biodiversity is an enormous and largely untapped trove of biological riches. This is particularly true with respect to drug discovery for the pharmaceutical industry; natural products from marine organisms enjoy remarkable success rates in drug development compared with those developed from terrestrial sources.[8] In a world embracing biotech, the ocean has also become a prime prospecting ground for novel enzymes for industrial processes, biomaterials, chemical compounds and much more.[9,10] One "poster child" of marine bioprospecting is green fluorescent protein — a source of jellyfish bioluminescence. Its discovery resulted in a Nobel Prize, and has found a wide range of biomedical applications and even been used to identify levels of environmental toxicity. Novel antibiotics are also being sought amid the ocean's biodiversity, as are naturally occurring polymers, which can detoxify pollutants including heavy metals.

In terms of marine genetic information alone, our data banks are growing exponentially as we explore the "ocean genome". The challenge is increasingly to decide the best way to integrate, share and utilise the data gathered from marine genetic resources (MGR).

5-year horizon:

Genetic resources continue to show their worth

Increasing use of open-source tools and open-access data maximises the inclusivity, transparency and value of MGR research. Platforms such as the Ocean Biodiversity Information System (OBIS) — the global open-access platform for science, conservation and sustainable development around marine biodiversity — offer a template for future progress.

10-year horizon:

Ocean-derived commercial products flourish

Medical, industrial and other products derived from MGR become ubiquitous. Machine learning systems speed up MGR-related discoveries across multiple fields, including pharmaceuticals, synthetic biology and biotech more broadly.

25-year horizon:

Deep-sea observatories gather ocean data

Developments in automation allow data gathering and sample processing to occur in situ, at autonomous deep-sea observatories, allowing scientific exploration of the ocean genome in regions in which physical sample return is not practical.

3.5.2 Transition ecosystems

One of the world's key transition ecosystems is the interface between the cryosphere and the hydrosphere, where glaciers melt into the streams they feed. What happens downstream of the cryosphere is a bellwether for climate change because these zones are extremely sensitive to warming.

These transition environments boast a rich biodiversity, including cold-adapted microbes, algae, fungi and archaea, making them fertile ground for bioprospecting. They also provide vast amounts of nutrients, such as phosphate, which enters the planet's mountain river systems in the form of "glacial flour": fine-grained rock ground from bedrock. Life on earth depends on phosphorus, and as glaciers disappear, less and less phosphate enters glacier-fed waterways, with potentially huge impact on life downstream.

We know too little about these ecosystems, yet they are steadily disappearing before our eyes. The rate at which the world's glaciers are thinning doubled in the first 20 years of this century.[11] Over the next 25 years, some regions of the Earth — including central Europe — are already expected to lose more than half of their current glacial mass.[12] Due to climate inertia, these changes are largely locked in. We have a closing window in which to redouble our bioprospecting efforts, before many of these transition ecosystems melt away forever and valuable knowledge about those micro-organisms vanishes.

5-year horizon:

Storage and study of cold-adapted organisms begins

Scientists around the world collect samples of the cold-adapted biodiversity that exists in these frontier ecosystems. The beginnings of an international repository to store and preserve such microorganisms, fashioned after Svalbard Global Seed Vault, is initiated, with genetic sequences of these microorganisms shared to an open-access database. Cold-adapted enzymes, discovered from bioprospected organisms in glacial zones, generate significant and low-waste bio-activity at low temperatures. These exquisitely tuned biological catalysts are now in widespread use, making industrial, medical and many other processes more efficient and environmentally friendlier.[13]

10-year horizon:

Transition ecosystems inform Earth modelling

The integration of biodiversity models of these transition ecosystem into larger-scale Earth-system simulations to produce predictions of the effects of glacier loss.

25-year horizon:

Glacial bioprospecting pays off

Metagenomic analysis of the world's glacial transition ecosystems results in a comprehensive public repository of genetic information about these rapidly disappearing environments.

3.5.3 Repairing the ocean

With ocean ecosystems under increasing strain, a two-fold strategy of ensuring precautionary approaches and sustainable management and a simultaneous significant expansion of marine protected areas (MPAs) will be essential. The science associated with MPAs speaks most clearly to the seafood industry, identifying many instances in which MPAs have resulted in the restoration of fish populations as well as increased yields (spillover) beyond the boundaries of the MPA. One recent study noted that a 5 per cent increase in the MPA network could improve future catch by 20 per cent or more.[14] With less than 3 per cent of the ocean classified as "fully or highly" protected today, an increase to 30 per cent will require substantial additional research and collaboration to understand both these spillover effects as well as management and equity implications associated with the displacement of fishers or fishing effort when MPAs are designated.

Tremendous carbon mitigation benefits are associated with the dietary shifts to replace terrestrial animal protein with more ocean-based protein — the High Level Panel for a Sustainable Ocean Economy, for instance, concluded that this could result in reductions of up to 1.24 gigatons of CO_2 equivalent by 2050.[15] Advances in the use of integrated multi-trophic aquaculture and seaweed production can reduce the environmental load of intensive single-species aquaculture, and result in substantial co-benefits. So far results have shown that aquaculture can not only provide sustainable food and employment, but also restore and enhance the ocean ecosystems they exploit.[16]

Corals must be another focus. The combination of warming oceans and CO_2-fuelled acidification of the waters has meant half of the world's reefs have already been lost.[17] Although this is a hugely troubling statistic, scientists are engaged in a wide range of conservation efforts worldwide, with some grounds for optimism.[18]

5-year horizon:

Data-gathering improves understanding

Increasing democratisation of the access to technology will increase global participation in data gathering, to help us answer questions such as how ocean ecosystems respond to human disturbance. Machine learning tools will start to improve the monitoring of some of the ocean's most vulnerable ecosystems such as blue carbon ecosystems (coral reefs, seagrass beds and salt marshes), aiding in the development and implementation of improved management plans.[19]

10-year horizon:

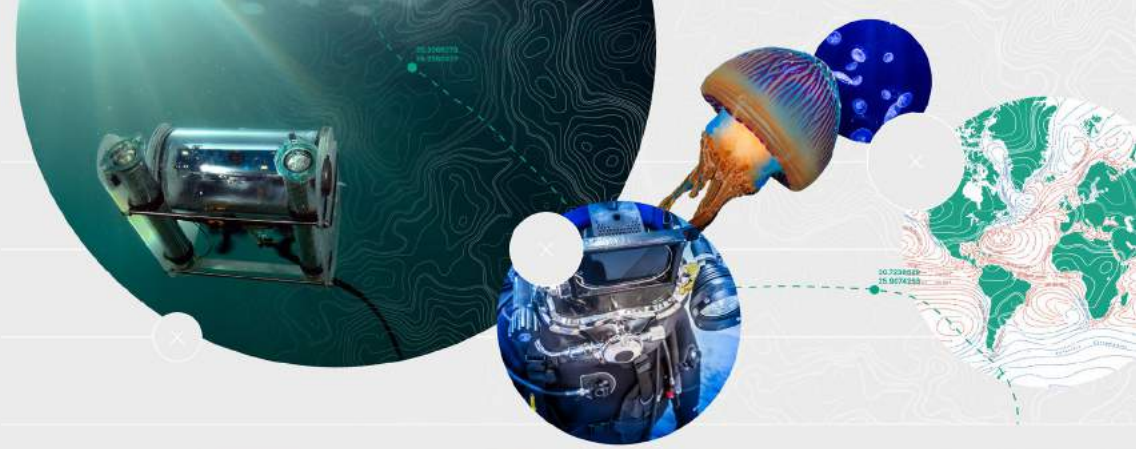
Large-scale coral interventions begin

Improved monitoring, use of genomic technologies and other innovations result in a step-change in scientific understanding of ocean habitats and basins and their connectivity, which helps to explain the relationship between human activity and what happens in our deepest waters, informing policy-making. Iconic ecosystems of disproportionate importance for ocean health, like coral reefs and seagrass beds, are conserved and restored based on the successful implementation of tailored interventions developed in fully inclusive and participatory processes. These will rely on multidisciplinary collaboration and use of automation tools to deliver on the required scales.[20]

25-year horizon:

Carbon pricing evolves to protect oceans

Traditional carbon-emissions pricing and "blue carbon" pricing, which puts a monetary value on coastal ecosystems such as tidal marshes and seagrass meadows that lock up large amounts of carbon, evolves into an all-encompassing "nature pricing" approach encompassing ocean stewardship.



3.5.4 Improved ocean observation

Observing how ocean temperatures, currents, oxygenation, sea life, and ocean plastic are changing through the water column over time and around the world is necessary, but impossible with current technology and resource allocation. This is a glaring omission, given the ocean's enormous biodiversity, importance for regulating the climate and of course providing sustenance.

The deep ocean, for example, is by far the largest habitat on the planet, in both area and volume, yet it is also the least observed. This is a significant problem: the scale and dynamism of the oceans means we have relatively little data available with which to model its complexities and thus predict its future state. While the GEBCO Seabed 2030 Project is mapping the planet's entire sea floor,[21] the difficulty in collecting and mapping other types of fundamental data means the ocean remains largely unknown.

In addition, climate change is driving changes in the ocean environment that are moving faster than scientific research can track. The importance of the ocean ecosystem to all other life on Earth means that it will be essential to redouble our efforts to understand and predict ocean activity in the coming decades. Also vital is the development of a more systemic view of the web of interrelationships between humans, marine biodiversity, climate change and ocean tipping points.

5-year horizon:

Widespread monitoring becomes possible

The increasing availability of inexpensive sensors and related technology for use in the ocean will make widespread ocean monitoring more viable.

10-year horizon:

Robots begin to gather ocean data

Deployment of autonomous research craft and robots closes the gap between the rapid changes occurring in the ocean and our limited gathering of fundamental marine data, becoming a key driver in the development of deep-sea science and modelling.[22,23]

25-year horizon:

Global hydrosphere models inform policymaking

Advanced machine learning models, combined with huge amounts of incoming data, allow the entire planet's hydrosphere to be dynamically modelled rather than its various aspects being dealt with in research silos. This enables enlightened policymaking through accurate predictions of future ocean scenarios.

3.6 Solar Radiation Modification

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]

SRM approaches operate on a range of spatial scales. Some options for manipulating the reflectivity (albedo) of the Earth's surface are primarily local: while this means they are inherently limited in their effectiveness, it also means there are fewer potential complications in their implementation. At the other end of the spectrum, planetary scale options like stratospheric aerosol injection would affect the entire planet, with complex environmental, social and geopolitical consequences.[2]

SRM also encompasses a range of technological complexity. Some options involve nothing more complicated than painting roofs white. Others entail constructing fleets of high-altitude aircraft or even space-based mirrors. These latter methods have the most potential to offset the entire global climate warming, but involve resolving fundamental scientific questions, developing and implementing new technologies and addressing key governance challenges. The optimal solution may be one that uses SRM deployment alongside other climate responses such as emissions reduction and carbon dioxide removal.[3] Overall, there is growing scientific consensus that this approach would work in a technical sense, with some limitations.[4,5]

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, but the political aspects of its implementation and subsequent governance remain highly problematic and poorly understood. There is thus a pressing need to develop international governance frameworks for deciding whether or not to conduct SRM field experiments; if so how — and to prepare for making decisions whether or not to deploy at some point in the future. Governance frameworks for potential future deployment need to be designed for the long. term, because SRM deployment would need to be sustained and monitored for decades — and possibly a century or more.

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Anticipation Potential

EMERGING TOPIC:

Solar Radiation Modification

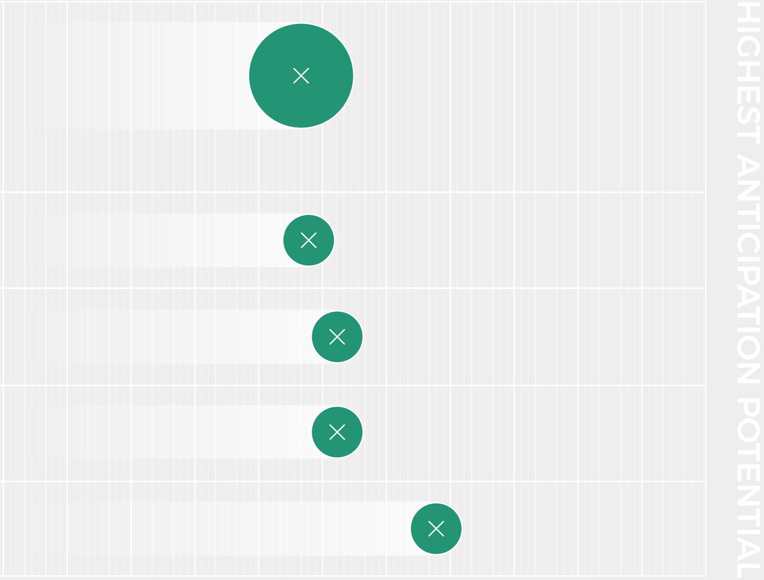
SUB-FIELDS:

Stratospheric aerosol injection

Cloud engineering

Terrestrial solar radiation modification

Space-based solar radiation modification



SURVEY OBSERVATIONS:

Solar radiation modification (SRM) could fully or partially offset the temperature rise caused by greenhouse gas emissions, reducing some of the harmful impacts of climate change. The high anticipation scores are reflective of the relative immaturity of the science and technology required to modify or deflect the sun's rays, low awareness of the field and disruptive potential if development is successful. Some experts question whether the social and political ramifications of being able to deploy such technologies should preclude further investigation.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In July 2023, an avant-garde proposition from István Szapudi, working at the university of Hawai'i, was presented in 'Solar radiation management with a tethered sun shield'. Using a tethered sun shield positioned at a specific gravitational point, this article proposes a more efficient and cost-effective method for Solar Radiation Management, leveraging lunar dust or asteroids for most of its weight, revolutionising space-based climate interventions. In August, another innovative concept emerged from a collaboration between German, UK and US researchers in the publication titled 'Marine Cloud Brightening: an airborne concept'. This paper sheds light on the promising method of employing drones to deliver industrially-produced salt nanoparticles, potentially revolutionising marine cloud brightening. The newfound efficiency, however, brings with it pressing governance dilemmas related to regional climate interventions. Also in August, researchers from the University of Bern provide a sobering perspective in 'Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise'. While the potentials of Solar Radiation Modification are acknowledged, the research underscores the indispensable need for traditional emissions reduction to truly address the looming threat to the West Antarctic Ice Sheet.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r3-6

3.6.1 Stratospheric aerosol injection

The most prominent and most studied approach to SRM is stratospheric aerosol injection (SAI). This entails injecting chemicals into the lower stratosphere to reflect back some incoming sunlight, reducing the amount of solar radiation that the Earth absorbs.

Sulphate aerosols are the most commonly proposed substance: these would essentially mimic the effect of a large volcanic eruption, which can inject such aerosols into the stratosphere. The 1991 eruption of Mount Pinatubo led to a detectable global mean surface cooling of up to 0.5 °C, which lasted over a year.[10] 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.[11] 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.[12]

The overwhelming majority of studies of the effectiveness and consequences of SAI have been carried out through computer modelling. A small number of field tests have been proposed, but these have been called off after facing opposition.[13] Because SAI is a global intervention by design, any significant real-world test of efficacy would be indistinguishable from actual implementation — not least because the effects would probably take years to become detectable in global temperature data due to internal variability.

Implementing SAI would entail the development of a new class of aircraft able to carry heavy aerosol loads to altitudes of approximately 20 kilometres. It has been estimated that it would take over $2 billion to bring such craft into use.[14] Overall, it has been estimated that a global programme of SAI would cost $18 billion per year for every °C of warming offset.[15] This is well within the reach of a coalition of governments, or even billionaire enthusiasts.

5-year horizon:

SAI conversations begin

We may have gained a renewed sense of climate urgency after the report of the Global Overshoot Commission, COP28's Global Stocktake, UNEA 6 and UN General Assembly considerations, and a special report on SRM of the IPCC. These allow 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, 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 to adapt to climate change. Governance frameworks that had been 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 SAI 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 make marine clouds reflect more solar radiation back into space, cooling the surrounding region. This would be achieved by spraying droplets of seawater into the sky, with sea salt crystals providing additional seed nuclei for water droplets to condense.[16] This condensation into more droplets makes the clouds whiter and more reflective. A range of spray technologies have been considered.[17]

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.[18] 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.[19]

Whereas SAI has a global 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.[20] A field test of this has been conducted over the Great Barrier Reef, though there is no publication of the results from these experiments.[21] The sea spray used may also produce a cooling effect in regions with little or no cloud, by forming reflective aerosol particles.[22]

5-year horizon:

MCB experiments are promising

The Australian MCB experiments yield encouraging results, and result in the launch of 10-year programme to apply MCB to contribute to the protection of the Great Barrier Reef.

10-year horizon:

Small-scale MCB begins

We have the first prototypes of automated ships that can spray seawater for MCB. The first official small-scale use of marine cloud brightening 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 planet lighter — increasing its "albedo" — can have cooling effects.[23]

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.[24]

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.[25]

At the more extreme end of the scale, there are proposals to artificially re-grow 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.[26]

5-year horizon:

Urgency spurs international research

Following the COP28 Global Stock Take, 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:

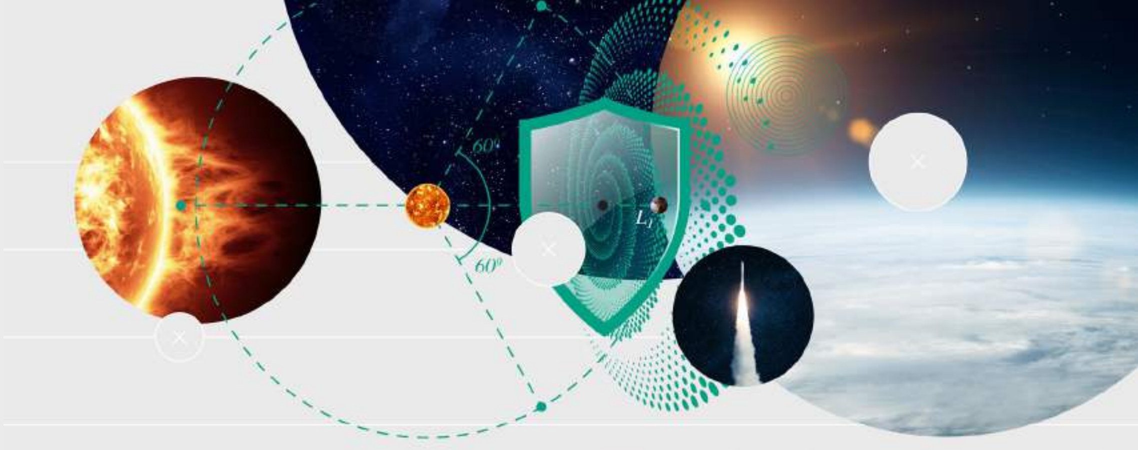
Building codes embrace albedo brightening

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. The disc would need to be fitted with steerable rocket thrusters to maintain its position: it could also be manoeuvred into different orientations, giving a measure of control.[27]

Researchers have also considered a number of alternative reflectors for reducing the radiation incident on Earth.[28] These include Fresnel lenses, diffraction gratings and mirrors.[29] In theory, all of them could produce sufficient cooling to offset the warming effect of our greenhouse gas emissions.[30] The key considerations are the robustness of the design to meteoroids and other threats, and the mass of the structure — all of 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.[31] 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 spaceflight 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 spaceflight 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

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 wellbeing.

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.

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. The complementary banners of One Health and Planetary Health offer frameworks to understand disease in this way.

Wanda Markotter
Director of the Centre for Viral Zoonoses
University of Pretoria

Anticipation Potential

EMERGING TOPIC:

Infectious Diseases

SUB-FIELDS:

Pathogen biology

Zoonotic disease

Vector control

Outbreak prevention

SURVEY OBSERVATIONS:

Infectious diseases remain a major threat to human health, with climate change causing diseases to emerge or affect new populations. While detection and monitoring technologies have been expanding in recent years, the disruptive potential of these technologies boosts its anticipation score. In comparison, our understanding of pathogen biology and the ability to control diseases spread by a vector organism — like malaria or dengue — are less well established. Awareness of vector control research is also relatively low, suggesting it should be an area of particular focus in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In January 2023, Canadian researchers published a critical examination entitled 'Respiratory infectious disease outbreaks among people experiencing homelessness: a systematic review of prevention and mitigation strategies'. Highlighting the exacerbated risk faced by the homeless population during respiratory outbreaks, including COVID-19, this review offers invaluable strategies to guide future public health responses.

In May, Spanish researchers highlighted the intricate relationship between humans, animals, and their shared environment in an article on the 'Epidemiology of Wildlife Infectious Diseases'. Emphasising the One Health approach, this work underlines the rising rate of zoonotic diseases and the crucial need for cross-disciplinary efforts to preserve both human health and biodiversity. 'Leveraging artificial intelligence in the fight against infectious diseases', published by US researchers in July, showcases the transformative potential of AI in modern healthcare. By fusing AI with synthetic and systems biology, the article presents groundbreaking solutions for drug discovery, diagnostics, and in-depth insights into infection biology, setting the stage for enhanced responses to pandemics and infectious outbreaks.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r3-7

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.[11] 2021 saw one of the biggest successes of recent years, with the approval of the first successful malaria vaccine RTS,S/AS01 or Mosquirix.[12] There are also approved vaccines for the Ebola virus,[13] and several Zika virus vaccines are undergoing clinical testing.[14] If these vaccines can be successfully rolled out to vulnerable populations, the burden of these diseases will be substantially reduced.[15]

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.[16]

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 disease

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. While researchers have devised 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.

5-year horizon:

One Health comes closer

Data demonstrates the benefit of treating human and animal 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 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 mosquitos or tsetse flies can make it impossible for them to host the parasites responsible for disease development in humans.[17]

Similarly, genetically modified *Aedes aegypti* mosquitoes have been released in Florida, carrying a gene that kills females in the larval stage.[18] 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.[19] Previously, trials have used mosquitoes infected with Wolbachia bacteria, which have successfully reduced the transmission of dengue.[20]

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.[21] At present these are monitored separately, often by distinct agencies.[22]

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.[23] 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, and it will be important to develop cheap, effective and easy-to-use rapid testing tools. This will be particularly relevant in communities where human and animals are in regular close contact.

Our preventative strategies will be most effective if we approach human health in more social-ecological terms. One framework for this type of approach is One Health, which aims for cross-disciplinary work integrating human health, animal health and environmental health.[24] There is also a framework called Planetary Health, formally launched by the Rockefeller Foundation and The Lancet in 2015.[25] This draws on the concept of "planetary boundaries" that should confine human activity. Both are useful, and there is a clear complementarity, with the overarching concept 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.[26] 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.[27] In addition, better ventilation and air filtration systems can reduce the spread of airborne viruses like SARS-CoV-2[28] and reduce the harm from air pollution into the bargain.[29]

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:

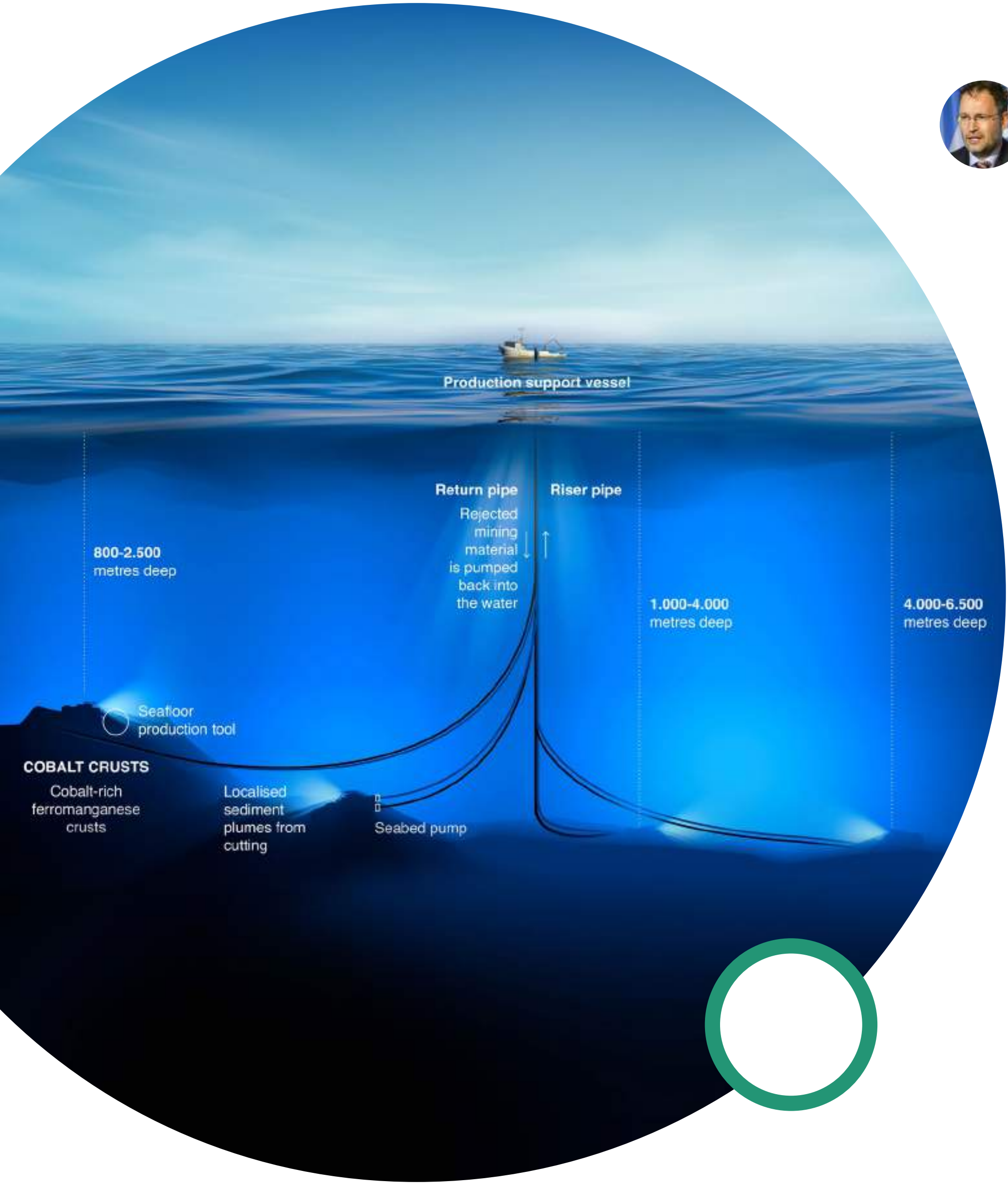
Public health systems strengthened

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

We establish an integrated global pandemic early warning system 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.



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Invited Contribution: Deep-Sea Mining

The global transition to green energy depends on the continuing supply of particular metals and minerals. With many of the readily accessible sources of these commodities already being fully utilised, there has been a dramatic increase in interest in the harvesting and extraction of such minerals from the deep seabed, through submarine mining on an industrial scale.

This would represent an extraordinary investment of technical and commercial resources, mandated by the urgency of climate change. However, the deep seabed is one of the most poorly understood of all the earth's environments. Thus, there is also a significant risk that such mining may severely harm a part of the environment that has so far escaped harm from humanity — and that harm could last for thousands of years. We are therefore confronted with a unique tension between two environmental goods.

Deep-sea mining has been the subject of multi-national debate since the 1960s, when it was thought that it might provide a solution to the perceived problem of diminishing terrestrial resources. Low and Middle Income Countries (LMICs) feared that this activity would be led by wealthy industrialised nations which more easily develop the technological capacity to conduct these activities, "making the rich richer and the poor poorer" in the words of Arvid Pardo, then Malta's ambassador to the UN. This debate, in which Pardo played a key role, resulted in a fundamentally permissive legal regime for deep-sea mining, included in the United Nations Convention on the Law of the Sea – also referred to as the "constitution for the ocean".

This was one of the first attempts to create a truly fair and just regime for a global common, namely the mineral resources of the deep seabed and the seabed as such, deep-sea mining, based on benefit- and technology-sharing. However, terrestrial resources turned not to be running out after all, so the issue lay dormant for several decades. Now, however, it is back at the centre of the international agenda. Demand for raw materials such as lithium, cobalt and other resources required for wind turbines, solar panels and other renewable energy infrastructure essential for the green energy transition, is rising fast. Three classes of deep-sea deposits – polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts – have attracted particular commercial interest due to their enrichment in metals such as nickel, cobalt, copper, titanium and the rare earth elements needed for lithium-ion batteries. However, many anticipate that mining for these deposits poses such large environmental risks as to throw into question whether it should be allowed at all.

Crucially, we do not have a robust factual basis for the environmental risks of deep seabed mining. After all, many renewable energy technologies have environmental impacts. For example, the erection of offshore wind turbines damages the habitats of otherwise highly protected species such as harbour porpoises and seals. Terrestrial mining for key metals and minerals can itself cause serious environmental degradation and social injustices. We accept these downsides because we believe the benefits are greater. However, scientists predict that the effects of deep seabed mining activities today will have repercussions for thousands of years in the future — possibly even longer, since polymetallic nodules take 1 million years to form, putting associated ecosystems at significant risk of extinction.[1] Identifying an acceptable level of environmental risk, or indeed whether there is any acceptable level, is the single biggest challenge of this debate.

To meet this challenge, we need more research into the environmental effects of deep seabed mining. There are three broad areas that require investigation. First, we need to understand the effects of mining on the relationship between deep seabed fauna and the polymetallic nodules on which they rely. These species have extremely long lifecycles, and don't easily recover from disturbance. Second, we need to investigate the effect of the changing column of water on the organisms that live on or just beneath the sea floor, and understand their role within the overall climate system. Third, we need to understand how effectively the areas surrounding mining sites can be protected, and how much damage might be done by (for example) the plumes arising from the mining. Is it possible to localise the effect of mining activities, or not?

A few years ago, it seemed that deep-sea mining was an inevitability. However, an increasing number of state and corporate actors have more recently declared their opposition. In 2020/21, French President Macron publicly argued in favour of a complete moratorium on deep seabed mining. Other countries, including Germany, Australia and New Zealand, have called for a "precautionary pause" to allow time for further research on the environmental impacts of mining on deep seabed ecosystems to take place. Some companies have also publicly said they will not (yet) use commodities sourced from the ocean, notably including the auto manufacturers Renault, Volvo, BMW and Volkswagen.

So far, the states that advocate for a precautionary pause and a moratorium seem to be a minority – albeit a growing minority, heavily influenced by NGOs and supported by an increasing number of businesses. It may be that in time a consensus develops that deep-sea mining activity should be significantly constrained or even banned. But as things stand, the International Seabed Authority is called upon to finalise its regulations for deep-sea mining exploitation due to a “two-years-rule” activated by Nauru in 2021. If the exploitation regulations are not agreed upon this summer, the International Seabed Authority must make a decision on the application of Nauru – and potentially also of other States – based on preliminary materials and the terms of the law as it stands. What exactly this standard implies is a matter of considerable legal uncertainty.

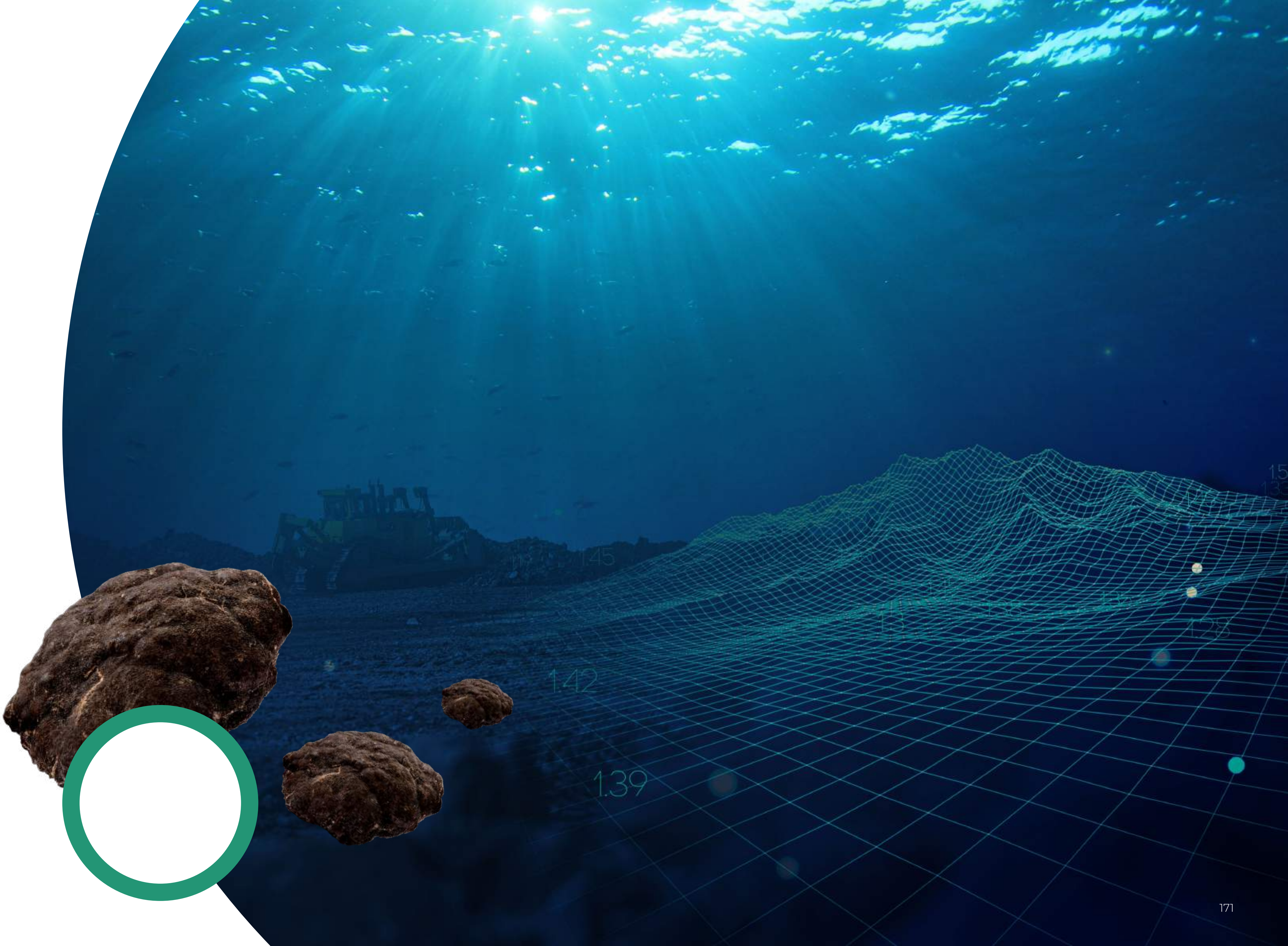
This deadline was activated in July 2021 by the Republic of Nauru, and expired in July 2023. Intense discussions led the council of the International Seabed Authority to adopt a decision on a timeline following the expiration of the two-year period, with a commitment to full discussion of marine environmental protection in 2024 and a view to adopting the exploitation regulations in 2025. This outcome was hailed by opponents of deep-sea mining, who welcome it as an opportunity to put an end to the proposals once and for all – but it remains unclear what will happen if further applications are made.

Separately, international negotiations completed in March 2023 also resulted in the formal adoption – on 19 June 2023 – of an agreement on sustainable use and conservation of biodiversity in areas beyond national jurisdiction. This so-called BBNJ agreement, sometimes called the “High Seas Treaty”, will also be of potential relevance to deep seabed mining as it establishes a minimum standard for conducting environmental impact assessments. It cannot be excluded that this standard will, again, impact the discussions about the environmental standards to be included in the final version of the exploitation regulations of the International Seabed Authority.

It is conceivable that Nauru, or any other state, could choose to go it alone. Once the precedent has been set, others might join it. However, the likelihood of this scenario is arguably minimal, due to widespread acceptance of the framework established by the UN Convention – even by states that have not become party to it, such as the USA. This is a rare example of consensus within international politics; for the moment the debate continues to be conducted within the relevant multilateral fora. The most relevant – and controversial – issue is the question of the specific environmental standards to be included in the ISA exploitation regulations. Furthermore, a debate has evolved around the question on how to prevent the coming into existence of “sponsoring States of convenience”, which may be attracted by revenues to accept to sponsor companies from industrialised States without sufficiently caring about the environmental and social standards applied by such companies.

Ultimately, there may not be a single yes or no answer when it comes to deep-sea mining, but rather a multi-level process leading to the formation of a rigid and precautionary legislative basis for such activities. We should accept that the marine environment must be protected, but we might at the same time be forced to accept that deep-sea mining of certain minerals, or in certain areas, may turn out to be unavoidable to fend off the worst of climate change. Thus, we should seek a balanced approach to deep-sea mining, with regulation based on as much well-informed science as possible. Ideally, we would use the years to come to conduct an intensive research programme before embarking on any deep-sea mining activities. We should also fully consider the potential for alternatives, such as greater utilisation of terrestrial mining.

In conclusion, we depend on a multifaceted strategy which reluctantly accepts that difficult decisions may need to be taken over deep-sea mining. A potential broader outcome is that – where unavoidable and complementary approaches are not possible – a balance between remediation of the climate and protection of the marine environment needs to be found. We need to inform these decision-making processes to the greatest extent possible by advocating for better scientific evidence, making decision on the basis of that evidence, and negotiating internationally in good faith.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Professor Department of Molecular Genetics, University of Toronto, Co-Director of the CIFAR Fungal Kingdom: Threats and Opportunities Program

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Invited Contribution: **Fungal Pandemics**

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 wellbeing.

Fungi are integral to health, agriculture, biodiversity, ecology, manufacturing and biomedicine. They are the 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 six million species of fungi, more than two hundred 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 World 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 agricultural fields, 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 five to ten 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 each year; 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.

A better 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/treatment plants; better control of fungal pathogens that affect trees would increase the biomass available for the absorption of carbon dioxide, 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.


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4

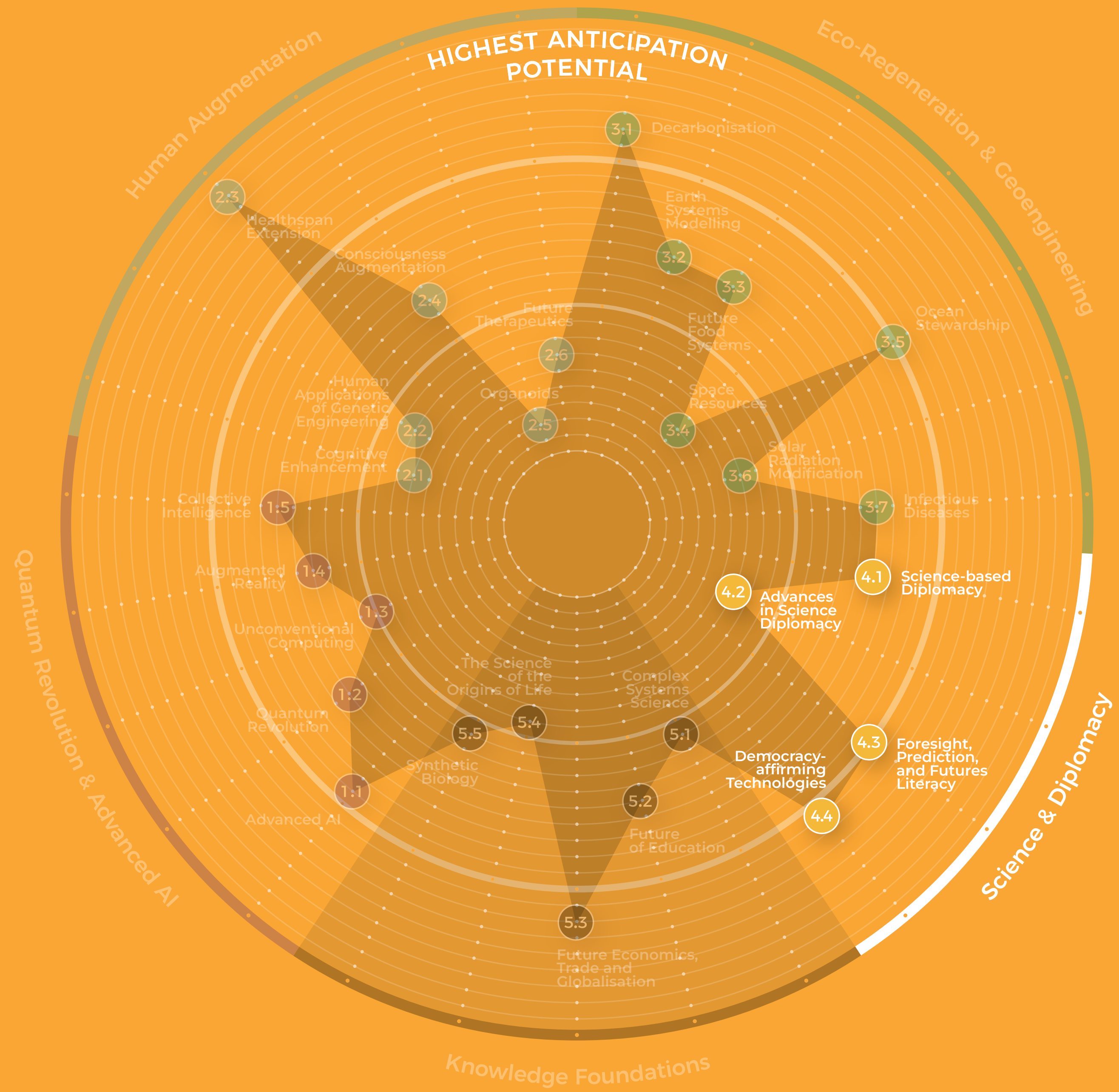
Introduction to Science & Diplomacy

It is now almost impossible to separate diplomacy from the influence of science and technology. Computational modelling, analysis and artificial intelligence are set to play important roles in international relations, especially when it comes to interactions between groups of people. Researchers are already compiling vast databases of historical interactions between actors in various international forums. Mining these databases produces an instant picture of an actor's past statements and positions and helps to find common ground in negotiations. These databases are the bedrock of science-based diplomacy, a strategy that is likely to become more powerful, more comprehensive and more widely used. Indeed, negotiation engineering aims to "depoliticise" these discussions by automating certain aspects of the process.

The products of science, such as vaccines and intelligent machines, are increasingly recognised drivers of global health and wealth creation. These advanced technologies are now becoming part of the currency of multilateralism. **Advances in science diplomacy** seek to create an evidence-based foundation for this endeavour, and the increasingly diverse set of actors who practice it. One issue is how to train, incorporate and empower these actors at state level and at non-state levels, from global companies, from grass roots organisations that exert pressure on legislation through unsanctioned use of technologies, and from non-governmental organisations. Issues of conflict and big science projects themselves are becoming increasingly part of this landscape, as are the goals of governments in emerging economies. Together these groups must find ways to progress their own ambitions, and collaborate across sectors, nations and groups of nations, while managing the global commons fairly and effectively.

Anticipation of future trends, events and scenarios is an essential part of the effort to create a better future for people, society and the planet. Prediction and foresight is a rapidly-growing field of research that aims not to make specific predictions, but to understand what futures are (and are not) possible, likely, desirable and — in some cases — avoidable. In specific scenarios, "superforecasters" have achieved some success, and understanding the cognitive skills being deployed in such achievements is an important area of research. Similarly, growing our appreciation of how the average human mind thinks about the future can help with developing "futures literacy" in the wider population, facilitating participation in scenario planning and other anticipatory activities. Though resource-intensive, and thus not accessible to all, modelling and simulation efforts are also helping research to map out a range of possible futures, and encourage conversations about how best to engage with the issues they raise.

Much has been written about the potential of technologies like social media and data analytics to spread disinformation and polarise societies, thus weakening democracy, but there is now a countervailing movement: an effort to create, nourish and grow **democracy-affirming technologies**. Further advances come from innovations in fact-checking websites and tools that have been designed to help people better assess the validity of information online; digital identity technologies, which are emerging as a critical tool for helping democracy transition into the digital age, and technological means to evade attempts at censorship.


HIGHEST ANTICIPATION POTENTIAL
Human Augmentation
Eco-Regeneration & Geoengineering
Science & Diplomacy
Knowledge Foundations
Quantum Revolution & Advanced AI
3.1 Decarbonisation
3.2 Earth Systems Modelling
3.3 Future Food Systems
3.4 Space Resources
3.5 Ocean Stewardship
3.6 Solar Radiation Modification
3.7 Infectious Diseases
2.1 Cognitive Enhancement
2.2 Human Applications of Genetic Engineering
2.3 Healthspan Extension
2.4 Consciousness Augmentation
2.5 Organoids
2.6 Future Therapeutics
1.1 Advanced AI
1.2 Quantum Revolution
1.3 Unconventional Computing
1.4 Augmented Reality
1.5 Collective Intelligence
4.1 Science-based Diplomacy
4.2 Advances in Science Diplomacy
4.3 Foresight, Prediction, and Futures Literacy
4.4 Democracy-affirming Technologies
5.1 Complex Systems Science
5.2 Future of Education
5.3 Future Economics, Trade and Globalisation
5.4 The Science of the Origins of Life
5.5 Synthetic Biology

4.1

Science-based Diplomacy

The "Scientification of Diplomacy" is based on computational social sciences, mathematics, optimisation theory or behavioural research and 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. As such, Computational Diplomacy is revealing not only the complexity of modern international relations but the potential knock-on effects of future actions. 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. In doing so, it particularly draws on the decomposition and the formalisation of the problem(s) at hand and the heuristic application of mathematical methods, such as game theory and mathematical optimisation. This way, it can de-emotionalise negotiation problems and allow for resolutions of more complex real-world issues.

Other fields of growing importance that are considered under "scientification of diplomacy" are predictive peacekeeping (see 4.2.3) and trust and cooperation modelling (see 4.2.4) which all combine advances in other disciplines with the practice of diplomacy. For the process of diplomacy, these new approaches, in particular Computational Diplomacy and Negotiation Engineering, raise the possibility that future negotiations will successfully bring together broader groups of stakeholders in more complex negotiations, while allowing progress with fewer missteps. The expected outcome is a contribution to greater chances of international stability.

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Michael Ambühl
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Anticipation Potential

EMERGING TOPIC:

Science-based Diplomacy

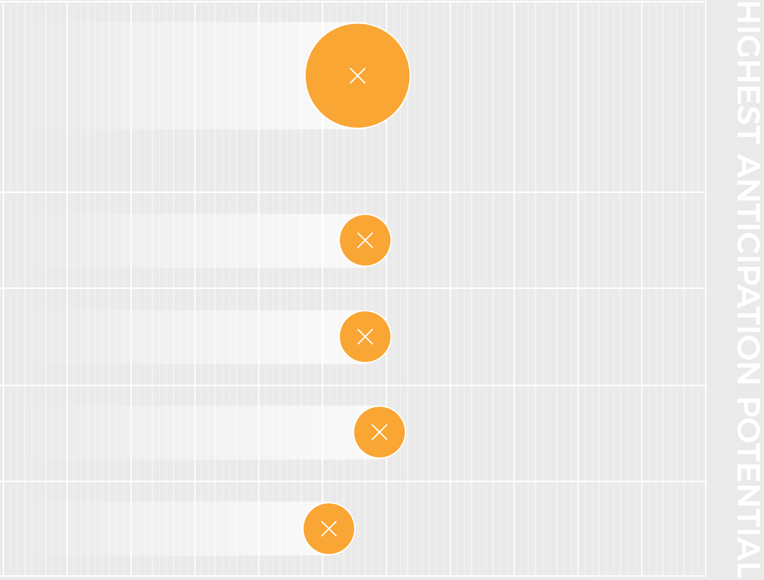
SUB-FIELDS:

Computational diplomacy

Negotiation engineering

Predictive peacekeeping

Trust and co-operation modelling



SURVEY OBSERVATIONS:

The idea of applying computational approaches to diplomacy is still relatively new. This is reflected in the uniformly low awareness found across the four key domains investigated. These approaches are not expected to become mainstream for another 10-20 years and all four were judged to require considerable interdisciplinary collaboration to achieve breakthroughs. While the low awareness may be due to the fact that computational diplomacy is currently only being discussed by a small community, as and when it goes mainstream the field could have profound impacts on international relations suggesting there is considerable need for anticipatory planning.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In July 2023, Florian Cafiero from Paris' Sciences Po presented a comprehensive dive into the burgeoning realm of digital international relations in 'Datafying diplomacy: How to enable the computational analysis and support of international negotiations'. Spotlighting the promise of "computational diplomacy," the article pinpoints a crucial challenge: ensuring the dependability and availability of data tailored to diplomatic needs. Shyama V. Ramani and Maximilian Bruder published 'How ChatGPT might be able to help the world's poorest and the organisations that work with them' in August. Venturing deep into the potential and limitations of ChatGPT in marginalised areas, the article sheds light on the delicate balance of AI's empowerment potential against the lurking threats of misinformation. In September, Thomas Chadefaux of Trinity College Dublin published 'An automated pattern recognition system for conflict', exploring the cutting-edge capabilities of pattern detection. The system, designed to provide real-time conflict escalation forecasts, heralds a new era for computational diplomacy by offering diplomats vital information on geopolitical risks.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r4-1

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 so on. Until now, this data has not been well used to inform the process of diplomacy, to amplify cooperation and to improve outcomes. With the emergence of computational diplomacy, and its use of big data, machine learning and computational thinking, this looks set to change.

There is much low-hanging fruit here. The networks of actors on the international stage are already beginning to be mapped[6], giving a deeper understanding of the connections that can influence negotiations. The text databases at some international organisations are also being mined using natural language processing to study the way language use evolves over time, to measure the consistency of statements and how this might be used to better understand future discussion.

There is still much more that can be done. Computational approaches will allow researchers to model the various aspects of real-world diplomacy and to simulate the outcomes of different approaches, for example. The hope is that this will lead to more fruitful outcomes from future diplomatic interactions.

Developing the expertise that can manage and exploit these processes is a significant challenge. Future actors in this area will need a good grounding in computer science as well as a fluency in the language and process of diplomacy, and building this capacity is a key short-term goal.

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.

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.

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.

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 facilitate the reaching of agreements.[7] In essence, Negotiation Engineering attempts to break down the negotiation problem (or problems) into smaller sub-problems. Once reduced to their most formal structure, the sub-problems can then be translated and restated into mathematical language. That allows for the tools of mathematics to help further analyse the sub-problems based on objective and measurable criteria and ultimately seek solutions to real-world problems. 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 P5+1 group of nations.[8]

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 very limited application. For instance, not all problems are quantifiable or should be reduced to a quantitative level — interpersonal conflicts, for example. However, in case 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 help de-emotionalise underlying negotiation problems and allow for more logical accuracy and the finding of pragmatic solutions. To that end, significant capacity-building is required for future development.

5-year horizon:

Capacity-building accelerates Negotiation Engineering

The success of online courses in Negotiation Engineering during Covid stimulates the evolution of this discipline, significantly building capacity in this field.

10-year horizon:

Mathematical thinking focuses international discussions

An increasingly wide variety of international actors apply 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 peacekeeping

Predictive peacekeeping uses technologies related to machine learning, big data and computational modelling to better understand conflict, to predict where it is likely to occur and to help develop mitigation, preventative and rebuilding strategies.[9] For example, by studying the patterns of social, cultural and economic data in the run up to past conflicts, artificial intelligence applications may be able to predict the likelihood of conflict arising from current and future scenarios.[10]

The field has been bolstered by a number of successes. For example, the number of news articles about conflict in the Middle East have been shown to be predictive of imminent conflict. And increases in food prices above a threshold level are correlated with civil unrest in many parts of the world.[11]

However, the complexities of human conflict have a strong dependence on the behaviour of unpredictable actors. Natural disasters, such as drought, famine, earthquakes and so on, also play a crucial but inherently unpredictable role. These factors place important limits on the spatial and temporal accuracy of predictive peacekeeping.

Nevertheless, there are growing efforts to improve the quality of data that informs these models to exploit this data more effectively and to forecast a wide range of possible futures from one-off events, be they military coups or civil wars.[12] Models like this will help to keep the world safer and help policymakers explore potential outcomes before acting.

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.

10-year horizon:

Mass-data gathering creates peacekeeping tools but raises 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.

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 co-operation modelling

Computer scientists have begun to create systems in which autonomous agents have to find ways to co-operate by distinguishing good agents from untrustworthy ones. 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 co-operation studies are useful—in modelling the way people behave in the groups that make up societies.[13]

In any society, business or network, the ability to evaluate and then trust partners is a crucial component of co-operation. For that reason, trust has been described as "part of the glue that holds our society together."[14] 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 an important time. 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 and can have significant consequences in processes and negotiations where much is at stake.

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.

10-year horizon:

Stakeholders battle over reputation and trust

Reputation-building and trust 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. Managing trust and reputation are potential battle grounds for some actors.

25-year horizon:

AI oversees data veracity

Machine vision and artificial intelligence become important arbitrators of trust in data, news and images. However, an insidious cat-and-mouse game continues between malicious actors and those attempting to shut them down.

4.2 Advances in Science Diplomacy

The products of science are increasingly celebrated as drivers of global health, sustainable development and wealth creation. 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 co-operation 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.

The field of science diplomacy seeks to establish an evidence-informed foundation for this kind of endeavour. This foundation will support and empower the increasingly diverse set of stakeholders who practice science diplomacy — it is not just nations, but non-governmental actors, groups of citizens and indigenous communities, for instance — through the challenges ahead. Climate change, especially with the rapid opening of ice-free routes through the Arctic Ocean and the geopolitical tensions this is creating, is one of the many key proving grounds for this work.

"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 build capacities and evaluate this work, to create a continual cycle of learning and improvement in the practice of science diplomacy.

Pierre-Bruno Ruffini

Professor of Economics at the University of Le Havre

Anticipation Potential

EMERGING TOPIC:

Advances in Science Diplomacy

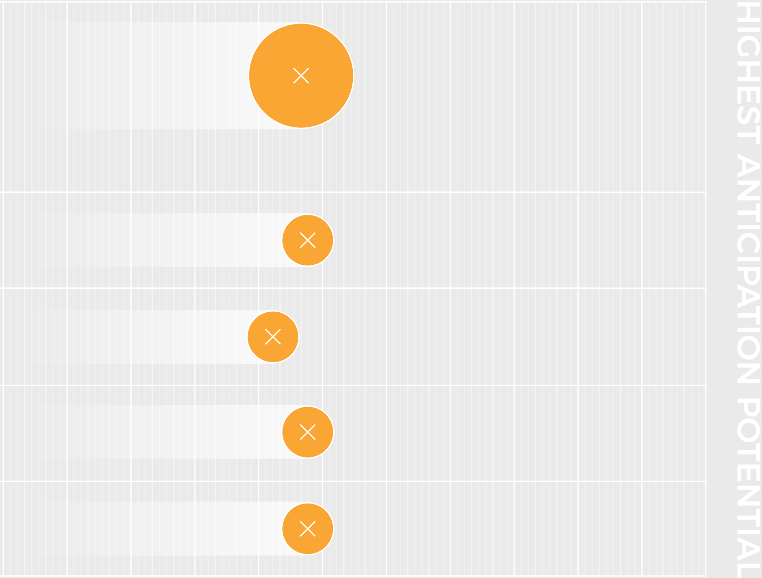
SUB-FIELDS:

Science diplomacy for effective multilateralism

Technology diplomacy and the role of non-state actors

Science diplomacy and emerging economies

Science diplomacy as a response to conflict- and inequality-driven tensions



SURVEY OBSERVATIONS:

The field of science diplomacy is becoming ever more established as a field of study. Technology diplomacy and the rising role of non-state actors in global governance has been judged as a relatively mature development with strong transformative potential. Other topics, such as the evolution of science diplomacy in times of conflicts or its integration into a more effective multilateralism, are more controversial and will receive increased attention over longer timespan. Both topics are expected to gain traction in the coming decade, with a time to maturity estimated at 12 years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In June 2023, researchers from Germany and Russia unveiled a fresh perspective on the interplay of science and international affairs in 'Science diplomacy from a nation-state's perspective: a general framing and its application to Global South countries'. Grounded in International Relations theories, the article spotlights how developing nations harness science diplomacy to address internal challenges while bolstering their global stature. US researchers published a provocative argument entitled 'Want to speed up scientific progress? First understand how science policy works' in August. Their article champions the transformative value of "use-inspired" science-policy research. By highlighting the potential of academia-policy collaborations and urging a paradigm shift in academic norms, this article resonates with the pressing need to enhance science's societal contributions.

In September, Ian Bremmer and Mustafa Suleyman published 'The AI Power Paradox', which delves into the profound and multifaceted ramifications of unchecked AI proliferation. Proposing a reimagined global governance model, the article offers an anticipatory framework to navigate the intricate nexus of emerging technologies and geopolitics, thereby enriching the ongoing discourse on AI's role in world affairs.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r4-2

4.2.1

Science diplomacy for effective multilateralism

A key goal for science diplomacy is to find ways to balance competition against strategic cooperation. Science diplomacy has traditionally established itself as a way to use science as a "soft power" that can advance diplomatic objectives through scientific collaborations that create goodwill between nations. 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 co-operation. 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, the reality of global politics and geo-economics means that there are increasingly areas of international and inter-group tension that involve science and technology. US restrictions on use of certain foreign resources for technology development, the importance of Taiwan's semiconductor industry to its independence and security, and the location of key science projects such as the Future Circular Collider, are all potential sources of conflict and competition. The same is true of the way some indigenous groups suffer disproportionately from the effects of climate change, seeking to use the relevant science as a lever to encourage action by majority population groups. Similarly, the uptake of certain scientific technologies, such as gene therapies and anti-ageing interventions, by small groups of adventurous self-experimenters, puts pressure on hesitant regulatory bodies.

All these issues create challenges for science diplomacy's efforts to establish useful channels for improving multilateralism, but can also be seen as opportunities for initiating dialogue.

5-year horizon:

National bodies call for action over resources held in common

As nations seek to shorten supply lines and strengthen trade links, new regional interest blocs emerge. This changes balances of geopolitical power and how international science projects are established, as science resource sharing and collaborations mirror economic patterns. 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 and prove rich territory for science diplomacy to prove its worth.

10-year horizon:

Lunar exploration brings science diplomacy challenges

The US, India, China, Europe, Japan, Israel and others launch missions that include exploration and exploitation of lunar resources. These missions increase the profile of the Moon in public debate and highlight the necessity and importance of science diplomacy to tackle the issues these activities raise. The importance of regional interest blocs increases, with numerous developing economies — especially in Africa and Latin America — playing significant roles in global science diplomacy. Non-governmental actors develop greater influence on national strategies and become a significant factor in science diplomacy. IPCC-like bodies emerge for a variety of scientific areas such as biodiversity, space exploration and infectious disease control.

25-year horizon:

Trained experts in science diplomacy begin to steer policy

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

Today, it is well-known and widely accepted that transnational companies, and industry associations have significant diplomatic influence on policy, pushing regulation (in the case of self-driving cars and deployment of orbital resources, for example) and creating tangible effects on policy. But the attempts at influence go both ways: 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.

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 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 information.

In some regions, where regulatory environments are weak, hobbyists, activists and grass roots organisations are pushing the boundaries of science with their work on anti-aging therapies and gene editing, some of which can influence regulatory policy-making, and sometimes accelerating 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.

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.

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. IPCC-like organisations with transnational responsibilities and influence are significant powers in the science diplomacy arena.

25-year horizon:

Private sector actors are integrated in governance

New ways of achieving governance and agreement on exploitation of deep-sea, orbital and mineral resources for manufacturing are pioneered by private sector actors. City and regional planners and policymakers 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. In recent years, CERN has extended this to embrace partnerships with the world's emerging economies, such as, Chile, India and Pakistan. 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 Light Source, 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.

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 skillsets and training will be needed to fully explore reciprocity in science. Another important dimension is the generational shift, where issues such as social justice are becoming increasingly important to actors in science diplomacy.

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. The emerging generation of science diplomats has increased focus on social justice and its consequences. 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

The scale of global challenges linked to technology and involving a wide range of actors from around the globe, beg require greater global focus and cooperation. Graduates from science diplomacy-focused training courses, skilled in the languages of science and diplomacy, 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:

Emerging economies invest in science diplomacy training

The slowly-growing influence of science diplomacy results in improved transparency and openness of international road maps, and scientists and science leaders who acknowledge their influence and obligations, and engage with science diplomacy efforts. Large-scale science projects that involve co-operation 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. According to the UN, conflict and violence are an increasing part of human experience. Regional tensions, climate change, economic disparities and scarce resources are just some of the factors involved. Despite the fact that many conflicts are between non-state actors, rather than between nation states, science diplomacy has a role to play in helping to resolve conflict.

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.

Historically, science diplomacy has helped to minimise the damage to scientific progress caused by conflict, helping relocate German scientists to Europe and America before and during the Second World War, for example. It is notable that the European Research Council is attempting to find scientific research work for Ukrainian scientists fleeing the current conflict. Some have argued that the same could be done for Russian scientists looking to relocate.

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 assists in re-establishing research in conflict-affected regions

Researchers dispersed by conflict are brought on board with projects at their temporary location, establishing international professional links that will help create future collaborations. The scientific diaspora will play a key role in these reconnections. Science diplomacy helps create projects and plans that contribute to peacekeeping efforts, inter-group negotiations and maintenance of stability.

10-year horizon:

Science facilities 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 role in science diplomacy.

25-year horizon:

Science diplomacy becomes a "hard tool" for international relations

Science diplomacy is a recognised path for avoiding conflict and establishing peaceful, collaborative and equitable futures. But scientists continue to feel pressure to align with their national government's policies and ideologies.

4.3 Foresight, Prediction and Futures Literacy

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. In other cases, however, there may be many distinct and plausible outcomes, and these may vary significantly. In these cases, we have to exercise *foresight* — a collective term for methods of gathering information relevant to these outcomes and exploring their ramifications. This activity can be carried out “top-down”, as in *strategic foresight*, or “bottom-up” as in *participatory futures*.

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Prof Emerita, Finland Futures Research Centre, University of Turku

Anticipation Potential

EMERGING TOPIC:

Foresight, Prediction and Futures Literacy

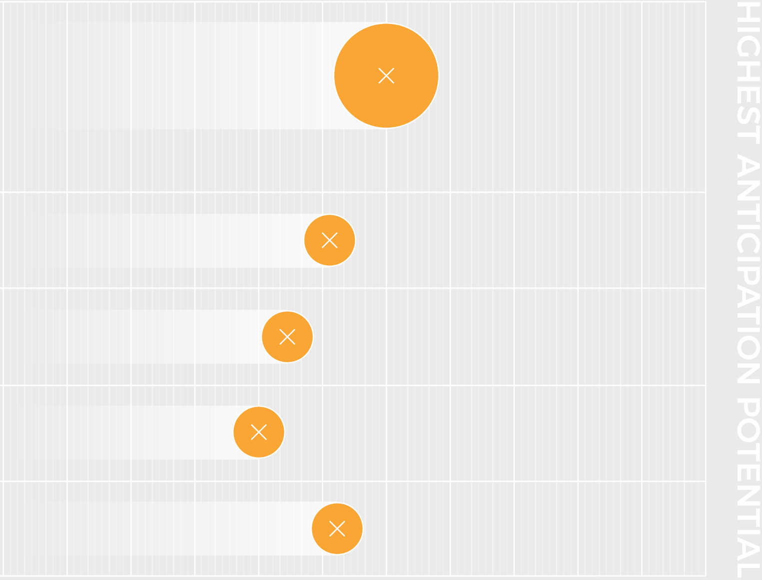
SUB-FIELDS:

Superforecasting and prediction markets

Modelling and simulation

Scenarios and foresight

Participatory futures and futures literacy



SURVEY OBSERVATIONS:

The field of prediction and foresight has a high anticipation potential, most notably because of its potential impact on the environment and our relation to the planet. The strong interdisciplinary nature of the field and the ground-breaking contribution of new AI techniques will transform the field in the future, raising the Anticipation Scores. Awareness of modelling, simulation, foresight and scenario-building techniques is however very high and less action is perceived as needed for those two topics. Survey respondents expect an average time to maturity of 11 years for the topics considered.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In February 2023, The Forecasting Collaborative published 'Insights into the accuracy of social scientists' forecasts of societal change', highlighting the impact of expertise on forecasting. The profound impact of AI in extracting insights from vast digital evidence was explored in an April discussion from Slovenja entitled 'AI, What Does the Future Hold for Us? Automating Strategic Foresight'. This article painted a future where strategic foresight could be delivered automatically through AI-powered knowledge graphs and machine learning. 'Forecasting Existential Risks Evidence from a Long-Run Forecasting Tournament', published in July, explored the findings of the Existential Risk Persuasion Tournament, revealing significant variances between historically accurate forecasters and domain experts on looming threats, most notably on AI-induced existential risks, posing pressing questions about the vast disparity in risk assessments.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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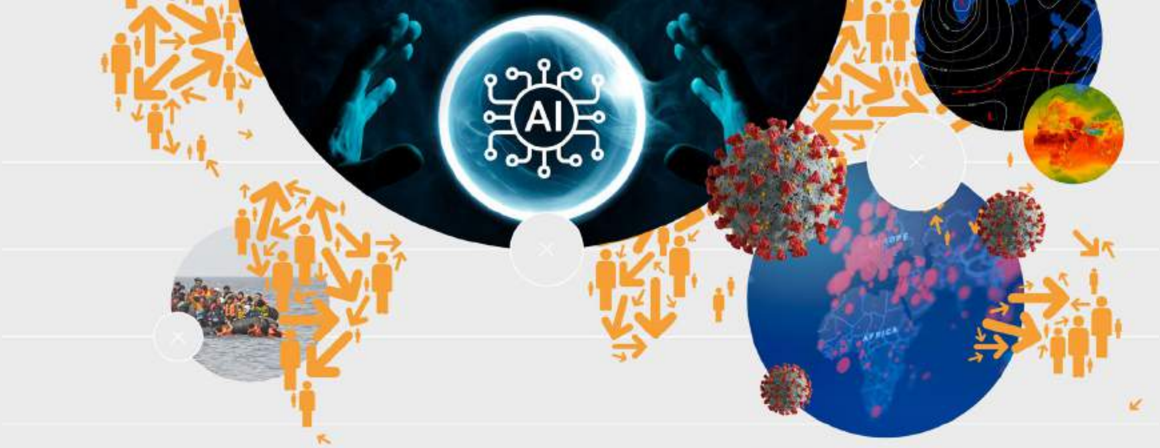


4.3.1 Superforecasting and prediction markets

Evidence has mounted in recent years that some individuals are capable of predicting geopolitical events with a success rate that significantly exceeds that of experts in a given field. These *superforecasters*' success is rooted in their psychology, including their skill at focusing on a few key determinants of an outcome and exceptional willingness to update their predictions as new information becomes available and arguments are made.[1]

Superforecasting appears to be an innate talent, but one that can be significantly improved through training and by organising the best performers into elite teams. The biggest gains appear to be from reduction in noise (filtering out erroneous or irrelevant information) with significant contributions from improved information-gathering and reduction in bias (incorrectly prioritised information).[2]

Research is ongoing into how effectively superforecasting can be taught,[3] how successfully it can be applied to domains other than geopolitics, and whether predictions can be further improved through integration 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.[4]

Prediction markets also harness the human ability to synthesise many types of information, but do so by aggregating the predictions made by many individuals (some of whom may be superforecasters).[5] Participants are offered financial or reputational incentives to make accurate predictions, and market mechanisms are used to establish consensus positions. On political events,[6] technological developments[7] and corporate strategy.[8,9]

The optimal design of such markets is an area of active investigation.[10] 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.[11]

5-year horizon:

Superforecasting training becomes routine

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:

Predictions are increasingly cited

Robust evidence emerges for the real-world accuracy forecasters and prediction markets, and their predictions are routinely cited by journalists and policymakers. 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:

AI assistes prediction markets

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,[12] in situ networks of ecosystem[13,14] and urban[15] sensors, and automated aggregation of economic and social data.[16] 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,[17] but as our data-gathering capabilities have expanded, we have now started to model ecosystems[18] and various dimensions of societies such as urban planning[19] and health[20] as well. Research is underway into the use of these models as decision-support tools for policy makers.[21]

Technology vendors have put forward the idea of integrated "digital twins" that spans 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,[22] and on immersive technologies that allow decision-makers to better evaluate the results of urban or environmental interventions.[23]

5-year horizon:

Modelling techniques become widely used

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, and low-cost, low-risk simulation of different solutions to development and environmental challenges.

10-year horizon:

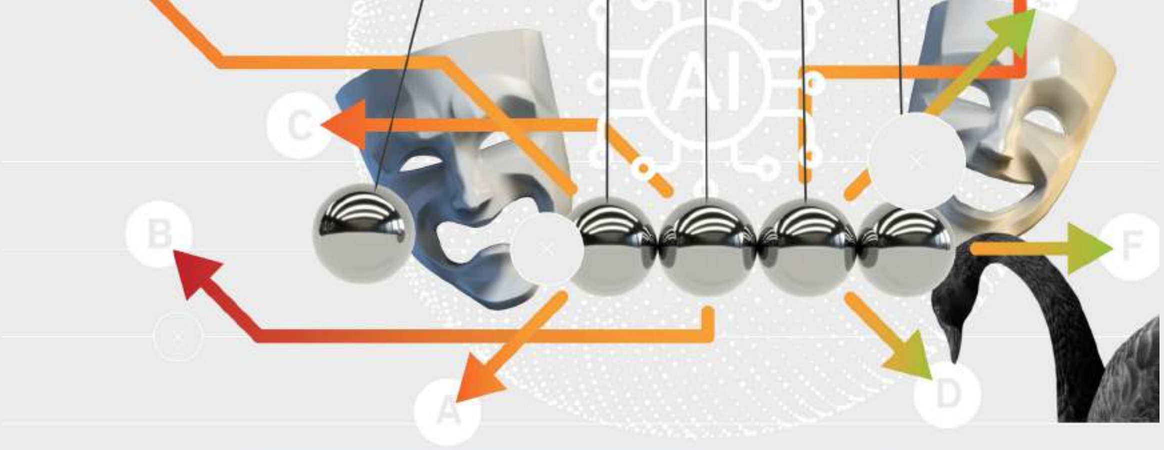
Computational power assists high-resolution modelling

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 regional become interconnected

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

There are many domains in which there may be multiple possible outcomes, presenting very different opportunities and risks. These cases have been addressed using a variety of predominantly qualitative approaches known collectively as *foresight* (or futures) methods, which typically focus on developing narratives and imagery rather than numerical predictions. The most widely used 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. The intention is to disrupt their conventional thinking, thus allowing planners to anticipate a range of possible outcomes, including novel and extreme possibilities. Ways of prompting this disruption continue to be developed, with potentially interesting new avenues being the use of synthetic data and machine learning to support the creation of unorthodox narratives.[24,25]

These techniques may help to address the current tendency of foresight work to identify positive or preferred futures. If we are to be truly open to what the future may hold, in order to better manage its challenges as well as exploit its opportunities, we must also consider "un-futures": uncertain futures, unlikely futures and undesirable futures. This includes concepts that have become widely known, such as "black swans" and "existential risks", but further work needs to be done to map and understand the space of "unfutures".[26]

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.[27] A second is an expansion of the application space, to address such issues as identity or the interests of transnational communities as well as more traditional strategic questions. There is also a need to better understand what constitutes successful scenario generation and how it can be integrated with decision-making.

5-year horizon:

Cognitive neuroscience and interaction design inform scenario creation

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:

Synthetic data assists governance foresight

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:

Mixed reality technology brings scenarios to life

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 practiced by states, multinational agencies and large companies, who naturally have an interest in these areas for strategic purposes.[28] However, these are not neutral activities. The outcomes envisaged and conclusions reached will depend on the sponsor of the work, who will deliberately or inadvertently tend towards those which suit their purposes.[29] These will not necessarily align with those considered most desirable or achievable by other stakeholders.

As a result, work has now begun towards encouraging communities to understand how to think about the future — futures literacy — and engage with participatory futures activity. 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,[30] and it has set up more than 100 "Labs" aimed at fostering it[31] Research continues to explore how the human mind envisages the future, and how this process might be duplicated or augmented with machine intelligence and immersive technologies.

Participatory futures take a variety of forms, but generally aim to tackle a more specific challenge, generally beginning with a briefing designed to expose participants to alternatives, often employing fictional or narrative elements to engage imaginations. Structured discussion follows to identify and expand on a set of preferred futures.[32] 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.[33]

Beyond these, we can start to work towards futures resilience, the capacity to survive emerging challenges, obstacles, risks and crises and come out from them relatively unharmed. This is a general capability and infrastructure, rather than the identification and specialist management of individual risks and includes the ability to learn from them in a way that leads to re-thinking existing structures, systems, and practices and regarding the needs for possibly changing them accordingly.[34]

5-year horizon:

Citizens gain futures literacy

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:

Participatory futures activities become 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:

Constitutions mandate participatory futures activity

The results of participatory futures activity becomes legally binding in certain jurisdictions, being written into constitutional procedures for decision-making.

4.4 Democracy-Affirming Technologies

The Democracy Index, as measured by the Economist Intelligence Unit, has recorded a snapshot of global democracy every year since 2006. Its latest report for 2021 suggests that 45.7 per cent of the world's population live in a democracy, a significant drop from 49.4 per cent the year before.[1] This is one, but by no means the only, indication that democracy is in decline.

One factor playing an increasingly important role in the processes of democracy is digital technology, which can enhance or diminish it, depending on how it is used. And that raises important questions about the impact and potential of today's technologies and those in the pipeline. Their influence operates at all scales.

At the individual scale is the issue of personal identity in a digital world: how it can be best captured, verified, protected and used. At the scale of communities and societies are digital technologies that can influence the nature of governance and even anticipate and manipulate it. These technologies have the potential to profoundly alter our relationship with democracy in unanticipated ways.

All this sits within a broader debate about the veracity of information, and how to identify and counter misinformation. The ways in which information can and should be moderated is a topic of significant debate, with much agreement that misinformation and hate speech cannot be allowed to spread largely unfettered, as they do today. But moderation must be carefully managed to permit secure, anonymous communication, particularly for whistle blowers and in authoritarian regimes where free speech is stifled.

The decline in global democracy has puzzled many political scientists who have tended to think of democratic change as an ever-increasing process. But recent research has begun to treat democracies as complex systems that are vulnerable to unexpected and unpredictable change.[2] Many researchers working in this field are keen to better understand the role that technologies will play in the operation of democratic societies, as well as the philosophies and frameworks necessary for them to be put to best use.

Eileen Donahoe
Executive Director of the Global Digital Policy Incubator (GDPI) Stanford University

Anticipation Potential

EMERGING TOPIC:

Democracy-Affirming Technologies

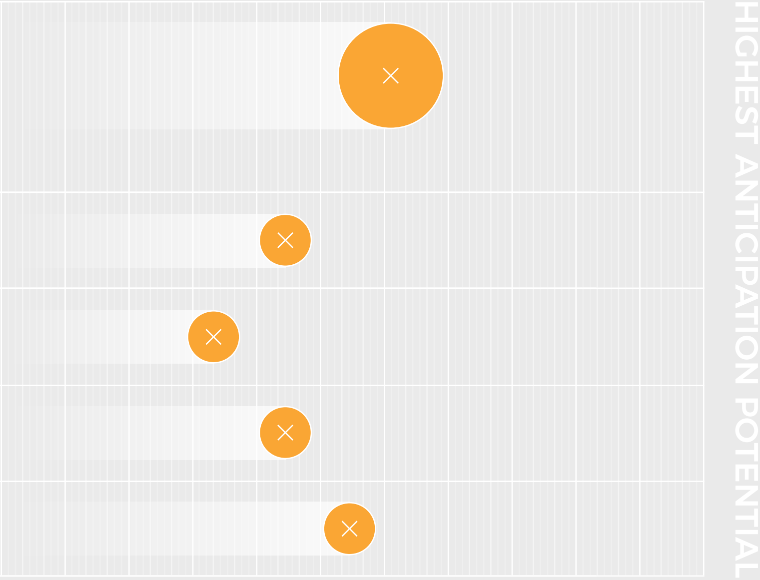
SUB-FIELDS:

Verification technologies

Digital identity and trust

Privatisation of governance

Censorship circumvention and content moderation



SURVEY OBSERVATIONS:

Digital technology can enhance or diminish the democratic process depending on how it is used. While the security of our online identity has high disruptive potential, it is an established area of development, lowering its anticipation score.
In contrast, verification technologies and approaches to moderate online content without censoring it are around 15 years from maturity according to our experts. These areas should be the focus in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In May 2023, Alexandra Giannopoulou, researcher at the University of Amsterdam, shared 'Digital Identity Infrastructures: a Critical Approach of Self-Sovereign Identity', which delves into the evolving landscape of digital identity, focusing on the promises and pitfalls of self-sovereign identity systems. While touted as a tool for empowerment, the study warns that its European-wide adoption may inadvertently perpetuate historical identity challenges and place individuals in a vulnerable position. In June, experts from the United States underscored the role of AI in public administration with their work 'Catching up with AI: Pushing toward a cohesive governance framework', emphasising the need for unified AI governance. In July, Chinese researchers introduced 'MDS coding enabled proxy-based Internet censorship circumvention system', revealing a groundbreaking technique for bypassing Internet restrictions through maximum distance separable coding.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r4-4

4.4.1 Verification technologies

The difference between information from trusted sources and malicious actors is becoming increasingly difficult to spot. This is due, in large part, to a range of technologies that can fashion realistic faces,[9] images and videos. Such technologies enable the rapid and deliberate spread of misinformation via social media platforms, often before it can be clearly labelled as fake.

This raises a wide range of challenges for society. At one level is the arms race to develop technology that can spot synthetic content, such as deepfakes: this is likely to be constantly challenged by better techniques for making them.

Blockchain technologies can help here, reliably certifying the source and provenance of information. This is increasingly used in areas like healthcare and in emerging digital democracies such as those in Estonia. Healthcare tech is likely to lead the way in this area because the new health services that digitisation provides are much needed in most societies.

However, blockchains come with certain risks. They are vulnerable to certain kinds of attack and their security is not always clearly verifiable. Some blockchain instances require institutions to give up control of their data — a requirement that may prove too much for certain organisations. For example, many governments are reluctant to embrace blockchain-based cryptocurrencies for fear of losing control of monetary policy.

At the same time, the war in Ukraine is forcing governments to consider controlling cryptocurrencies to prevent them being used to circumvent sanctions[10]

Biometric technologies for identifying individuals provide an alternative means of digital verification, and in many cases have reached sufficient maturity to be useful in this area. However, they will be increasingly sought-after as a way to gain illicit access to confidential records and to financial, health and security-related systems.

5-year horizon:

Digital trust remains elusive

Blockchain is increasingly incorporated into institutional structures to certify provenance of information and to monitor and control access. However, high profile attacks and vulnerabilities in nation-state digital identity systems continue to undermine trust in these systems. Biometric data is increasingly secured with post-quantum cryptographic techniques to protect it against sophisticated attacks from quantum computers.

10-year horizon:

Secure systems flourish

Open digital economies and well-secured digital healthcare systems evolve into fully fledged digital worlds in both democratic and autocratic societies. Data leakage from improperly secured digital identity systems undermines public confidence in biometric security in some parts of the world. Knock-on effects include a drop in international visitors to these countries for fear that tourists' biometric data will leak. Concerns over data security, data privacy and digital human rights becomes a key battleground for campaigners.

25-year horizon:

Cryptocurrencies become mainstream

Carbon neutral blockchain technologies allow cryptocurrencies to gain broad support and state backing in some parts of the world. The ability of AI systems to mimic real humans, down to the level of biometric detail, raises important questions about the nature of digital identity and how it can be verified in future.

4.4.2 Digital identity and trust

As people's lives move increasingly online, they become more concerned with the nature of their digital identities. Among the central issues are security and privacy: digital identities need to be safe and secured. This has been a huge success in Estonia, where the country's digital identity system is secured by blockchain and widely trusted by the public. It is used to record citizens' daily transactions, to make tax payments and even to vote.

Other systems have been more controversial, however. India's Aadhaar digital identity system has over 1.3 billion users, a number that has helped to kickstart the country's digital economy. But it has also been engulfed in controversy, with lawyers, academics and civil rights activists claiming that Aadhaar allows massive state-level surveillance and that security is inadequate, allowing data breaches and even fraud.[11]

At the heart of all these challenges lies the issue of trust. It is already clear that the nature of trust is highly nuanced and that people will rely on a particular technology in one set of circumstances but not another.[12] For example, research into the use of QR codes to convey vaccine status has shown that people are willing to trust this technology in relatively anonymous situations, such as when travelling, but are much less likely to trustit at work, where it can reveal their health status to colleagues.

At the same time, trust in institutions — including democracy — has declined in recent years. It is not clear how technology will affect this trend, but there is risk of a drift towards unchecked use of widespread surveillance.

Digital identity is likely to further evolve in the "metaverse", where online versions of ourselves and objects around us will become increasingly active. "Digital twins" are already being used in purchasing decisions, voting, health studies and so on.[13] It is likely that they will be augmented by artificial intelligence that can offer better-than-human capabilities, making establishing and verifying the identities of these "centaurs" a vital concern.

5-year horizon:

Digital identity issues come to the fore

The demands for transparency and accountability on digital identity platforms ensure that the issue of digital identity becomes a central issue in many countries.

10-year horizon:

Access to blockchain divides regions

Where secured by blockchain technologies, digital identities begin to strengthen many democratic institutions, pushing public trust to an all-time high. However, many regions rely on less secure technology which undermines public trust and enables autocratic regimes to flourish.

25-year horizon:

Identity thieves target AI-enhanced humans

Humans augmented with AI capabilities become a powerful sector of society, leading to a growth in attempts to steal or clone their identities.

4.4.3 Privatisation of governance

As private sector actors play a larger role in society, their modes of operation are having a bigger impact on the way we live and work. For example, AirBnB has profoundly changed the nature of some cities, such as Barcelona, which have been forced to regulate the company's activities. However, the way AirBnB has reacted to those regulations has had important effects on local citizens trying to buy and rent properties. These people have limited democratic influence over AirBnB.

The same is true of the tech companies who act as gatekeepers to the world's apps by controlling digital practices. These operations, where non-state actors take on the role of regulators, represent a gradual but significant erosion of democracy that needs to be continually assessed and resisted: citizens must be able to influence outcomes where appropriate. These issues are likely to become more acute as human activity becomes increasingly virtual and our interactions with machine intelligence become more common.

The outworking of governance is also being changed by the outsourcing of human roles to digital technologies. Digital decision-making via artificial intelligence systems, for instance, is being used in courts to help with sentencing and with many more routine legal processes. This raises a number of important questions for the judiciary and for society at large.[14] For example, judicial decisions need to be transparent and explainable so that those involved can understand them. They also need to be free from bias.

A broader issue is how machines can help to automate much of the routine work behind democratic institutions, such as local councils and regional assemblies. These systems will be able to harvest opinions, make judgements about local priorities and determine optimal allocation of resources. This could significantly improve the efficiency of many democratic processes and functions but also raises questions about the transparency of these decisions and whether they will be applied fairly.

5-year horizon:

Concerns for democracy grow

Public disquiet forces law-makers to examine the role of private sector actors in regulating aspects of society, and how to make this situation more democratic.

10-year horizon:

AI becomes standard legal tool

AI systems become standard tools in the legal system as a number of high-profile legal cases make their advantages clear. Defendants in complex cases begin to successfully defend themselves using AI counsellors for advice.

25-year horizon:

Democratic systems make use of AI

AI becomes an indispensable tool for local government and civil servants, who use it to optimise the distribution of scarce resources in their communities, making it a vital and influential tool for effective democracy.

4.4.4 Censorship circumvention and content moderation

Digital communication technologies have allowed unprecedented innovation and development in communication, information access and content creation. However, rapid, unfettered access to information and communication platforms does not always lead to positive outcomes. Hate speech, online bullying and misinformation can have devastating effects on individuals and communities, and information-sensitive complex systems, such as financial markets, can exhibit unexpected and unpredictable behaviour that can have significant adverse consequences.

As a result, there are increasing calls for more effective moderation of information content, such as "circuit breakers" for financial markets.[15] Social networks have been less successful at preventing the way hate speech and misinformation can spread.

One possibility for the future is to introduce social circuit breakers that make it more difficult to retransmit social messages.[16] Another is to improve moderation practices and technologies. Indeed, Europe's Digital Services Act and Digital Markets Act[17] places a greater burden on social media companies to create safe spaces for their customers, although critics say it does not go far enough.[18] There are suggestions that blockchain can be used to create a "public consensus algorithm".

All this has to be balanced against the right to freedom of speech. This requires careful legal safeguards and constant monitoring. In places where free speech is curtailed, a number of technologies can help individuals circumvent censorship. One example is The Onion Router (Tor) network, which enables anonymous communication.[19]

This is being opposed, in some regions, by authoritarian regimes using AI to turbocharge their means of repression — mass surveillance, face recognition and gait tracking, for example.[20]

5-year horizon:

Post-quantum encryption rolls out

As quantum computers threaten to become powerful enough to break conventional encryption approaches, post-quantum encryption techniques become more widely used, securing public trust in communication systems and commerce/finance platforms.

10-year horizon:

Privacy tools evolve

Attacks by autocratic regimes against anonymous communications networks such as Tor become significantly more sophisticated as a combination of other surveillance techniques are used to discover when and where Tor is being used.

25-year horizon:

Technology enables authoritarianism

The way surveillance technology, combined with AI techniques, has moved the whole world in an authoritarian direction becomes increasingly clear. This triggers a widespread backlash and demand for greater openness and better oversight on how this technology is used.

Mina Cikara
Professor of Psychology, Director of the Intergroup Neuroscience Lab, Harvard University

Invited Contribution: Misperceptions, Meta-Perceptions and Conflict

The evidence is overwhelming that humans are by default co-operative, moral and deeply averse to harming others. Our very co-existence in cities with millions of residents, on a planet with billions of inhabitants, testifies to that. And yet, by some counts, over 200 million civilians have been killed in acts of genocide, war, and other forms of collective conflict over the last century alone.

As a social psychologist, I have come to understand that our worst acts are often carried out in service of good group membership. Our ideas of what is acceptable, fair or just change dramatically when our psychological viewpoint shifts from “me and you” to “us and them”. Intergroup dynamics are thus a critical boundary condition on our most cherished theories of morality, justice and human nature.

And yet we still don’t have a deep understanding of what a group actually is, or how it behaves. And how do we know to which groups we belong? How do we assign others to groups? Why do those assignments sometime change so abruptly and brutally? How do people go, in only a few years, from marrying one another and raising each other’s children to supporting or even participating, in genocide?

One important challenge is that most intergroup researchers study what might be best characterised as group geometry — whether people lie within or outside a social category, what shape the resulting networks take, and so on. More specifically, the contemporary intergroup literature emphasises static category-memberships, usually in conflict dyads — for instance, black vs. white people — although many conflicts obviously involve more than two groups.

This approach is limited because it is inflexible: social categories are not fixed monolithic entities. Associations with specific categories change over time: Italians in the U.S. were considered ethnic outsiders for decades before becoming racialised as white in the early 20th century. Allegiances between categories can change: Americans and Japanese today enjoy cordial relations, whereas 80 years ago they were mortal enemies. Group boundaries contract and expand over time and contexts, and are constantly being redrawn and negotiated by those within and outside those groups. Not all categories are psychologically potent or purposive: societies have never been worried about an uprising by brunettes.

Finally, a static framework cannot explain how people transition from being cooperative neighbours to enemy combatants. Moreover, there are leaders and central actors who foment, carry out, and perpetuate conflict. Many experts have weighed in on what conditions allow those actors to succeed but it is also crucial to consider the social contexts in which those conflicts unfold. What about everybody else? Who supports the conflict? Who protests? Who stands by?

Study and management of conflict in international relations and the social sciences generally focuses on out-group threats — economic challenges, clashes of values, political differences, resource conflicts or pathogenic risks. But those threats often exist without any concomitant conflict taking place, which suggests that while some form of threat is necessary for conflict to arise, it is not sufficient in itself. Dislike or prejudice against an outgroup does not mean that there will be widespread support for harming them.

This is why I study the physics of groups: the psychologically meaningful forces that regulate the formation, organisation and dissolution of purposive groups. My work proceeds on the assumption that groups are best understood as distributions of members who will continually reorganise themselves under the influence of forces which bind them together and rend them apart. This coalition-based framework accounts for groups' dynamic nature: the very same people who may stand by in one context can be activated to violence in another, so long as certain conditions are met.

The ways in which coalitions form and re-form, and the conditions under which threat turns to conflict and then to violence, are changing under the influence of information technology. We are not dispassionate processors of information. Just as prisms bend light, so too do our minds distort information, making some information more likely to be noticed, remembered or shared.

For example, individuals have the tendency to attend to, learn from, and weigh negative news more heavily than positive or neutral news. This negativity bias may be further compounded by factors such as the availability heuristic, which leads people to consider events to be more likely and credible if they can readily recall similar incidents. This is why threatening propaganda can be very effective in generating hatred against particular groups or organisations.

So even if there was no dis- or mis-information being broadcast to the public, we still wouldn't have a veridical picture of the world in our heads. This matters, because false beliefs inform behaviour. For example, inaccurate, pessimistic beliefs about the other side's feelings are associated with decreased trust, and negative expectations about mutual interactions. The farther I think you are from me, the less I trust you or want to talk to you. Perceived polarisation leads to actual polarisation.

In addition to first-order perceptions, my colleagues and I study meta-perceptions. A perception is what I believe about you. A meta-perception is what I believe that you believe about me. We think these are important because they guide whether or not we believe we can live or work together. Democratic governments inevitably require coordination amongst people who disagree; that coordination is what brings citizens services, infrastructure, and security. But if my meta-perceptions are overly negative — I believe you're appalled by me and outraged by everything I do — that forecloses on the possibility that we can get anything done. It would be a waste of time to try.

That situation would seem to summarise the current situation in American politics, so we put it to the test.[1] We found that Democrats and Republicans alike disapproved of hypothetical actions the opposing party might take, such as naming a highway after a controversial figure, or gerrymandering an electoral district in their favour. They weren't generally enraged—but they did think other members of their own party would be. And they thought that if the situation was flipped, so that their own party was the "offender", members of the opposing party would be hugely offended. The more strongly they felt this, the more strongly they believed their opponents to be obstructionists themselves.

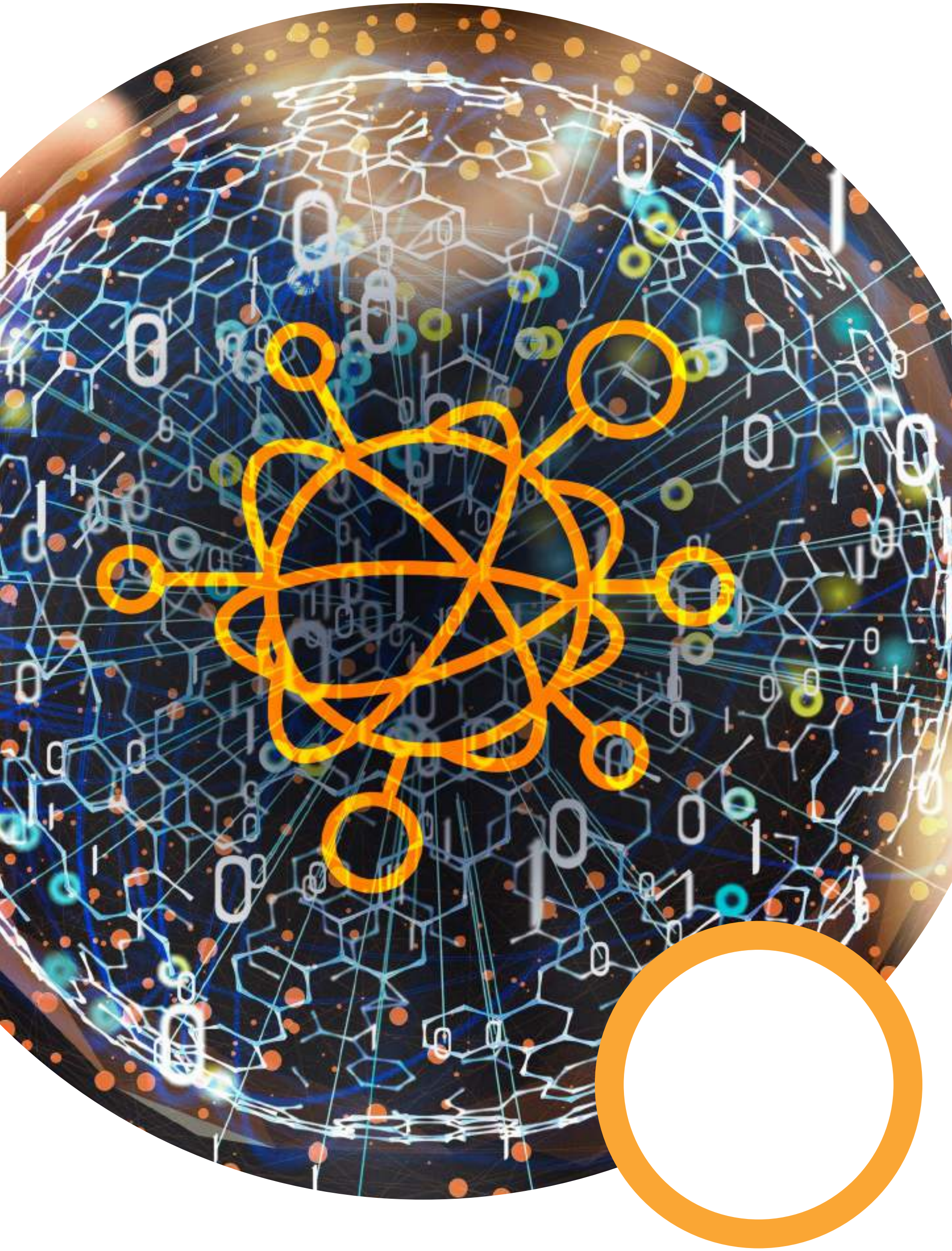
This is not just the case in the domain of politics. For example, my colleagues have found that Americans who learn that Arabs or Muslims blatantly dehumanise Americans are not only more likely to dehumanise Arabs and Muslims in return, they're more likely to say they support torture and drone strikes. This finding replicates with Hungarians' beliefs about Roma people, and Israelis beliefs about Palestinians. In other words, 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.

This might sound dispiriting, but there is a silver lining, because combatting misperceptions is easier than trying to change people's actual positions or prejudices. People are obviously very concerned with their own image in others' eyes: we all want to be liked and respected. So if we learn that the other side isn't as hateful towards us as we originally thought, that can cut through in a way that attempts to improve our view of them simply won't. When we told our political survey participants that their opponents were much less easily offended than they had assumed, they became less likely to assume those opponents were driven by spiteful obstructionism — and the more pessimistic they originally were, the bigger the effect of the intervention. These results replicate across cultures and group contexts. As part of a team of over 80 researchers we have replicated both our effect and our intervention with more than 10,000 participants spread over 26 countries.

Note also that meta-perceptions can also be more specific; they can be about what we expect the other groups to do, not just how they feel. For example, my colleagues at Stanford asked people in the U.S. how likely they thought the other political party would be to engage in partisan violence. Then half of those people received a correction (based on real data) indicating that only a very small percentage of the other side would actually support or engage in violence on behalf of their party. Those who received the correction were significantly less likely to support others' violence or say that they themselves would engage in violence.

Of course, political, social, and religious factions are doing the opposite: promoting errors in meta-perception. The message is: they hate you so it's okay to hate them back. Almost any behaviour is morally acceptable if it's done in self-defence. These group leaders are building coalitions against their opponents, talking their members into conflict and violence.

Looking forward, I think that individuals, institutions, and governments have a deep responsibility (and challenge) to communicate accurately just how close we are in our values and desires. People now have access to unprecedented volumes of information, but they need to see how much distributions of attitudes and issue positions overlap. They are often only told how far apart the mean positions are — not that this is only because of a few people in "the tails." Support for climate change is a perfect example of why this matters. In one series of surveys, 80-90 per cent of Americans underestimate the prevalence of support for major climate change mitigation policies. They live in a false social reality: they think only a minority of citizens support climate action whereas the true numbers range from 66 to 80 per cent. The provision of reliable information from trustworthy sources to a data literate public is paramount for large scale collective coordination.



Nicolas Levrat
Director of the Global Studies Institute,
University of Geneva

Invited Contribution: Understanding the Reality of Multilateral Relations with Computational Diplomacy

International relations studies the interactions between states from a multidisciplinary perspective. It has led to the development of specific disciplinary fields such as international law, international political economy, international relations and transnational history. All these fields share the premise that the basic unit of international relations is the State, which aggregates and represents national interests at global level. As a rational evolution of interstate relations, multilateralism has been developed to reduce transaction costs when a common international regime is needed to bind a large number of states.

Nowadays, multilateralism has become extremely complex and sophisticated, to the point where existing analytical approaches have limited success in capturing its behaviours and outcomes, despite the efforts of academics to refine their models. However, there is a new way forward. The amazing development of computing power is starting to affect all scientific fields and the ways they apprehend reality. The approach of building a simplified model to reproduce and understand a complex natural phenomenon – first developed within natural sciences but which has long since expanded to the social and human sciences – will soon be obsolete. The data crunching capacity of increasingly powerful computers now allows us to deal directly with the abundant and complex raw material, without the reductionism and simplification of a modelling phase.

This is particularly relevant for multilateral diplomacy, where the capacity to curate and exploit the data produced by the multilateral system may have a huge impact on the theory and practice of international relations. It would be a welcome development, since multilateralism is globally stalled, both as a consequence of increased understanding of the complexity and interlinkage of issues, and the fragmentation of the playing field, as a result of the deliberate specialisation of international organisations.

An instructive example of the shortcomings of the current multilateral governance system was provided by its inability to efficiently answer the challenges of COVID-19. First, states practiced “forum shopping”, moving the issue through WHO, WTO and WIPO, with a different balance of power in each institutional setting, different rules of the game, and different perspectives — coming from health, trade and intellectual property — for dealing with the issue. This led to diverging priorities, each rational and optimal within an individual sub-system — and ultimately resulting in an incapacity to act. Second, and less obvious, the control factors — the capacity to produce and distribute vaccines — were not in the hands of states but in those of multinational private companies (in this case, the big pharmaceutical companies).

Similar remarks could be made about, for example, the way in which control over online communication ultimately resides with big technology companies, and debates over its regulation similarly pass from one forum to another: intellectual protection, broadcasting and censorship, national security. In the traditional conception of international relations, states mediate such interests; however, multinational companies now control the very infrastructures of our societies. Even if states were to agree among themselves at the multilateral level, they would not be in a position to impose the agreed arrangement on such powerful corporate actors.

Computational diplomacy may allow us to circumvent such shortcomings. Collecting and curating all the data produced by the multilateral system — texts, agendas, attendance of meetings, implementation processes and actors, and so on — and letting researchers look for patterns and connections between actors and output (or the absence thereof) will help to capture how international relations really functions today. It is likely that this will find that the links and interactions between some categories of actors are stronger than those between representatives of the same state in different multilateral fora (for example the US negotiating agenda in ILO and WTO), thus shedding light on hitherto obscure ways in which dialogue is conducted and decisions made.

This could lead to the creation of genuinely new analytical tools to understand the functioning of multilateral diplomacy: that would amount to a decisive breakthrough in our societies’ capacity to act in a coordinated manner when faced with pressing global challenges such as pandemics, climate change, water management, and so on.

Currently, computational diplomacy is divided into two schools: model-driven and data-driven. The first uses simple models — which might be "off the shelf" game-theoretic approaches — and relies on computing power to simulate many possible rounds of interactions and thus produce statistical models of the potential outcomes. The second school is currently curating existing data — a substantial task, since these are abundant and stored in widely varying formats — and translating it into formats that allow its exploitation. The first outputs of this effort are promising, hinting at novel information about the actual processes at work in multilateral fora.

A credible five-year ambition for computational diplomacy would be to produce a comprehensive open access database of the multilateral system. By reproducing the multilateral environment through usable data, researchers expect to be able to propose original pathways to collaborative solutions. This should also allow the reunification of model-driven and data-driven computational diplomacy.

If this is achieved, we might expect that the analytical models of international relations will need to be rethought within 10 years. The difficulty there lies in the interaction between results produced through natural sciences methods (computational sciences) and models developed by social scientists. We have seen this play out in climate, where policy-makers (and their social science trained advisors) have found it difficult to translate IPCC findings into policy decisions.

This problem is linked to the system of production and circulation of knowledge, which is currently fundamentally divided between the natural sciences on one side, and the human and social sciences on the other. This needs to be overcome by developing educational programmes which simultaneously teach the logic of both the natural and the social sciences, in order to be able to exploit the outcomes of the first phase of computational diplomacy.

What will happen next is inevitably difficult to predict. But broadly speaking, either a rational decision-making system will emerge, allowing the production and implementation of innovative and efficient solutions to humanity's major challenges, or the tools of computational diplomacy will be exploited to elevate the cycle of co-operation and confrontation to a new level of sophistication. We should try to ensure that it is the former, not the latter, which prevails.

5

Introduction to Knowledge Foundations

This platform covers areas of foundational knowledge which run transversal to the four other frontier issue platforms, and which have important consequences for us as individuals, society and in relation to the planet. It covers topics from basic sciences, engineering sciences, social sciences and the humanities, which do not fall easily into one of our existing four platforms because they draw on research from multiple disciplines and have effects that span numerous human, social and environmental spheres.

A good case in point is **complex systems science**. Our world is hugely susceptible to the powerful winds of change unleashed by economic, social and political forces that interact in intricate feedback loops. In the past, scientists have struggled to understand and model these forces. But in recent years our ability to gather and process data has enabled computer models and simulations of our world on a wide variety of scales with increasing predictive power. While this approach is in its infancy, it raises the prospect of more stable economies, more fruitful and productive negotiations and more peaceful societies.

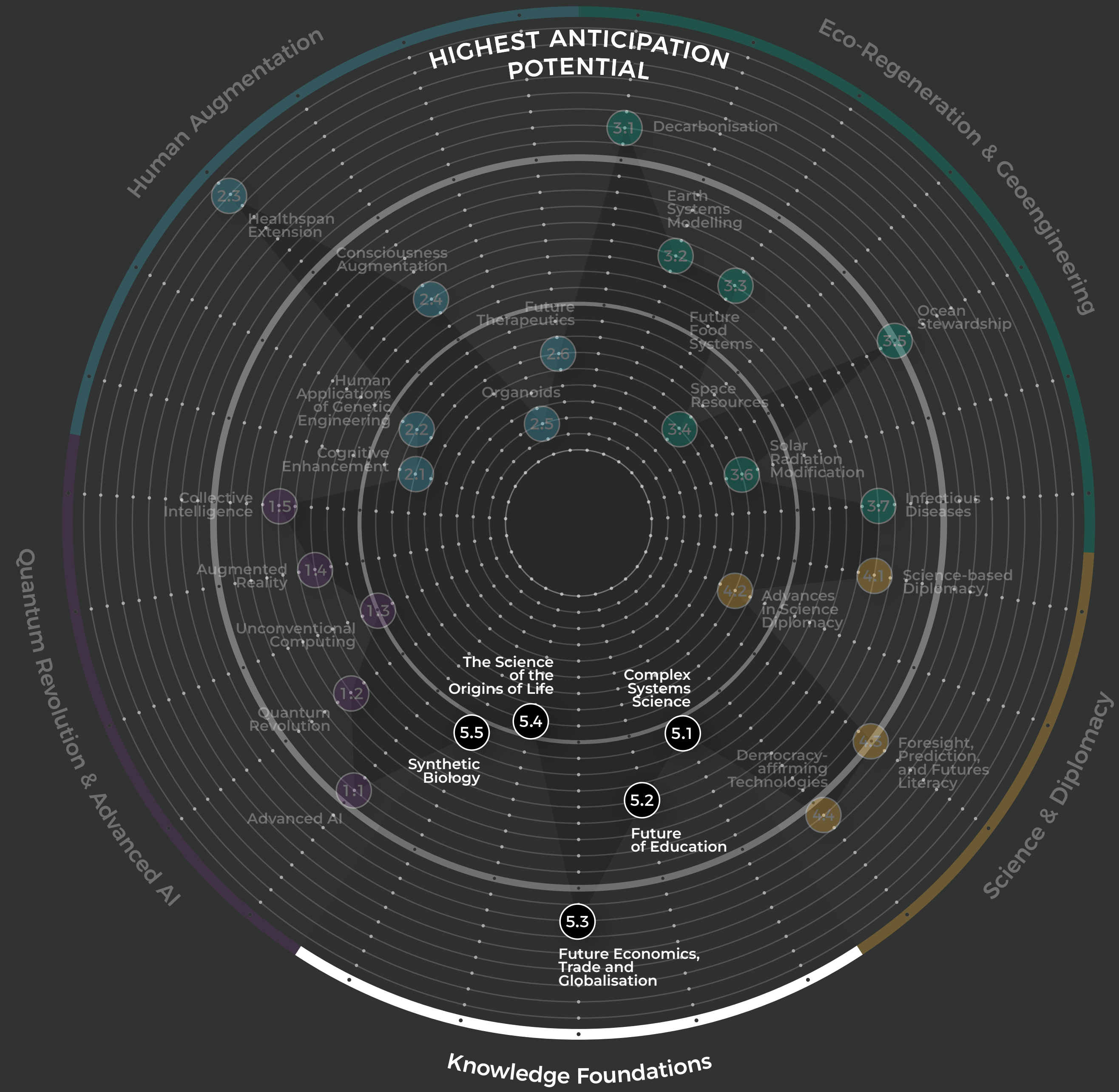
Much of the progress in all fields of research over the next quarter-century will depend on the knowledge we gain, exploit and pass on to our children. But the **future of education** goes much wider: we need to find ways to exploit educational technology for individual, lifelong learning and we need to understand better how learning happens in the brain. Education is the lifeblood of humanity, and improving its delivery is central to all of our futures.

The global effort to make humanity's existence sustainable, with societies, cities and citizens that are resilient to inevitable change, is vital. Most countries' and most global companies' strategic futures now aim to include policies that engender sustainable approaches to **future economics, trade and globalisation**. The move to renewable power has considerable momentum. Less well developed are attempts to create circular economies that exploit Earth's resources while leaving its capital unchanged. The impact of intelligent machines on the way we work will also become a driver of social, economic and political change.

Few questions have preoccupied scientists quite as much as where life itself originated. This is not a purely academic question, however: **the science of the origins of life** has implications ranging from the philosophical to the medical and environmental — which is why we have included it as one of our new Radar topics. Only if we understand where life comes from can we understand many aspects of our own existence. Research into this topic is highly diverse, bundles a range of fundamental sciences and has been the site of heated debates, but the future of the field looks likely to be increasingly multidisciplinary.

Breakthroughs in our understanding of biology and our ability to manipulate it are now making it possible to redesign nature. Driven by breakthroughs in our ability to read and re-engineer the genetic code, **synthetic biology** is on the cusp of transforming agriculture, medicine and manufacturing. The use cases for synthetic biology are likely to have a direct economic impact that runs into the trillions of dollars.

Funded and researched appropriately, these foundational topics will serve science — and ultimately society — for generations to come.



HIGHEST ANTICIPATION POTENTIAL
Human Augmentation
Eco-Regeneration & Geoengineering
Science & Diplomacy
Knowledge Foundations
Quantum Revolution & Advanced AI
3.1 Decarbonisation
Earth Systems Modelling
3.2
3.3
Future Food Systems
3.5 Ocean Stewardship
Space Resources
3.4
3.6 Solar Radiation Modification
3.7 Infectious Diseases
4.1 Science-based Diplomacy
4.2 Advances in Science Diplomacy
4.3 Foresight, Prediction, and Futures Literacy
4.4
Democracy-affirming Technologies
2.3 Healthspan Extension
Consciousness Augmentation
2.4
Future Therapeutics
2.6
Organoids
2.5
Human Applications of Genetic Engineering
2.2
Cognitive Enhancement
2.1
Collective Intelligence
1.5
Augmented Reality
1.4
1.3
Unconventional Computing
1.2
Quantum Revolution
1.1
Advanced AI
The Science of the Origins of Life
5.4
5.5
Synthetic Biology
Complex Systems Science
5.1
5.2
Future of Education
5.3
Future Economics, Trade and Globalisation

5.1 Complex Systems Science

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 ongoing climate crisis and the current Covid 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 modeling alternative scenarios 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.

Dirk Helbing
Professor of Computational Social Science, ETHZ

Anticipation Potential

EMERGING TOPIC:

Complex Systems Science

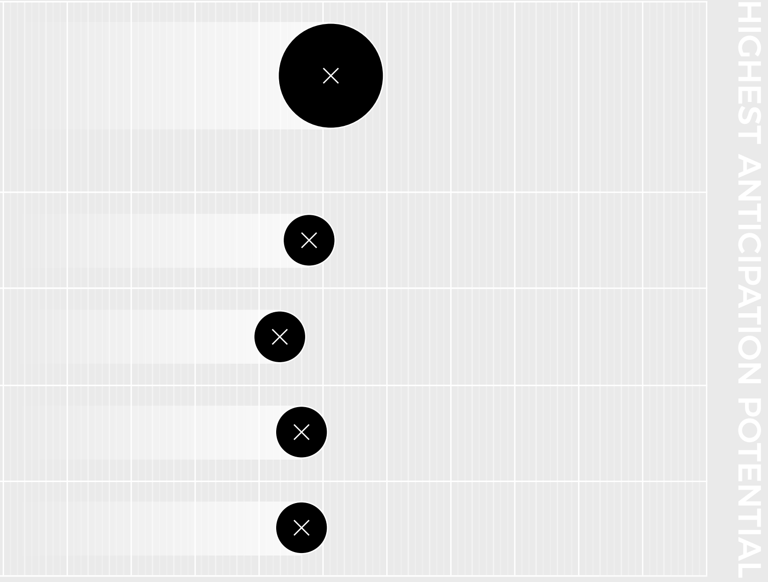
SUB-FIELDS:

Computational social science

Digital democracy

Collaborative behaviour

Design for values



SURVEY OBSERVATIONS:

The increasing digitisation of all aspects of life is opening up new opportunities to re-engineer our societies. These efforts are not expected to reach maturity for over a decade, with timelines ranging from between 10–14 years. Getting there will be more about social innovation and building up infrastructure than scientific breakthroughs. Most of the required technical capabilities already exist and the challenge will be more to increase the scale of existing activities. Smart cities were judged to have particularly high disruptive potential, but the anticipatory need was tempered by the fact that this is a field that has already received considerable attention from policymakers.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In April 2023, a US-China collaboration spotlighted the role of tools like ChatGPT in the Computational Social Science domain. 'Can Large Language Models Transform Computational Social Science?' emphasised their potential in enhancing research efficiency. In the same month, an ethical discourse from UK, 'In Conversation with Artificial Intelligence: Aligning language Models with Human Values', broached the imperative of moulding AI dialogues to echo human values and norms more authentically. 'Democracy by Design: Perspectives for Digitally Assisted, Participatory Upgrades of Society' was published in July by a Swiss research team, who unveiled the empowering possibilities of digital tools in augmenting participatory democracy and pushed for a harmonious blend of technology and democratic tenets.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r5-1

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 to gather more meaningful datasets in an ever-growing range of experiments and 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.[5] 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 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:

Tested outcomes guide 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, e.g. to improve sustainability and resilience 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.[5] 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.[6] Furthermore, digital tools also open the way for malicious actors to subvert democracy and to undermine society. Securing public confidence will therefore require a transparent design and operation of a robust, reliable and trustable, sufficiently participatory framework.

5-year horizon:

Digital tools become commonplace tools 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 are combined with digitally-gathered data and increased access to machine learning algorithms. The result is a mechanism that prompts politicians and policymakers towards solving real-world problems collaboratively and measuring the success of actions 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 behaviour and in ensuring its fruitfulness, 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.[7] Computer modelling provides a way to study how collective intelligence emerges (and why it sometimes doesn't).[8] 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 re-deploying 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.[9,10] Desirable values include, for example, equality between men and women, healthy living, personal safety, sustainable living, environmental responsibility and valuing democracy. [11]

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 their constitutional frameworks, human rights, as well as the 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. 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 technological 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 science.

25-year horizon:

Policymakers 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 Future of Education

The importance of education is hard to overstate. The UN's fourth Sustainable Development Goal is to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. Education is a vital part of creating a sustainable world populated by healthy, collaborative, creative people who are able to solve problems, contribute to economic success and enjoy a high quality of life.

Over the last few decades, science and technology have provided new sets of tools that can help us innovate in education to create a better educated human population. Many of these tools involve innovations such as digitised sensors, artificial intelligence and wearable computing components. However, just having access to these technologies is not enough: they have to be used in smart, thoughtful ways, and with an eye towards equity, if we are to create a better educated world.

Advances in understanding the science of learning are helping here. Insights into the neural processes of learning, the dynamics and cognitive aspects of teaching, and the importance of social interaction in learning are proving useful when creating learning contexts, curricula and tools for developing learners' potential.

Amy Ogan
Thomas and Lydia Moran Associate Professor of Learning Science, Carnegie-Mellon University

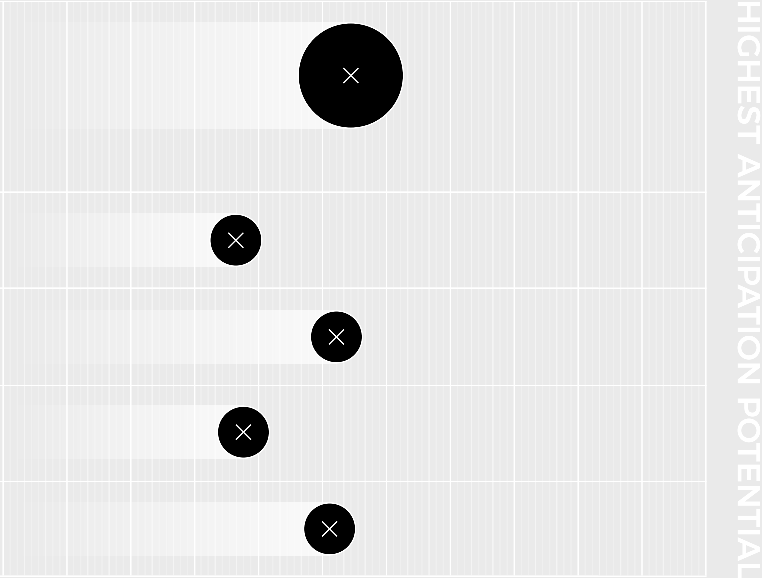
Anticipation Potential

EMERGING TOPIC:

Future of Education

SUB-FIELDS:

- Learning analytics
- Educational sensing
- Out-of-school learning
- Neuroscientific aspects of learning



SURVEY OBSERVATIONS:

Making improvements to our educational systems is not a novel idea, but major innovation appears to be imminent. Respondents expect breakthroughs in all of the areas investigated within the next 5-15 years, which suggests the window for anticipation is already narrowing. The possible outliers are education sensing and the neuroscientific aspects of learning, which are expected to reach maturity last and currently have relatively low awareness. Given the potential privacy issues raised by widespread surveillance in the classroom, education sensing is likely to require more work than the other topics to map out the potential ramifications and find solutions to any problems uncovered.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

A Turkish study from December 2022, 'Developing students' creative problem solving skills with inquiry-based STEM activity in an out-of-school learning environment', underscored the influential role of extracurricular STEM activities in sharpening students' creative prowess. In March 2023, Finnish and Norwegian researchers delved into the fragmented state of learning analytics within virtual labs. 'Learning analytics in virtual laboratories: a systematic literature review of empirical research' called attention to the urgent need for standardised methodologies to optimise the potential of analytics in online educational frameworks. A Chinese-Australian team published a groundbreaking discourse in July. 'The TEK Design Principles: Integrating Neuroscience and Learning Environment Research' unveiled the TEK design principles, an innovative fusion of neuroscience and learning design, championing the power of learning environments in stimulating sustained, student-led knowledge endeavours.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r5-2

5.2.1 Learning analytics

In an age of big data, more use can and should be made of the digital information that is gathered in educational settings. Mining this data makes it possible to assess student progress, improve educational theory, prevent drop-out and create personalised learning programs, which are adaptable to suit the student's strengths, goals and interests, and adaptive learning programs, which can deliver different kinds of content and different kinds of support through diverse means depending on the student's situation, learning environment or even mood.

To fulfil the potential of this area, researchers need to work on a number of fronts. It is not yet clear, for example, whether using individual learner demographics as input to models will increase inequity. It is possible that predictive models may be too prescriptive about learners' potential, and limit achievement expectations. It is also still necessary to identify exactly which datasets are most relevant to which aspects of education, and how best to mine and draw inferences from them.[4]

It is also important to find ways to present the results of data mining in ways that motivate and inspire teachers and learners to reflect on and understand their own learning processes and outcomes, and find ways to improve them.[5] Clear and straightforward learning dashboards have enormous but as yet unrealised potential to have significant effects on educational outcomes.

Researchers are also looking to create tools that provide dynamic measurements of students' cognitive states — including metacognition, emotion and motivation. These can assist in developing educational technologies that adapt learning goals and methods to a student's state of mind, helping them to recognise, regulate and even create their own optimal learning state.[6]

5-year horizon:

Data-gathering becomes normalised

Educational institutions begin to see the results from data analysis and realise the benefits of increasing their data gathering and analysis. Analysis software becomes affordable and ubiquitous. Open data sharing and analysis platforms democratise the gains made through learning analytics. Digital platforms for teacher-to-teacher collaboration begin to emerge. The availability of data on which to test theories gives teachers the ability to perform "action research", running their own experiments in their classrooms.

10-year horizon:

Analytics help shape optimal careers

Students leave education with a digital portfolio of their learning journey, equipping them to make insightful next-step choices, and for employers to check aptitudes, skills and cognitive abilities without reliance on a few results from snapshot high-stakes tests.

25-year horizon:

Smart tech optimises educational engagement

Machine learning algorithms with access to education datasets create and optimise personalised curricula and collaborative practices during progress through education to maximise engagement with and usefulness of educational opportunities.

5.2.2 Educational sensing

We can now observe and examine learning practices using digital technologies. By gathering and analysing anonymised data using computer-based vision technology, student-held devices and other tools, researchers are beginning to make sense of the best practices in teaching, and to understand what enables effective learning.[7]

When focussed on the science of teaching, sensing tools allow us to expand our understanding of teachers as learners and as agents of change in education. They also facilitate the provision of constructive feedback about their instruction, avoiding the pitfalls of memory limitations and bias.[8] When focussed on learners, digital tools combined with machine learning algorithms, can provide a range of insights.[9] They can, for example, differentiate students who are struggling from those who are just avoiding effort.[10] Collected data can include factors such as student and teacher locations and proximity to one another, gaze direction, classroom conversations, student engagement, participation, facial expressions, and hand raises, all of which can help in improving learning outcomes.

As these tools improve, the insights gained can be applied in teacher-training programs and in the development of new teaching resources, as well as disseminated through teaching forums, professional development courses and other outlets for innovating in teaching practice. At the same time, care must be taken to build safeguards against both deliberate and inadvertent misuses of this powerful technology. It is also worth noting that, although these kinds of learning resources are currently likely to be available only where resources are plentiful, it is possible their use would greatly benefit practitioners in poorer areas of the globe.

5-year horizon:

Frameworks for sensing are established

Data-protection, privacy and ethics standards for sharing data are agreed. New metrics are developed to better understand how best to use information gathered in classrooms. Outcomes of classroom-based research begins to feed into teacher-training programs. Dashboards for students, parents/guardians and teachers lead to better understanding and deeper engagement.

10-year horizon:

Sensing technology goes mainstream

Classrooms are routinely equipped with sensing technology to observe learning, while AI processes data in real time to offer suggestions for enhanced learning. Behavioural data from body and eye trackers will help fine-tune teaching methods and help better understand learner characteristics such as executive function.
New sensor technologies emerge that diversify from purely visual and audio input allow greater study of collaboration skills and how they can be learned.

25-year horizon:

AI and wearables change the learning experience

Wearable technology enables teachers and students to receive real-time feedback, direction and assistance during learning. Machine learning algorithms process learning data and provide tailored learning journeys.

5.2.3 Out-of-school learning

Technological developments have opened new opportunities for lifelong learning, novel learning environments and self-directed education, but it is not yet clear how we can make best use of these opportunities. This investigation can use participation data from provisions such as hybrid learning environments to understand the patterns of study, demographic breakdown, the role of social networks and socialised learning, and many other aspects of these non-traditional learners.[11]

Honing existing offerings and creating new ones on the basis of carefully analysed data will enable us to bring efficient and successful learning to those who may have failed in traditional education, require training for the workplace[12], seek up-skilling opportunities[13], live in remote areas with little access to formal learning or who simply want to learn for pleasure. It has been clearly established that a population with access to opportunities for high-quality education will have a more prosperous economy, better health and improved life satisfaction.[14] It is therefore easy to see that research into all aspects of informal learning could be of significant worth to individuals, societies and even humanity as a whole.

5-year horizon:

Online education fills Covid gaps

Educational establishments, some in partnership with corporations, seek to up-skill and accelerate progress of future students, many of whom have suffered disrupted education due to Covid, by offering free online catch-up/accelerator courses.

10-year horizon:

Educational technology becomes a business offering

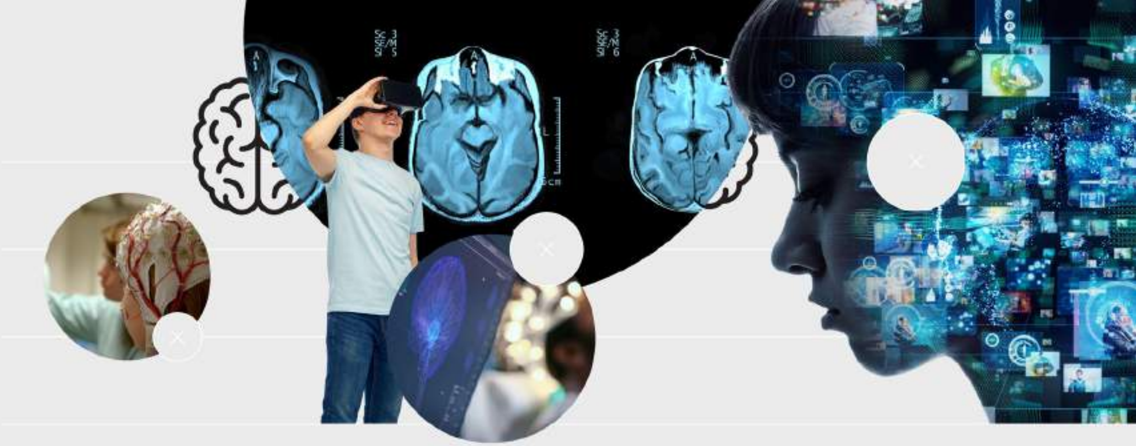
The first trillion-dollar teaching technology platform, which includes resources for out-of-school learning, highlights the potential for investors and creates a better environment for EdTech investment generally. Digital twins of schools provide ways to experiment with education strategies.

25-year horizon:

Informal learning provides a certified education in some regions

Passing AI-enabled online courses becomes a certified educational achievement. People around the world, especially from disrupted or low-infrastructure nations, begin to achieve degree-level education without formal schooling.

5.2.4 Neuroscientific aspects of learning



Although investigations of neuroscience as applied to learning have yet to deliver significant tangible breakthroughs in educational philosophy or practice[15], there are reasons to continue efforts to understand how the brain functions when learning.[16] A better grasp of the operations behind working memory, executive function, attention, cognitive flexibility, theory of mind, and inhibition, for example, would open up avenues for improving the efficiency and outcomes of education. The role of social factors is also an important subject of investigation here: has evolution equipped us to learn differently in groups as opposed to when we are alone?

Research has suggested that brain stimulation devices[17] and pharmaceutical interventions[18] can also have effects on our ability to focus our attention, retain information and learn new skills, but little is understood yet about how best to implement these findings. Investigations in neuroscience therefore comprise a tantalising suite of possibilities for revolutionising the way we deliver and receive learning opportunities.

5-year horizon:

Progress in basic neuro-learning research

Neuroscientific research begins to tease out the physiological and environmental conditions necessary for optimal learning.

10-year horizon:

Brain tech comes of age

Improved brain-sensing and stimulation technologies begin to have a positive impact on establishing focus for learning.

25-year horizon:

Augmented reality accelerates education

Enhancement technologies such as brain stimulators, AR and VR headsets, and collaborative virtual environments combine with access to AI-enabled teaching software to accelerate the process of learning.

5.3

Future Economics, Trade and Globalisation

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 wellbeing 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, by excessive emissions and 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 origin and the destination, and agriculture through altered environmental conditions. Our societies also have to solve issues of globalisation, and of 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.

Jean-Pierre Danthine

Managing Director of Enterprise for Society (E4S), President of the Paris School of Economics and Professor at EPFL

Anticipation Potential

EMERGING TOPIC:

Future Economics, Trade and Globalisation

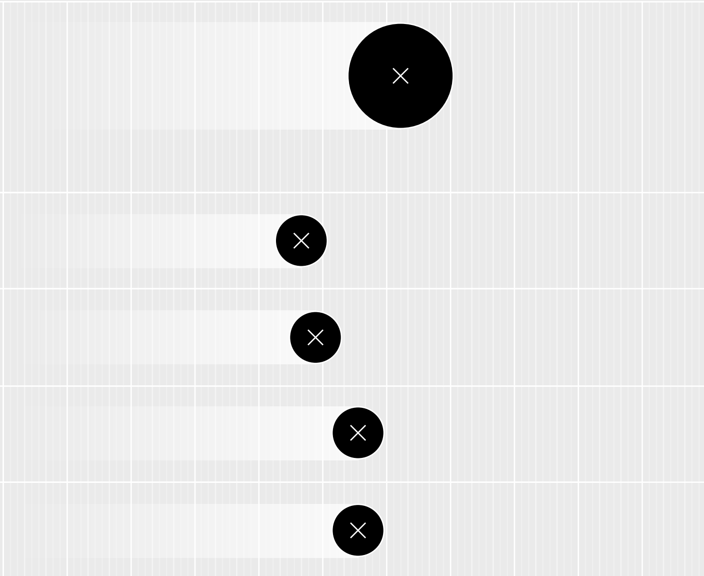
SUB-FIELDS:

Managing climate externalities

Automation and work

Bootstrapping circular economies

Sustainable global trade



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 underway. The potential impact on both the planet and society were 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.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In January 2023, two researchers from Pennsylvania State University delved into the potential of major oil conglomerates in leading the charge against climate externalities. 'How Big Oil Can Internalize Climate Change Externalities' suggested an industry-centric approach for escalating green investments, emphasising their vital role in offsetting climate impacts.

In July, Australian and US researchers published 'Advancing a slum–circular economy model for sustainability transition in cities of the Global South', offering a fresh perspective on the circular economy's role within Global South's slums, and advocating for the reconceptualisation of slums as springboards for urban sustainability. On the technological front, a collaboration between UK and Nigerian researchers published 'Human-Robot Co-working Improvement via Revolutionary Automation and Robotic Technologies – An overview'. This charts the new horizons of the Fourth Industrial Revolution, spotlighting cutting-edge automation technologies tailored to enhance and streamline human-robot synergy.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r5-3

5.3.1 Managing climate externalities

Our traditional economic models have already created substantial challenges. Atmospheric levels of carbon dioxide have been rising steadily since the industrial revolution, leading to global temperature rises that threaten the habitability of parts of the 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

SSome 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.

5.3.2 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, intelligent machines 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 globalised 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:

Machines perform low-skill work

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 perform low-skill work

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 growth of social and economic inequalities.

5.3.3 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 carbon dioxide 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 in 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 material 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.

5.3.4 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 re-organisation 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 had been touted as 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.

5.4 Science of the Origins of Life

Understanding the origins of life is an enormously challenging multi-dimensional problem. It takes in biology, chemistry, geology, palaeontology, physics, cosmology and information theory; attempts to solve it from any of these perspectives in isolation have not proved fruitful, indicating that cross-disciplinary research is essential.

The central challenge is that living organisms as we know them today are the extremely complex products of a long period of evolutionary change. Those attempting to understand how life arose from inert matter must therefore imagine highly simplified versions of living organisms that could have arisen by a stepwise process of chemical evolution. This has created ongoing debates about whether nucleic acids or other polymers came first, or metabolic reactions, or lipid-based compartments, or something else entirely.[1,2]

The overarching field incorporates a number of supporting investigations, each of which intersects with all the others. These include determining conditions on the early Earth and how they changed; fundamental issues in systems chemistry; and identifying 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.

Two significant philosophical difficulties add to the challenges. First, how the origin of life happened is a fundamentally historical question that science cannot definitively answer. The best that can be achieved is to experimentally demonstrate geologically plausible processes that lead to life-like behaviours. Second, there is no agreed definition of life — and it may not be possible to develop one. Certainly, there has been little progress on that question in recent decades. This means that judging the success of a given experiment is unusually subjective, because researchers can legitimately disagree over whether the end product is truly alive.[3]

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Anticipation Potential

EMERGING TOPIC:

Science of the Origins of Life

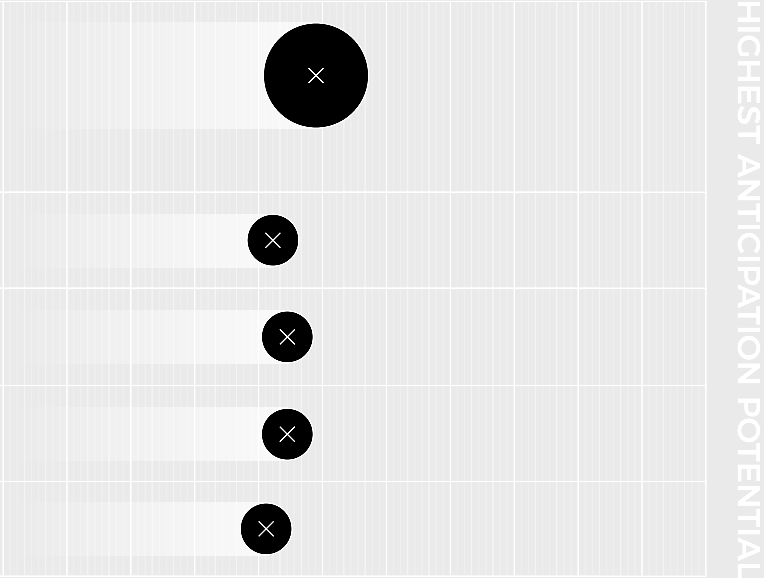
SUB-FIELDS:

Prebiotic chemistry

Systems biology

The geological record

Exobiology



SURVEY OBSERVATIONS:

Understanding the origin of life is an enormously challenging, multi-dimensional problem. But progress is being made, with experts predicting breakthroughs in the next 10-15 years. The anticipation scores in this field are mainly driven by the need for interdisciplinary research and the relatively low awareness of topics like geological evidence gathering and the low rated impact of breakthroughs in this area on our society.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In February 2023, US researchers published 'Relatively oxidized fluids fed Earth's earliest hydrothermal systems'. This paper unearths previously undiscovered attributes of Earth's ancient lithospheric fluids, signifying a more oxidised state than earlier believed and highlighting the potential sites for early prebiotic synthesis or microbial activities. 'Coevolution of reproducers and replicators at the origin of life and the conditions for the origin of genomes', published in March by a team of researchers from the US, Armenia and France, breaks ground with a comprehensive model elucidating the early evolutionary interplay between cellular structures and genetic entities, shedding light on the delicate balance required to thwart parasitic dominances and foster the emergence of intricate cellular life. In August, 'Electron transport chains as a window into the earliest stages of evolution' mooted electron transport chains as the nexus between the early evolutionary timeline and the protocellular phase.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

radar.gesda.global/r5-4

5.4.1 Prebiotic chemistry

This field of research aims to make the chemical building blocks of life in a way that is "prebiotically plausible", meaning likely to have occurred naturally on Earth.[7] A key challenge for prebiotic chemists has been to minimise the number of active steps taken by experimenters, instead creating self-organising chemical systems that work without active human help.

In the last decade there have been increasing attempts to perform prebiotic chemistry experiments in a unified way: that is, to obtain multiple biochemicals, relevant to different aspects of the living organism, from the same feedstock and environment.[8] This effort is sometimes called "systems chemistry" because it involves complex mixtures of interacting substances.[9] Experiments have demonstrated that a small number of starter chemicals can lead to hundreds of products, through reaction networks that are highly robust.[10]

There is a concerted effort to study how the attributes of multiple, individual chemical reactions can form aggregate or network-level chemical systems that express attributes associated with living systems. Network analysis, for example, is a field that is developing tools that might be used to correlate the presence or absence of systems-level features with life-like behaviours.[11]

It remains to be understood how systems of chemicals can change over time, and in particular what it might mean for systems of chemicals to "evolve" in the absence of true genetic control. Recent findings indicate multiple attributes that might define a genuinely "complex" chemical predecessor to life at the systems level. One is the emergence of a set of chemicals or processes that is robust even amid changes to the rest of the system. Another is chemical systems that are far from chemical and thermodynamic equilibrium. Yet another is emergent chemical systems that are capable of processing information, but which do not require explicit structures.[12]

5-year horizon:

Automation begins to pay off

Chemical systems have been developed that display open-ended evolution, i.e. avoiding equilibrium. Increased use of automation and AI allows us to conduct high-throughput experiments.

10-year horizon:

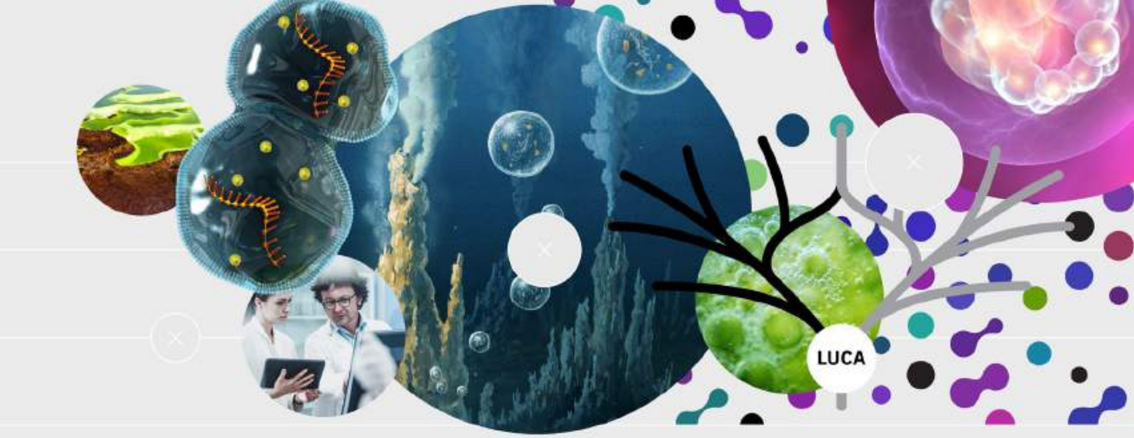
Chemical computation becomes possible

"Protocells" with self-replicating nucleic acid driven by metabolic reaction(s) 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 will be used to distil a small number of correlative factors implicated 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.



5.4.2 Systems biology

The great challenge of explaining how life originated is 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 of 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 to 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.

The move towards studies of complex systems presents a considerable analytical challenge. Modern origin of life experiments often involve setups in which dozens of chemicals, or even more, interact with one another. As a result, there is a pressing need for 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:

Extinct biomolecules are reconstructed

Palaeoenzymology uses the tools of synthetic biology and phylogenetics to reconstruct "extinct" biomolecules.

25-year horizon:

Model of LUCA brings benefits

A model of the Last Universal Common Ancestor (LUCA) based on synthetic biology, phylogenetics and palaeontology, provides useful understanding of life's history.

5.4.3 The geological record

Our knowledge of the early Earth is a key constraint on hypotheses for the origin of life. The Earth is 4.5 billion years old, and the earliest fossil organisms to have yet been discovered are 3.5 billion years old.[17] 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,[18] and so all we know is that life arose during a one-billion year window — an enormous span of time, roughly twice as long as complex animals have existed.

The limited geological evidence also means there is little information about conditions on the early Earth. The temperature range, the presence or absence of exposed land, and the chemical makeup of the oceans and atmosphere, as well as the elemental composition are all central issues for understanding which scenarios of the origin of life are plausible.[19,20] For instance, some scenarios rely on the existence of ponds or pools on land, but if the oceans were too deep there cannot have been any land.[21] These questions are bound up with fundamental problems in geology, notably the origin of modern plate tectonics.[22]

Improvements in our understanding of the geological record will continue to narrow down when and how life may have formed. A key challenge for palaeontologists and geologists is to narrow the time window for the origin of life, either by finding hard evidence of earlier life, by building on innovative synthetic biology and evolutionary systems biology tools to reconstruct ancient life,[23] or by demonstrating that conditions before a certain point were unremittingly hostile.[24]

5-year horizon:

Criteria for assessment of evidence for life 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.

5.4.4 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. As a result, we only have one living system to study, rendering it extremely difficult to make general statements about what life is or what it requires.

That may change as we continue exploring other worlds in the solar system using robotic vehicles, and potentially crewed spacecraft. Even if no living organisms are found on other worlds, 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 challenge for the coming decades will be to send out sample-return missions that can bring high-quality samples back to Earth for detailed study. Because of the long development process for deep space missions, such a project would likely take more than 25 years to come to fruition.

The prospects for discovering life beyond the solar system remain remote. 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, the technical challenges are considerable. Even if they are overcome, there is also the problem of interpretation: on Earth, oxygen is only produced by living organisms, but it is difficult if not impossible to rule out abiotic processes.[26] This problem has already bedevilled researchers who detected methane on Mars and phosphine on Venus, and will be far worse when dealing with distant exoplanets for which information is more limited.[27]

5-year horizon:

Mars gives clues to Earth-like prebiotic chemistry

Data from Perseverance rover on Mars indicates Earth-like prebiotic chemistry billions of years ago.

10-year horizon:

Solvents for life 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.

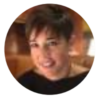
5.5 Synthetic Biology

Synthetic biology is a set of technologies which enable the modification and creation of living cells and organisms, and of their building blocks. These include genome editing,[1] artificially evolving biomolecules, tissue engineering and potentially even the creation of synthetic organisms. Collectively, these could lead to major breakthroughs in fundamental biology, as well as a multitude of possible applications in fields ranging from nutrition to pharmaceuticals and engineering.[2]

The time may come when we can use these techniques to program functionality into living organisms in the same way that we can program a computer to perform specific tasks. However, this is profoundly challenging because of the extreme complexity of living organisms. Editing an organism's DNA has direct effects on the proteins it synthesises, but we are not yet able to reliably and swiftly map genotypes to phenotypes — that is, the effects of this editing on its overall traits and behaviour are far more indirect and difficult to predict. Here, AI is expected to play a crucial role in enabling "rational design".[3]

If harnessed to its full potential, synthetic biology could radically remake many industries and sectors of society. It may help mitigate climate change, for example, through engineering of organisms that pull CO_2 from the atmosphere. It also has great potential to assist the move towards a circular bioeconomy, reducing the exploitation of natural resources and the associated harms to the Earth system through increasing emphasis on reuse and recycling of existing biological products.[4]

A key challenge for synthetic biologists is to create universal platforms on which research and development can be carried out.[5] Such standardised systems — analogous to the operating systems of computers or the protocols which underpin the internet, and thus sometimes dubbed the "biotic internet" — will accelerate progress by making synthetic biology's tools much more accessible. The aim is to make synthetic biology a widespread and accepted cultural practice, just as computer coding has already become.



Bridget Baumgartner
Director of R&D, Revive & Restore

Andrew Hessel
Chairman, Genome Project-Write;
Founder Humane Genomics

Anticipation Potential

EMERGING TOPIC:

Synthetic Biology

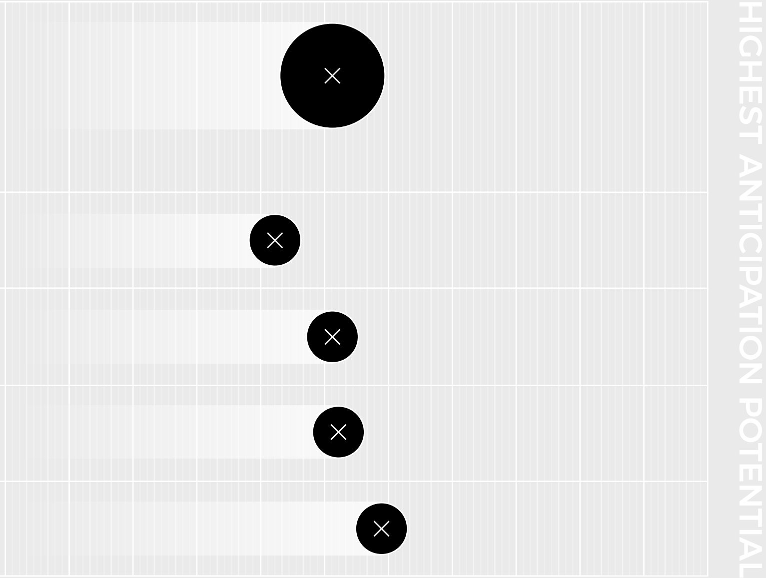
SUB-FIELDS:

Synthetic biomolecules

Synthetic cells

Synthetic tissues

Synthetic multicellular organisms



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 are expected in the next six years, progress in synthetic cells, tissues and organisms are considerably further away. Low awareness of the importance and potential of synthetic biology, combined with the need for interdisciplinary research, suggests synthetic biology is a field that requires particular attention in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In June 2023, experts published on the innovative techniques that had allowed synthesis of synthesizing entire E. coli genomes in a record time of under two months. 'Continuous synthesis of E. coli genome sections and Mb-scale human DNA assembly' presented profound implications for genetic exploration and manipulation. In August, a research team in Australia and the US published 'Engineered bacteria detect tumor DNA, an innovative application of synthetic biology in devising cellular biosensors'. These engineered Acinetobacter baylyi are adept at detecting DNA from colorectal tumors, proving instrumental both in vitro and in vivo, unveiling the potential of CRISPR-discriminated horizontal gene transfer as a revolutionary biodetection tool. 'Programming multicellular assembly with synthetic cell adhesion molecules', presented by a research team from California in December, introduces a gamut of synthetic cell adhesion molecules. These custom-made molecules offer insights into cell-cell interfaces evolution and enable systematic cellular organisation and tissue modification.

For more information on this Emerging Topic, with an expanding collection of key resources, scientific citations, associated activities and global experts, visit:

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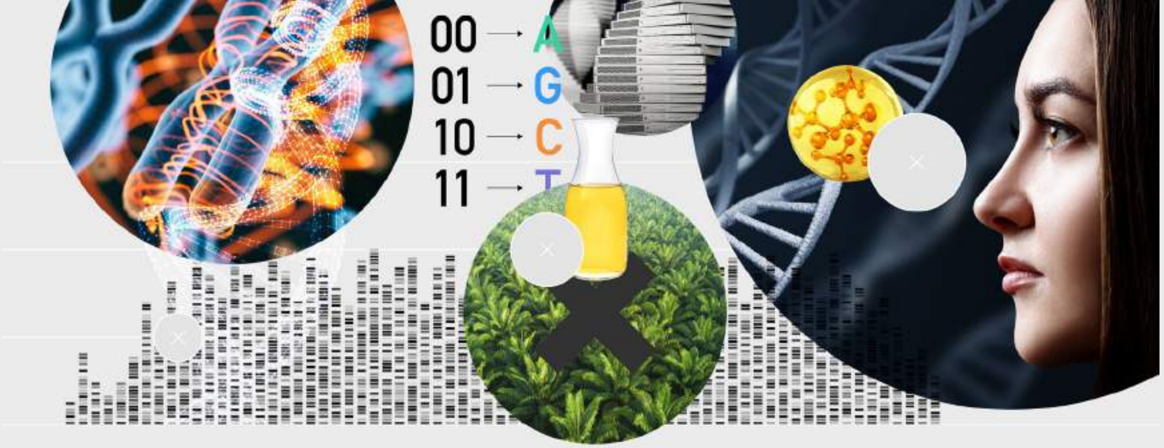

5.5.1 Synthetic biomolecules

A key promise of synthetic biology is the manufacture of molecules and materials that do not exist in nature.[10] This can take a number of forms.

One approach aims to imbue non-living materials with some of the useful properties of living organisms — spontaneous self-repair, for example.[11] The resulting products would not be alive and may include few or no biomolecules.[12] Besides their potential to be useful, such products would be of interest to biologists studying the origins and mechanisms of life.

However, much of the work on synthetic molecules relies much more directly on existing biological organisms. Synthetic biology can be used to engineer single-celled organisms to produce desirable molecules using technologies such as genome editing, DNA synthesis[13] and directed evolution. The end products could include new pharmaceuticals and synthetic alternatives to commodities such as palm oil. Producing these materials in bioreactors could alleviate the environmental harms associated with industrial chemistry and intensive agriculture.

A related area is the creation of artificial versions of key biomolecules, such as nucleic acids and proteins. For example, research projects have created "xeno nucleic acids" which are chemically different to the familiar DNA and RNA, but which behave in similar ways. Within the last decade, researchers have successfully introduced artificial nucleotides (the building blocks of nucleic acids) into the genomes of bacteria. This gives the organism the ability to synthesise proteins using more than the canonical 20 amino acids of terrestrial biology.[14] These "enhanced" bacteria have gone on to replicate successfully, giving us the potential to scale up the production of artificial molecules by orders of magnitude.

5-year horizon:

DNA information storage becomes mainstream

It becomes possible to reprogram cells to produce medicine, industrial compounds and induce biodegradation. Storing information in DNA begins to become mainstream. Techniques in synthetic biomolecule engineering bring new anti-ageing and personalised medicine products to the market, and AI helps to identify new biomolecules that are worth attempting to mimic.

10-year horizon:

Synthetic food products become available

DNA synthesis becomes 10 to 1000 times cheaper than it is today, opening the door to relatively low-cost microbial genome synthesis. Commercially available synthetic alternatives to naturally-sourced products such as palm oil become available. Acute agricultural needs lead to synthetic biology breakthroughs, such as replacing petrochemical-based fertilisers with chemicals produced by microbes. We begin to use DNA for computation.

25-year horizon:

Biofoundries print molecules

Researchers develop a standardised shared platform for synthetic biology. Widespread biofoundries are able to "print" any biomolecule on demand; the use of other technologies is guided by artificial intelligence, which identifies the most plausible designs within the massive multidimensional space of possibilities. Urban environments begin to contain "living buildings" that react to internal and external conditions. The first synthetic human genome is produced.

5.5.2 Synthetic cells

The next scale up is engineered single cells, where the end product is the cells themselves.[15] In one dramatic example, a microorganism had its entire genome removed and replaced with an artificial one, which then "booted up" inside the cell.[16]

Engineered microorganisms can be put to work in a range of fields. For example, they may well play a role in mitigating the impacts of climate change by removing carbon dioxide from the atmosphere: large-scale algae farms are one of the most effective forms of CO2 removal, and synthetic biologists can optimise the algae's ability to take up the greenhouse gas.[17]

Cells can also be engineered to act as sensors that can detect threats. Such biosensors may be used to scan for pollutants such as heavy metals or even the explosive (or its breakdown products) leaking out from buried landmines.[18] Similar biosensors have been designed to detect pathogens or signs of disease such as cancer. In future some of these may be engineered into wearable forms: for example, facemasks that detect the presence of the SARS-CoV-2 virus.[19]

A related field focuses on engineering viruses. By their nature, viruses inject their own DNA into the cells of the organisms they infect. Medical researchers are harnessing this capability to create viruses that fix the genetic defects that lead to severe diseases like severe combined immunodeficiency (SCID), also known as "bubble boy disease".[20]

5-year horizon:

AI and molecular electronics aid engineering

AI guides the re-engineering of cellular systems, while applications for commercial molecular electronics — such as in environmental monitoring — proliferate, allowing engineered molecules that emit electrical signals in response to environmental cues to be engineered into electronics as novel sensors.

10-year horizon:

Cell self-assembly becomes possible

It becomes possible to "boot" an engineered genome to start a process leading to self-assembly in a reproductive cell. Artificial organelles find commercial applications for drug activation and as biochemical reactors.

25-year horizon:

Artificial photosynthesis begins

Energy is generated through artificial photosynthesis, and microorganism-based petrochemical manufacturing platforms become commonplace. In the labs, researchers work with a whole-cell model that can be cheaply tinkered with. The first synthetic extremophiles are sent into space as part of a mission to Mars.

5.5.3 Synthetic tissues

Synthetic biology can be used to engineer multiple cells, creating artificial tissues such as muscle and organs.[21]

These synthetic tissues and organs could be used in place of donor organs for transplants. If they were produced using the recipient's own cells, the risk of rejection would be greatly reduced. Progress is being made: for example, mouse ovaries have been successfully 3D printed and implanted into sterilised mice, restoring ovarian function.[22] The hope is that similar technologies can ultimately be used in humans.

A related field aims to trigger tissue regeneration to heal severe injuries, avoiding the need for a full transplant by instead inducing the damaged organ to repair itself.[23] Some human tissues naturally regenerate, notably the liver, but not all — and controlling the process remains a considerable challenge.[24]

Artificial tissue is also being explored for the production of cruelty-free "meat" by culturing animal cells. So far, the artificial meats on the market resemble processed meats, such as burgers or mince. The next step is to recreate the complex three-dimensional structure of a cut such as a steak. This requires tissues that contain multiple cell types, correctly organised in space, and remains some way off.[25]

5-year horizon:

High-throughput tissue production begins

Automation, AI-driven standardised protocols and better tissue culture media enable high-throughput tissue production. Artificial meat derived from fungi becomes mainstream in the food marketplace.

10-year horizon:

Accelerated evolution becomes possible

Manipulation of chromosomes and stem cells accelerates evolution for research purposes, and "microphysical systems" of cells and bioreactors become a ubiquitous research tool. Cultured steak has become indistinguishable from the real thing.

25-year horizon:

Breakthroughs benefit food, fashion and transplant surgery

The fashion industry embraces synthetically engineered fake leather. Programmable stem cells produce organs for human transplants. The food industry uses biomanufacturing techniques to make non-animal meat at scale, helping to achieve better nutrition.

5.5.4 Synthetic multicellular organisms

Creating wholly synthetic multicellular organisms is probably synthetic biology's greatest technical challenge. The limiting factor in creating engineered multicellular organisms is the ability to write or assemble larger genomes, be they for animals, fungi, or plants, or completely novel creatures.

Much of the work on artificial multicellular organisms is at an early stage and the end results are not predictable. One prominent line of work involves "xenobots", which are tiny artificial organisms — or alternatively, biological robots.[26] These are not strictly synthetic, since they are derived from largely unengineered stem cells obtained from the developing embryos of Xenopus frogs. Existing xenobots only include two cell types: skin cells to provide structure and heart cells that act as motors. Nevertheless they can already perform a range of functions including swimming or rowing (using cilia as oars) through fluids. Xenobots may find uses as drug delivery mechanisms, or disposing of pollutants by swarming and trapping them.

The first genetically-modified organisms (GMOs) were produced using quite crude methods — for example, inserting a single gene into a random place in the genome. The products of this technology nonetheless have considerable potential: for example, "golden rice" has the potential to alleviate vitamin A deficiency, which can causes serious vision problems and is common in parts of the Global South.[27] Nowadays, modern genome editing tools like CRISPR-Cas allow much more precise and targeted genetic alterations, such as rewriting a few "letters" within a gene.[28]

The engineering of multicellular organisms may also have a role to play in conservation biology.[29] For example, it is possible to engineer threatened species to resist extinction-threatening diseases. American chestnut trees have been genetically engineered to resist the chestnut blight fungus, which nearly wiped out the species over the last century.[30] The tools of synthetic biology may also be brought to bear to revive species that are otherwise effectively extinct, such as the northern white rhino.[31]

5-year horizon:

Smart microbiomes come of age

Smart microbiomes, essentially logic-based synthetic gene circuits, are developed. These sense and respond to stimuli within a multicellular host. Research creates precision hybrids that combine traits of two related species. Policymakers develop regulations for gene-edited staple crops that can withstand climate-induced changes in their environment.

10-year horizon:

Engineering benefits corals

Corals benefit from engineered protection. Research shortens the timescales for coral reef regeneration and renewal. Large-scale rewriting of genotypes for a variety of applications becomes possible, thanks to advances in synthetic genomics and stem cell technology. Invasive species, disease vectors and agricultural pests are significantly reduced thanks to the development of synthetic biocontrol agents. Engineered multi-cellular systems offer a novel approach to logic and computation.

25-year horizon:

Some lost biodiversity restored

Artificial chromosomes, preloaded with genes for medications etc, can be uploaded into humans. Some lost biodiversity is restored through synthetic biology techniques, and the Earth hosts the first "synthetic ecosystems", in which many species have been altered or synthesised from scratch.

Sylvian Fachard
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Invited Contribution: The Future of Archaeology

Archaeology is a young science: over the course of the 20th century, it evolved from the collection and cataloguing of artefacts to the reconstruction of the human past through the contextual study of material remains. As a relatively young discipline, archaeology has gone through a long process of epistemological development in order to reach its current methodological and professional maturity. It may seem that today is a "golden age", with novel scientific and technological tools revealing much that was once assumed to be entirely inaccessible. Yet, like any scientific discipline, archaeology keeps evolving and reinventing itself, mainly thanks to collaborations with other fields.

Following World War II, archaeology firmly embraced science. Dendrochronology and carbon dating were the first among a wave of technologies and methods that transformed the discipline, followed by computer science (quantitative and computational methods), thermoluminescence, environmental sciences (geomorphology, micromorphology, palaeoclimate, palaeo-seismology), GPS, satellite imagery and remote sensing, laser scanning, geographical information systems (GIS), photogrammetry, LiDAR, and, most recently, ancient DNA.

Archaeologists have never had so many tools at their disposal for studying the human past. But that is by no means the end of the story. We can anticipate several trends that will continue to enhance the practice of archaeology and increase our ability to reconstruct the past.

Excavation techniques and micromorphology

An archaeological excavation can be likened to an historical “crime scene”: through close examination, archaeologists gather hints and fragmentary evidence that allow them to reconstruct past events. Although popular imagination primarily associates archaeology with fieldwork, current and future excavations will be increasingly supported by laboratory studies. New developments in the microscopic analysis of soils and sediments will help archaeologists understand the formation and nature of archaeological sites, detecting the signature of past events and practices in settlements, houses, courtyards, public and religious complexes. This, in turn, will contribute to our understanding of past societal organisations and long-term social changes — ranging from the adoption of agriculture, the development of complex societies, the use of writing and technology, the emergence of market economies and capitalism, to the impact of human on the environment — with an extraordinary and unmatched level of detail.

Human-environmental interactions

Combined with excavation, archaeological field surveys conducted in large geographical areas study long-term human occupation, allowing us to learn when and how humans settled, farmed the land and exploited natural resources in a given region of the globe. Therefore, survey techniques and environmental research (geomorphology, pedology and palaeoclimatology, for example) that reconstruct past ecosystems and agricultural strategies can study landscapes shaped by past human actions, the long-term effects of humans on their environment and the history of climate change and its impact on human societies. In the future, such studies will be dramatically enhanced by LiDAR and satellite-based remote sensing, combined with geographical information systems (GIS) and machine learning, allowing us to detect further sites in extremely remote places and fragile environments, as well as to model past behaviours, settlement patterns and communication networks. Such advances will help modern societies monitor and protect world heritage sites, secular practices and ancestral memories, which are increasingly at risk due to overpopulation, densification, migration, and climate change. Recording past experiences stretching over 10,000 years will preserve “world memory” and inform us about the potential extent of human resilience and help us define future strategies for stabilising and occupying fragile ecosystems.

Palaeogenetics

Our ability to isolate and decipher ancient DNA continues to progress rapidly, making it possible to analyse highly degraded samples. The cost of such analysis also continues to decrease, meaning that it can be used more widely and routinely. These developments will revolutionise archaeological research by offering ground-breaking insights into the biology and biography of both individuals and groups. The enlargement of genetic libraries will allow us to explore the story of human colonisation and migrations around the globe, including the genetic composition of past and present ethnic groups, polities and states in the long term. They will also help us study the history and impact of past pandemics, as well as their long-term social consequences. In 15-25 years, we can expect to develop techniques that precisely date and determine the genetic group of burials, thus placing past individual trajectories within the global trends of world history. At the same time, an increased fact-driven understanding of past migrations and of the genetic identity of ethnic groups will modify the bases of current and future geopolitical and nationalist debates.

Overall, archaeology as a discipline will continue to be transformed through the refined application and integration of existing scientific techniques, and by the introduction of entirely new capabilities. Archaeology will become more fact-driven, science-oriented, and collaborative, benefitting from previously inconceivable precision in dating, analysis, and modelling.

Our ability to rationally reconstruct the past will thus improve greatly — as will our ability to apply what we learn to the future. As international organisations increasingly recognise the notion of world heritage, we will gain a more acute understanding of the natural and genetic history of humanity; migration and settlement patterns; past management of natural resources; human-environment interactions; historical climate change, and long-term human resilience. Thus, archaeologists will provide an historical and factual background to key current and future issues.

As Winston Churchill famously said, “The farther back you look, the further ahead you can see.” We can already see much farther back — and ahead — much more clearly than we once could. Soon we will be able to see farther and more clearly still.

Andrea Boggio
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Invited Contribution: **Responsible Anticipation**

We live in times of great acceleration in science and technology. This acceleration promises breakthroughs with transformative impacts on human life and the planet. Anticipating these breakthroughs is critical to ensuring that we can harness the most benefits from them. Is there anything the scientific community can contribute to this process besides the creativity and intensity needed to achieve these breakthroughs?

In fact, more is required by the human right to benefit from science — a right that receives relatively little attention but which is nonetheless codified by Article 15 of the International Covenant on Economic, Social and Cultural Rights. Under this article, the public has the right to enjoy the fruits of science, while signatory states must foster conditions under which scientific research is conducted freely and its benefits diffused widely.

The *quid pro quo* for this is that the scientific community should practice *responsible anticipation*. It should not simply take progress for granted. Rather, it should anticipate its own trajectory, reflect on its likely impacts, and, if needed, steer scientific progress in the direction most beneficial for society. This is resource-intensive, intellectually and emotionally demanding, and driven by constantly changing needs. But it is indispensable to ensure that scientific progress serves the welfare of humankind and contributes to protecting life on the planet.

To anticipate responsibly, scientists must engage, individually and collectively, in three activities: contemplation, control, and communication.

Contemplation is a self-reflective exercise of the scientific community when called on to anticipate the impacts of research. Contemplation connects present actions with future impacts. The future is the result of what happens in the present, and so the goal is to evaluate today's actions in light of what is anticipated, to ensure a desirable future in which science benefits humanity to the full extent possible. To be comprehensive and adequate, contemplation requires integrating two complementary approaches: *prospective* and *retrospective* anticipation.

Prospective anticipation relies on foresight tools to create a pathway to a desirable future. This form of anticipation deploys linear and systemic thinking to predict and/or guide what science and technology will make possible in the future. Typical tools include trend reports, horizon scans, scenario planning or pathway development.

Retrospective anticipation deploys the power of creativity to generate utopian and dystopian futures — to make the "unthinkable" thinkable. These "unthinkable" futures serve as the basis for reflecting on present practices, critically assessing foresight and its assumptions, and generating alternative worldviews of how science and technology can shape human civilisation's future. This perspective creates discontinuity. By creating a gap between the present and future, retrospective anticipation aims to reshape mindsets and change how scientific (and social) progress is perceived and addressed in the present.

Control: When contemplation indicates that the present trajectory of scientific progress must be corrected to achieve desirable future outcomes, the scientific community must activate and manage that trajectory. The most effective way to achieve this result is self-regulation, which refers to self-imposed constraints on scientific freedom. Self-regulation is led by scientists and directed toward scientists, although it may be influenced by external factors — for instance, by a pressing social need. It is independent of political institutions and the legal system, although it may be reinforced by outside forces in the form of laws and regulations.

Examples of self-regulatory controls are guidelines identifying standards and best practices; statements of principles of conduct; norms of conduct within collective arrangements such as research consortia; and outright moratoria on contentious areas of research.

The biomedical field offers several successful examples of self-regulation. The Bermuda Principles, mandating that all DNA sequence data be released in publicly accessible databases within twenty-four hours after generation, marked a departure from a tradition of making experimental data available only after publication and have become the norm in the field of genomics. The 1975 *Asilomar Conference on Recombinant DNA*, which convened 153 molecular biologists, sixteen journalists, and four lawyers to discuss the future of research and applications of recombinant DNA technology, produced a risk-based typology of research activities that is still the blueprint for these kinds of experiments, and led to a moratorium on riskier research pending the construction of facilities where this could be conducted safely. The *International Summit on Human Gene Editing*, which convened scientists to define a responsible pathway to experimenting with germline gene editing on humans, concluded its third edition with an organisers' statement that these experiments are premature because appropriate governance is still insufficient.

Communication: Finally, responsible anticipation demands that scientists explain to the public and policymakers why and how they have decided to manage the trajectory of scientific progress. Communication must be broad in scope, including information on the anticipatory processes and approaches used to generate ideas and the need for self-regulation, the values underlying self-regulatory processes and outcomes, and a vision of the next steps of responsible anticipation.

The goal is to inform nonscientists of the outcome of self-reflective and self-regulatory practices, to foster trust in the scientific community and science, and to empower citizens and policymakers with knowledge that can serve as the basis for formulating policies that balance risks and opportunities of scientific progress, while advancing human rights and promoting intergenerational justice.

Responsible anticipation is successfully practiced in the biomedical field because it is an area of science which very quickly comes into contact with societal values, opening up scenarios which could quickly challenge the collective understanding of what it means to be “human.” Scientists in the biomedical field operate in a highly regulated environments, with a long tradition of professional ethics dating back to the Hippocratic Oath at the origins of medicine and experimentation with the human body.

The achievements of responsible anticipation have thus far been less significant in other, less historically conditioned, fields of science. In the fields of AI and geoengineering, for example, governance has developed in regulatory environments that are much less structured than in biomedicine. In AI or geoengineering, scientists are thus freer to choose different paths, and responsible anticipation is therefore more challenging to coordinate. This is evidenced by the proliferation of self-regulatory pronouncements and statements: according to AlgorithmWatch, 167 self-regulatory statements have been produced in AI governance, while Herzog and Parson identified 18 calls for moratoria, including research moratoria, on climate engineering. Paradoxically, the greatest need for fostering a culture and practice of responsible anticipation exists in these less-regulated fields.

As responsible anticipation becomes more prevalent, we must ensure that scientists commit time and resources, educate themselves about anticipation, and integrate anticipatory practices into their ways of doing science, both in the public and private sectors. Society and governments must support it, commit to taking it seriously and appreciate the value of the scientific community’s efforts to define paths to scientific progress that prioritise the benefits for humanity.

More thinking must also go into enriching the toolbox to monitor and foster compliance with responsible anticipation. It would be illusory and unrealistic to expect that responsible anticipation prevents all “bad behaviour” among scientists. This is not the goal of anticipatory practices. Their function is to bring scientists together, engage them in a conversation about future impacts, set standards of conduct, and generate insights based on their expertise valuable to society and policymakers to carry on a broader conversation about scientific progress.

Ultimately, to be effective and respectful of human rights, the regulation of innovation does not rest in the hands of a single social actor, but it can only emerge from collective action. Focusing on responsible anticipation means organising an essential piece of that process. If scientists do not take it seriously and society also does not believe in its value, a critical opportunity to steer innovation towards a path beneficial for all is missed.

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The Philosophical Lens: **The Future of People, Society and the Planet(s)**

GESDA anticipates scientific and technological advancements to develop inclusive and global solutions for a sustainable future. Three fundamental and overarching questions drive its work:

- **Who are we, as humans?** What does it mean to be human in the era of robots, gene editing, and augmented reality?
- **How can we all live together?** What technology can be deployed to help reduce inequality, improve well-being, and foster inclusive development?
- **How can we ensure the well-being of humankind and the sustainable future of our planet?** How can we supply the world population with the necessary food and energy while regenerating our planet?

The Science Breakthrough Radar provides an overview of trends and breakthrough anticipations at 5, 10 and 25 years in 42 science and technology emerging topics that could have a strong bearing on the answers to these questions. However, reaping the benefits of anticipated science and technology advances will require that we develop appropriate considerations about the future of humans at the individual, collective, and planetary levels. To this end, the "Philosophical Lens" section extends initial insights from the previous editions of the Radar. Building on expert knowledge from an inclusive and diverse panel of leading philosophers collected through individual interviews, it reflects on how the science and technology advances anticipated by the Radar might transform who we are as humans, how we live together as societies, and how we relate to the planet.

By reflecting on the transformational potential of anticipated science and technology advances and the fundamental questions they raise, the Philosophical Lens has three main roles. First, it makes the underlying assumptions of these advances explicit by exploring their central points of tension and how they challenge the status quo. Second, it provides frameworks for making sense of these advances from the individual, the collective, and the global perspectives. To do so, it assesses the need to develop new concepts and reframe our questions about the individual, the collective, and the planet in light of said advances, while always eschewing simplistic answers. Third, it aims to help co-shape the environments that will facilitate the deployment of these science and technology advances toward shared goals.

To fulfil its roles, this contribution acts in the spirit of an "honest knowledge broker". In other words, we will always seek to open the solution space for future legal and regulatory frameworks of science and technology by expanding the scope of alternative choices available to decision-makers and relevant legitimate actors. Thereby, our purpose is to provide the elements to initiate debates about opportunities "to use the future to build the present" over the next two decades or so.

Who are we, as humans?

Science and technology advances described in **Quantum Revolution & Advanced AI** and **Human Augmentation** will radically transform our human condition at the individual level. These transformations will involve two core aspects of who we are as humans: our minds and our bodies. In doing so, they will compel us to rethink our concepts of the properties that we might have taken to be typical of us as humans and central to how we individuate ourselves. Such concepts include rationality, intelligence, consciousness, autonomy, agency (whether moral, epistemic or other), control, and identity (race, gender, etc.).

As an example, rational intelligence in the Western tradition has long been viewed as distinctively human (Aristotle's *zoon logikon*) and was implicitly paired with other typically human properties such as consciousness and understanding. But nowadays, non-conscious machines lacking any understanding can outperform human rational intelligence at sophisticated problem-solving tasks, thus prompting humans to acquire new heuristics by learning from the machines. This calls for a fundamental rethink of our very concept of rationality and what makes it so supposedly distinctive.[1] Along these lines, future massive offloading or delegation of "non-basic" human cognitive abilities to technologies will forever increase the need for such careful reassessments.

Rethinking the concepts at the basis of our understanding of who we are as humans invites us to reflect on the purported uniqueness of our human condition. What will be important to keep in mind in this regard is that all these basic human concepts are always value-laden. For instance, agency and individual autonomy are essential parts of contemporary human rights.[2] All these basic human concepts thus come with a normative bearing that tends to crystallise into ideals endowed with a standardising power (e.g., ableism, sanism, ageism, etc. in the case of health-related values connected to **Human Augmentation**). And as such, they can be discriminative and exclusionary too — like the very concept of a human itself; the granting or denial of human status has served to justify and maintain oppressive systems throughout humankind's history.

A key question at the individual level will then be to consider whether we might want to preserve certain properties, or a combination thereof, as the sole remit of human beings — asking in which context(s) and for which task(s) — and if so, which would these be? As we hinted at in the previous editions of the Lens, a possible way forward to tackle this key question would be to adopt a pluralistic strategy whereby we would make room for a "de-anthropocentred" variety of said basic concepts, performing differently at different tasks and in different contexts, and which would then no longer be distinctive of us as humans — had they ever been. For instance, we might have artificial or computational creativity alongside human creativity without the latter being genuine while the former is counterfeit. Thereby, we might be able to better create distinct spaces for human-artificial collaboration. While such hybrid spaces in the domains of creativity, decision-making, emotion, problem-solving, etc. will no longer be specific to humans, we might still want to prioritise instances of human involvement in these activities. One challenge this would raise is how to avoid "speciesism" when focusing on human instantiations. If we might want prioritise concerns for our fellow human beings, will this always result in discrimination against non-human agents with which we may lack kinship relations?

Considering the normative bearing and standardising power of these concepts, a challenge for us, as humans, will be to ensure their equal bestowal among individuals while striving to preserve a diversity of norms and ideals across cultures. At the same time, it might offer a tremendous opportunity to revise our basic ontological categories and oppositions — for example, subject vs. object, natural vs. artificial, humans vs. machines — towards a more respectful and integrative reality. In this context, it is not so much "who we are, as humans" that might matter anymore (in the search for some putatively "essential" properties), but "how we are, as humans, in the era of robots, gene editing, and augmented reality" — that is, in a world where artificially designed interfaces continuously interfere with our individual condition, as humans.

How can we all live together?

Science and technology advances described in **Advanced Artificial Intelligence and Quantum Revolutions** first and foremost, but also in **Eco-Regeneration and Geoengineering** more indirectly (as well as in Human Augmentation to a lesser extent), will radically transform the human condition at the collective level. These transformations will primarily concern the relational dimension of our human condition, that is, our "being human through others" (as per Ubuntu philosophy),[3] our "political animal" condition (following Aristotle), or our "relational self" (in the Confucian tradition).4 In so doing, they will incite us to rethink the concepts and principles at the basis of our social interactions. This will involve our interpersonal relationships in a very concrete way via notions such as responsibility, accountability, trust, property, sovereignty, security, friendship, or (group) privacy. At a more abstract level, it will involve our social institutions via notions such as democracy, justice, or citizenship.

The reason for these expected radical transformations is that we, as humans, are both socially and technologically interdependent beings, and that technological artefacts, on the other hand, are always embedded into socio-anthropological contexts made up of collective practices, norms, and values, which give these artefacts their cultural meaning.[5] This complex relationality of who we are at the collective level implies that changes in our technological environment will reflect on our social structures and practices from a specific cultural perspective and thereby eventually affect our human condition. This is reminiscent of the previous Lenses. What might be specific to the current and coming digital ages in this regard is that emerging digital technologies — qua information and communication technologies — have the potential to directly target human basic social structures and practices at the most fundamental level. The unprecedented scale of emerging digital technologies such as general-purpose artificial intelligence6 combined with future technoscientific convergence trends means that this radical transformational potential might be pervasive across all domains of our human condition at the collective level.

As with the individual level, the radical transformations of our human condition at the collective level by the science and technology breakthroughs anticipated in the Radar will challenge our most basic ontological categories, for instance, via the blurring of the real and the virtual or via the introduction of new kinds of non-human agents in our social realities, as we already noted previously. But emerging digital technologies specifically will also ever more alter the interindividual structures and dynamics of our communication environments (e.g., via echo chambers, epistemic bubbles, or group polarisation),[7,8] putting at stake the key concepts and principles of our interindividual relationships we alluded to above (trust, privacy, friendship, for example). Likewise, emerging technologies in general will transform how our social institutions' norms, values, and ideals are implemented on the ground, for instance, via the enforcement of policing strategies by ever more powerful surveillance technologies. In turn, these transformations of our social interactions and collective practices will feedback on the various dimensions of who and how we are, as humans, at the individual level, such as our well-being and mental health.

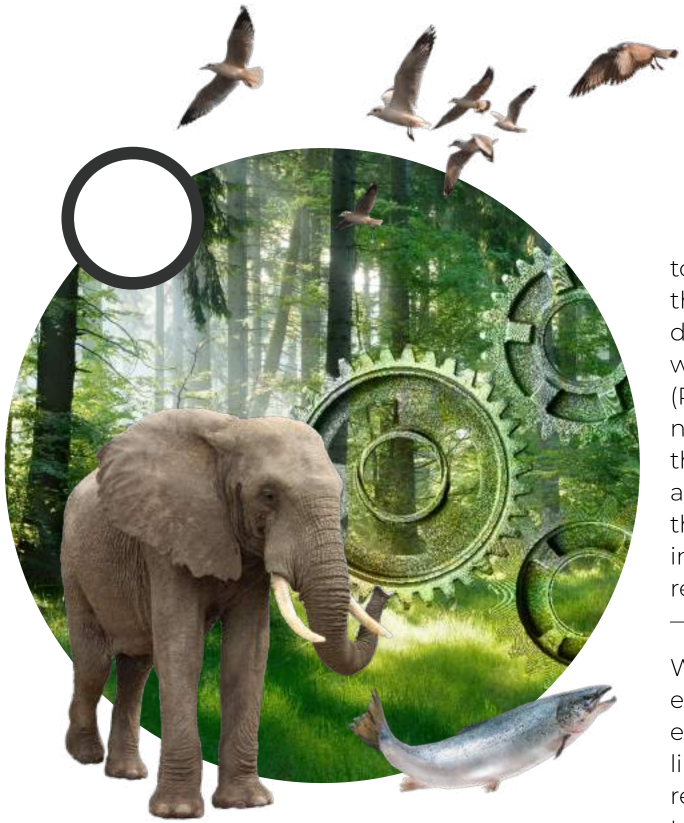
A key question will then not only be what but also how technology can be deployed to help reduce inequality, improve well-being, and foster inclusive development, as GESDA aims to do. In other words, which frameworks could we use to ensure the inclusive, responsible, and sustainable deployment of emerging technologies at the collective level? Tackling this key question will require improving

our understanding of our social and technological interdependent relationships as individuals. We might have to acknowledge the limits of the individualistic conception of the self as independent and autonomous, which is at the basis of modern Western culture, and complement it with a relational conception of autonomy[9] by which humans, as individuals, realise their autonomy through their relationships with others in socio-technological environments — or "socio-technical systems".[10] In this context, technology would not primarily serve the indefinite extension of the modern individual's limitless free will anymore but could aim at shared goals.

In this spirit, gaining a new understanding of our socio-technological relationality as humans would be an opportunity to democratise technoscientific research and innovation. In a socio-technical system, sensitivity to societal impacts is key, from the early phases of the design of the technology, even at the anticipatory stage, and then along the complete life cycle from technological deployment to dismantling and replacing. Inclusive, participative, and deliberative processes running throughout all development and use stages of emerging technologies would thus help foster their inclusive, responsible, and sustainable benefit across humans at the collective level. At the same time, because of the potential implications of these technologies for how we are at the collective level (in terms of well-being, for example), the advancements anticipated by the Radar will invite us to consider the structures of ownership and control that we, as societies, ought to set up. This would require overcoming current "techno-power" systems essentially driven by financial and political incentives. Without such a shift in the socio-technological relationality of our human condition at the collective level, it is indeed unlikely that the science and technology advancements anticipated by the Radar will align with GESDA's widely shared ambition to help reduce inequality, improve well-being, and foster inclusive development.

How can we ensure the well-being of humankind and the sustainable future of the planet?

Considering their environmental cost, most science and technology advances anticipated by the Radar will indirectly transform our human condition at the global level of our relationship to the planet. One consequence of anthropogenic environmental disruption, in general, will be the increased integration of the external environment into our very own human condition. This integration will proceed both from an environment-to-human direction, because of the increased individual and collective insecurity resulting from the foreseeable risk of ecological disasters, and from a human-to-environment direction, on the other hand, via the development of ever "smarter" environments. Breakthroughs in **Eco-Regeneration and Geoengineering** science and technology designed to address and mitigate the risk of ecological disasters will be of paramount significance: the environmental crisis will put even more pressure to deploy radical (and costly) technology solutions



to avert disaster. Through the deployment of these scientific advances and technologies, the dichotomous human-environment relationship, where humans are "the measure of all things" (Protagoras) and "the masters and possessors of nature" (Descartes) ruling "over the fish in the sea and the birds in the sky, over the livestock and all the wild animals, and over all the creatures that move along the ground" (Genesis 1:26), might eventually transform into a more responsible, sustainable, and inclusive relationship between humans and the environment — a "de-centring" of our human condition.

While challenging human-centredness toward a more ecocentric perspective, a key question posed by climate engineering technologies will then be to consider the limits of our relationship to nature as an instrumental resource under our control. Here, a challenge will be to negotiate an acceptable trade-off between the recognition of nature's intrinsic value and the need for us, as humankind, to preserve a certain degree of control over nature. And in doing so, we will have to demonstrate epistemic, moral, and ontological humility by recognising that we ultimately have no way out of our human condition in how we come to know, value, and belong to our environment. In the Anthropocene, the concept of environmental catastrophe can only be considered in terms of the human being capable of representing it. This subtle combination of anthropocentric humility and "de-centredness" might be decisive if we want to transition from a control-and-domination driven to a more sustainable, responsible, and inclusive relationship with the planet.

On a more practical note, the sustainable, responsible, and inclusive deployment of technologies to ensure the well-being of humankind and the sustainable future of our planet will presuppose normative frameworks based on public interest. Another challenge for human societies at the global level of their relationship with the planet will then be to find principled ways to distribute the costs and benefits of climate change, including climate engineering technologies' responses to anthropogenic environmental disruption if the cost and benefits of these technologies are not to exacerbate existing inequalities. Public discussions about such cost/benefit trade-offs along with the appropriate public control over technology usage on the planet will be needed to avoid an increased climate divide between citizens, companies, or countries. Our human condition at the global level of our relationship to the planet might thus ever more become a (geo)political issue above all.

Transversal observations

The Philosophical Lens reflects on how the science and technology advances anticipated by the Radar might transform who we are as humans, how we live together as societies, and how we relate to the planet in light of GESDA's fundamental and overarching questions. Now that we have considered each level in turn, we might take a step back and ask what, if anything, is distinctive about the science and technology advances anticipated by the Radar in comparison to similar transformational patterns in the technoscientific history of humankind. At this stage, a few observations crossing these three levels can be drawn.

On several occasions, we have highlighted the radical transformational potential of the science and technology advances anticipated by the Radar. However, it might not be the "metaphysical" nature of all three levels that will be transformed by emerging technologies as much as their concrete realisations. For instance, individual human lives will be radically transformed by emerging technologies, not by any putative human nature — whatever it might be. In this regard, emerging technologies might merely reveal, make more salient, and increase, implicit aspects of our human condition. As an example, **cognitive enhancement** technologies might make it more obvious that human cognition is and has always been an extended, distributed, and collective activity — that is, a socially embedded activity distributed among a collective of individuals whose cognitive processes heavily rely on external technological devices.[11]

From a transversal perspective, a striking fact about the revelatory power of emerging technologies is that they tend to increase, and make more salient, existing entanglements between the individual, collective, and environmental levels, through interdependencies and feedback loops. Specifically, the more transformational a technology, the more its impact will permeate across all three levels, simultaneously disrupting the most basic concepts of human self-understanding, social interrelations, and ontologies. For instance, data-driven intelligence transforms how we are individuated through algorithmic group affiliations, which in turn requires superseding an individualistic conception of privacy by a collective one, in order to eventually protect the individual's autonomy and identity.[12,13] Will it be possible to keep the "founding principle" that nothing should interfere with the individual's ability to take responsibility? A critical challenge in this regard will be to strike an appropriate balance between the integration and distinction of all three levels toward more respectful boundaries.

Overall, the transformational potential of the science and technology advances anticipated by the Radar is unprecedented in its scale and pace. For our human condition at the individual, collective and global levels, these anticipated science and technology advances might be more pervasive and immersive than ever before. They might also continually increase the mediation of our interpersonal and human-world relationships by technological devices and conversely diminish direct human-to-human or human-to-world interactions. Due to their intricate complexion, these transformational features of anticipated science and technology advances will involve "wicked problems" at all three levels of our human condition — that is, incomplete, contradictory problems with complex interdependencies and no unique answer nor definite stopping point, but whose solution creates or reveals new problems instead (such as security and trust in the context of technology-mediated interactions).[14] This will entail an increased unpredictability in decision-making contexts, with unknown unknowns about potential secondary impacts that go beyond the foreseeable. Such situations are typically captured by the Collingridge dilemma in technology assessment, governance, and regulation, which states a double-bind quandary between an information problem and a power problem: namely, that impacts cannot be easily predicted until the technology is extensively developed and widely used, while control or change is difficult when the technology has become entrenched.15 In other words, we either have high power but low information, or high information but low power, over a given technology. Here, the challenge will be to find the right adjustment between an acceptable predictive uncertainty and a reasonable capacity to influence technology development in a socially and environmentally desirable way.

A way forward?

The apparent synchronised, global awareness of emerging risks related to some science and technology advances anticipated by the Radar may be due to their proximity (as with artificial intelligence, for example), combined with the specifics of these anticipated advances (digital environments are maybe "more" artificial than any other technology before, for example). This might give a greater ability, or opportunity, for us, as societies, to purposefully steer science and technology development toward shared, macro-level goals. However, a systemic problem remains: we presently lack appropriate environments for responsible, sustainable technoscientific research and innovation to prevail. At this point, we might need to consider realigning technoscientific research and innovation incentives to promote inclusive and sustainable global human flourishing. A preliminary approach would be to better define what "global human flourishing" could mean in future technoscientific ages. And we would also certainly have to re-envision the traditional metrics we used for the global human flourishing we will try to foster.

There is a need for new tools to address global ethical issues. A way forward would be to reinvent ourselves in relation to technoscientific environments "from the inside out", first instead of through external research and innovation policy frameworks only (such as RRI or ESLA),[16,17] and further, to then derive appropriate normative principles from a much deeper understanding of who we are, as individual and collective, in a global context — a "global ethics," as we called it in the previous Lens. Notwithstanding complex cultural differences and geopolitical factors, the paradigm shift from an individualistic to a relational conception of autonomy, where autonomous individuals are socio-historico-technologically situated and interdependent across space and time (including from cross-cultural and intergenerational perspectives), would help move away from dominating ethno- and anthropocentrism toward a more inclusive and sustainable integration of humans, technology, and the planet.

In turn, this paradigm shift might change how we think about normative issues in science and technology ethics, policy, governance, and regulation. Beyond the "Design for Values" movement, it would allow an inclusive, participatory, and deliberative democratisation of the technology life cycle, from design to replacement via development and use. In this context, education will be key to improving users' technological literacy at the global level. Thereby, we might ensure better control, prevention, and resistance against problematic aspects of technology (e.g., artificial intelligence's built-in biases), minimise divides in terms of power, control, and access to technology, and increase awareness of intergenerational responsibility. But this might not be enough to further responsible, sustainable technoscientific research and innovation. Considering the multi-faceted dimension of the science and technology advances anticipated by the Radar, collaborations across domain-specific technoscientific disciplines and more holistic technoscientific curricula (including humanities and social sciences) will also be critical for experts to elucidate the core normative implications of using general-purpose technologies in multiple fields while avoiding endlessly reinventing the wheel. Keeping in mind GESDA's three fundamental and overarching questions throughout the deployment of these advances would help them "ultimately lead to a better life for humanity on a healthy planet," in terms used in a previous Radar.

In view of the science and technology advances anticipated by the Radar, the time might thus have come to "re-envision ethics" and our normative frameworks, as we suggested in the previous Lens. Combining a top-down implementation of normative principles that drive incentives for technoscientific research and innovation with bottom-up inputs that relay demands from citizen communities might pave the way toward a "positive" notion of ethics whereby normative principles would be integral enablers of technology for it to become a public good. By designing environments that can facilitate ethical choices, actions, or processes, we might eventually be in a position to anticipate and up-manoeuvre science and technology's implications at the individual, collective, and planetary levels. While it is exciting to think that we can engineer the future we want, we also have to consider what we might lose. Public and informed discussions of trade-offs in such a complex and uncertain space will be central to the honest brokering of science and technology.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The Geopolitical Lens: **The Future of Peace and War**

A report based on the 2023 discussions held at two high-level workshops in Geneva and New York. Full details of the workshops, together with full-length reports, can be found at radar.gesda.global. We gratefully acknowledge the Rockefeller Brothers Fund's support for the second workshop in New York.

Introduction: Anticipating the rise of tensions

Fragmentation, friction and uncertainty are becoming more commonplace. One result of this is unpredictability within many countries and between major power blocks. Often resulting in violence or conflict, these tensions can be aggravated by climate change and competition in the field of digital technologies. Therefore, anticipation and foresight informed by science and technology are critical in the field of peace and war. Such foresight allows the anticipation of a variety of futures. On the basis of these, it becomes possible to create and implement appropriate programmes and strategies to prevent or contain conflict, and to advance the more promising approaches to peace.

Applying GESDA's anticipatory methodology to mapping the future of peace and war involves a cross-regional, multi-disciplinary approach involving social and political scientists, as well as historians, technology experts, economist and climate scientists. Unlike anticipating breakthroughs or new applications in the field of technology, foresight in the fields of social and political sciences entails more fragile projections with a larger margin of error. A wide range of uncertainties, unanticipated tipping points and black swan events can come into play at any moment, transforming anticipated scenarios.

Ultimately, while it should be based on relevant science, longer term anticipation in this field also requires some exercise of the imagination. As a result, this is far from an exact science, and one that is constrained by our tendency to anchor scenarios in what is familiar from the present — the "tyranny of the now" — which tends to limit a required element of creative thinking. Nonetheless, the difficulties can be partially mitigated by acknowledging them and also by exploring counter trends, peripheral trends that may become dominant, as well as known unknowns.

Methodology: imagining a range of possible futures

The future cannot be predicted. Instead, we must use foresight and anticipation to think about a range of possible futures (the plural is important), as a basis in the present to help us steer towards a more desirable future.

There are, of course, issues concerning who gets to define what is a "desirable" future and the broader legitimacy of what is considered desirable. What is seen as "desirable" will vary depending on the viewing point. However, when it comes to issues of peace and war, there tends to be consensus that war, conflict, and other forms of unrest that restrict human wellbeing, equality, security and freedom to thrive are universally accepted as undesirable, especially by those across the globe who are the survivors and victims of violence and conflict.

To anticipate possible futures related to peace and war, while maximising the chance to influence policymakers, participants in the Geneva workshop decided to formulate a variety of scenarios — "portraits" of possible or probable futures — through construction of a two-axis framework. This methodology, borrowed from the academic realm of future studies, creates a way to analyse four distinct "families of futures", with one family in each quadrant.

The vertical axis of this scenario framework represents the continuum that separates peace from war (and/or extreme violence and/or mass violations of human rights). Recognising that we are on the cusp of major societal changes illustrated by the unprecedented speed and reach of science and technology breakthroughs, the horizontal axis focuses on how new scientific and technological developments and ruptures will impact the distribution of power in, and between, societies. To go deeper, we must first give space to the issue of definitions.

Precautionary considerations: the vital nuances of peace, war, science, technology and power

Focusing first on the vertical axis of our scenario framework, we note that any investigation of the continuum between war and peace necessitates a clear and nuanced definition of war, conflict and peace.

Much of our present world writhes and persists in the grey zone between full-blown war and an ideal of quality or "positive" peace. Moreover, a mere absence of war, or a so-called "negative peace", is not an ideal. Defining peace simply as the absence of visible conflict can conceal states akin to war where there is widespread violence, systemic suppression of human rights, terrorism, threat from organised crime groups and, at worst, genocide.

Additionally, we have to consider the importance of "legitimacy" in decision making. This is a central component in the definition of peace: conflict can escalate to violence when institutions cannot resolve differences between actors or stakeholders in a manner that the society or societies concerned broadly recognise as legitimate.

Based on the accumulation of academic expertise in this field, the agreed working definition of peace includes the following three dimensions: respect for physical integrity, a common readiness to resolve differences through peaceful means broadly recognised as legitimate, and the pursuit of equality values — while acknowledging that different societies have different levels of tolerance for inequality.

The horizontal axis, which relates to issues of technology and power, involves more complexity. Technology's pervasive influence within society can be likened to a climate that surrounds and pervades all aspects of modern life, and influences people's sentiments and behaviour. Contemporary and emerging technological developments and innovation have proven as transformative for the world as the invention of the printing press and the 19th century industrial revolution.

Emerging technologies have changed the way in which we access, perceive, and share information, and therefore have altered the foundations of political legitimacy and related institutions. This has already had wide-reaching and disruptive impacts, especially on democratic political systems with minimal online content moderation. AI-powered tools enable the generation of photorealistic images or video, and targeted polarising narratives can be used to accelerate these dynamics. The easy access to, and geographic immediacy of, digital technologies also allows for often untraceable cross-border disruption on a massive scale. The result is an increased possibility of greater political fragmentation and violence within and between societies in decades to come.

Should existing and emerging technologies such as social media and artificial intelligence continue to undermine the legitimacy of institutions, violence and conflict will continue to increase, as national and international institutions rooted in another era become increasingly unable to manage differences peacefully. Moreover, the growth in so-called cerebral-cortex warfare, where actors use emerging technologies to manipulate collective sentiments and evoke violence, is likely to increase. Such a trend could be exacerbated by breakthroughs in areas related to human enhancement, such as cognitive technologies or genetic engineering. Furthermore, as control over emerging technologies continues to be an important source of political power, intra-state rivalry over control and access may become a growing driver of instability within the international system.

In this context, major technology companies are not neutral actors who passively deliver technological tools. By virtue of a deficit in public policy and legislation, and due to their social, economic and political impact, some large tech companies now wield power comparable to nation-states, and actively participate in matters of conflict, peace, and security.

However, new technologies also afford us instruments and channels to further global peace. At a practical level they can help make peace processes more inclusive and hence more durable. They can help read threats faster, thus enabling earlier action for resolution or containment. They can provide a universal, real-time lens on human rights abuses furthering accountability processes. They also give rise to global, often youth-centred, cross-border movements that further action on issues such as gender equality and climate change, which in themselves can exacerbate conflict if given no attention.

The power of emerging digital technologies is proportional to the amount of data to which they have access. In the future, new capacities to collect, store, and communicate data and information are likely to reshape the distribution of political power. Thus, access to data itself is becoming a source of significant power — or lack of it. International and national regulation of access to, ownership and use of data will be an essential component of stalling or reversing the upward trend of local and global friction and conflicts.

As well as these clearly visible technology-driven issues, a number of technological issues sit behind global mega-trends, affecting the future landscape of conflict. For instance, emerging technologies such as cyberattacks, autonomous weapons, AI-enabled disinformation, and bio-engineering are creating new pathways and avenues for conflict. These can be deployed alongside conventional weaponry during war, or used alone for low intensity conflict which can disrupt infrastructure and cause loss of life. Should regulation, including global arms treaties such as that on Lethal Autonomous Weapons, not be deployed to constrain their use, emerging technologies will be increasingly used to destabilise and manipulate opponents even when "hot" wars are not waged. Low-level conflict in cyberspace is already a geopolitical reality.

QUALITY PEACE

Q1: High Concentration of Power, Relative Peace

- States and companies with high concentration of power over technology
- Tech-dependent and tech savvy regimes - profitable and stable for those with access to power/who behave
- Tech used by these states as a way of maintaining control and projecting power abroad
- Target-rich environment “subversive” elements either internally or externally, but big investment in hardening cyber defenses
- Big investment in R&D to maintain tech advantage
- Hegemonic companies with close contact to governments/military industrial complex
- Use of tech may be unequal in the population, with some cities and sectors having high tech penetration, while others very little
- Tech benefits the elite and control the public

Q2: High Diffusion of Power, Relative Peace

- High penetration of tech in society
- Strong regulatory framework
- Tech seen as public good, part of governance and improving way of life
- High levels of security but also transparency and data protection
- Participatory tech for governance rather than tech as control
- “Smart” military (tech used for gathering intelligence)
- Use of tech for enhancing supply chain efficiency
- Use of tech enhancements for the betterment of society
- Tech used to enhance cooperation between sectors and between countries (i.e., sharing of information, protection of global commons, innovation, etc.)

HIGH CONCENTRATION OF POWER

HIGH DIFFUSION OF POWER

Q4: High Concentration of power, Relative Instability

- Competition over scarce resources needed for tech, and use of technology to promote national or group agendas which causes intra- and inter-state instability
- Inequality between those with access to information and technology and those without
- Artificial Intelligence reduces human agency, increases control, and increases instability
- Technology used as a way of controlling certain population groups or weaponized against foes (internal and external)

Q3: High Diffusion of Power, Relative Instability

- Instability and atomisation
- Population has access to technology, but uneven
- Government has less ability to regulate technology use/abuse
- Innovation of technology - for better or for worse, higher entrepreneurial and adaptive society/companies
- Empowered civil society making effective use of OSINT
- Malign non-state actors making use of technology for their political and financial gains, potentially destabilising
- Tech as an enabler of organised crime
- Innovation without sufficient regulation/control

WAR

This is particularly problematic because it is highly likely that the spread of access to these technologies will remain uneven. What's more, these technologies have the potential to be highly destabilising if introduced within communities and states that lack experience, institutions and legislative guard rails to mitigate their harmful impacts. Varying access to new technologies within and between states can also exacerbate inequality, which can, in turn, nurture conflict.

As the world enters an era profoundly shaped by this new industrial revolution — which brings with it risks of fragmentation, polarisation and new, highly accessible means for promoting violence — geopolitical risk and societal disruptions will grow. This is made particularly problematic by the fact that pre-existing technologies, such as those for nuclear or biological warfare, have already led to unparalleled destructive powers. Humanity's "margin for error" has arguably never been narrower.

With all this said, it is far from clear how new technologies will affect the distribution of power between and within societies. It may be that current trends are causing an evolution towards power concentrated among a small number of actors who retain control over emerging technologies (such as states, and large tech companies). An alternative is that, given the declining costs and barriers for accessing technology, power will become increasingly diffused among a multiplicity of actors. It is worth noting that both trends can co-exist, and that peace and conflict are possible under both scenarios.

It is also worth noting that the concentration and diffusion of power may take place simultaneously in different parts of the world and potentially within different groups in societies. Concentration of power among only several powerful states could encourage political fragmentation and fragility in others. For example, emerging technologies could offer groups such as organised crime networks increased power within more fragile states that are unable to regulate or contain malign applications of these technologies.

Despite these multifaceted unknowns about what the future of technology will bring, one pivotal question emerges: will technology cause concentration, or diffusion, of power? For this reason, one end of the technology axis in our scenario framework reflects high concentration of power through the use of new technologies; the other reflects a high diffusion of power through the democratisation of technology.

Outcomes: populating the four quadrants

Having defined the two axes of the scenario framework — with a vertical axis representing the continuum of peace-war, and a horizontal axis measuring how the appropriation of technology is used to either channel or diffuse power — it becomes possible to populate each quadrant with anticipated families of futures.

In the upper-left quadrant (Q1), for example, the use of technology to underpin power results in various types of (relative) peace. Here, one can imagine tech-dependent and tech-savvy states, companies, and/or other non-state actors with a high concentration of power, agreeing among themselves to manage rivalry without open conflict. Yet, a high concentration of technological power also makes it more likely that access to technology is not equitably distributed. Across multiple units of analysis (e.g. local, intra-state, regional, international), this could mean that technology benefits a few states as well as global elites, while possibly also being used to manipulate and control — all while maintaining relative peace.

The boundaries of each quadrant must be understood as permeable. The relative peace in Q1, for example, may deteriorate to relative instability in Q4 (lower-left) were states (or groups within states) to find themselves in more conflictual relationships with each other.

Indeed, Q4 represents a family of futures where power is highly concentrated and the prevailing situation is one of conflict, instability, and/or violence. On the geopolitical front, one might imagine the culmination of a cold-war-like trajectory between tech power-players erupting, giving rise to outbreaks of violence. In this possible future, competition over scarce resources needed for technological development may become more salient and danger-ridden. Technology will be increasingly weaponised by the limited actors who have access and control.

Q4 may also be characterised by population control with few human rights guarantees, less respect for physical integrity of citizens, and a deficit in legitimised decision-making. Should technology be used to concentrate power, the fact that it is increasingly interwoven into all levels and facets of governance could result in an abundance of political systems characterised by strict and intrusive control over citizens. Here, one might imagine technology-driven consequences such as AI-driven surveillance technologies, digital identity manipulation, and uncontrolled human augmentation.

Q3 (lower-right) represents a family of futures similarly riddled with conflict and violence. Yet, the ability to appropriate technology for power is widely diffused. This would likely create different relationships between states, technology companies, non-state actors, elite structures, and populations than in Q4 — and immense competition over the information space.

There are various possible consequences here. With power in the hands of the many instead of the few, organised crime syndicates, terrorists and other violent non-state armed groups may pose new challenges to state leadership, especially without the existence of legitimised, inclusive institutions capable of effectively channelling grievances. Populations — particularly youth — similarly empowered by access to advancements in science and technology may enter into new types of struggles with elites; one might imagine, for example, a new generation of citizen hackers that looks to destabilise certain institutions or corporations.

The relative instability of Q3 does not suggest, however, that such a family of futures will not also see greater efforts to use technology for peace. The introduction of drone surveillance on the border between Rwanda and the DRC has dramatically reduced violence and trafficking, for example, and as indicated above, trans-national social media-driven movements have contributed to action against climate change and gender discrimination, reducing contributors to conflict.

In the midst of instability, Q3 may also see a civil society leveraging its own access to open-source intelligence (OSINT), or unregulated innovation contributing positively to peace. Additionally, access to technology may present new opportunities for political protest for disenfranchised groups, which could end in positive or adverse outcomes depending on other contextual factors.

Moving up the peace-war continuum from Q3 to Q2 (upper-right) would likely require strong, agile, innovative regulatory frameworks and capable institutions. In Q2, a high diffusion of power is paired with relative peace, and a multiplicity of powerful actors find avenues for cooperation.

In all four scenarios there will be a high penetration of technology in society. However, high levels of security, transparency, and data protection in Q2 could limit abuse and exploitation. Potentially viewed as a public good, technology may be leveraged to reduce inequality and exclusion, to improve education, health, agricultural, and small business sectors, as well as to strengthen supply chains and — for the purposes of peace and security — find increased utility in peacekeeping operations, diplomatic dialogue, and multilateral decision-making.

Ultimately, the future will likely present a complex mixing of these four quadrants. Populating this framework, however, should encourage anticipatory thinking and provide policymakers with an image of probable families of futures to enhance their understanding of the environment in which they make decisions, and what the consequences of those decisions may be over a longer period of time.

Conclusion: a call for a strengthened, innovative multilateralism and embracing of uncertainty

The course of history often takes us by surprise, with academics and practitioners alike frequently under- or over-estimating the disruptions that the interaction — and sometimes collision — of different trends and countertrends can produce. Moreover, any attempt at anticipating the future has to leave space for possibility of black swan events, which by definition cannot be foreseen. Also, a focus on technological or geopolitical vectors as drivers of change needs to be analysed in conjunction with variables such as climate change, macro-economic trends, migration and so on.

Of particular interest here, however, are the uncertainties generated by technology development. The precise nature of the technologies subject to the biggest developmental leaps over the next three decades will have profound effects on the future of peace and conflict. For example, should a small number of states achieve technological breakthroughs in particularly impactful areas (quantum computing and artificial intelligence (AI), say) and refrain from sharing them globally, the future of conflict is likely to be shaped by great-power competition. In such a scenario, those countries who lack these capabilities, or have uneven access to them, would be put at significant disadvantage. Where inequality and exclusion prevail, as many studies have shown, the likelihood of conflict is greatly increased.

The GESDA Science Breakthrough Radar® examines five families of scientific fields and related technologies, and not all of them are straightforward science-driven technologies like quantum computing and AI. For other types of technology on the Radar, such as those enhancing climate adaptation and resilience (negative emission technologies, energy storage, and nuclear fusion, for example), an uneven and partial spread could result in a lack of urgency to avert global climate breakdown. This would likely exacerbate existing inequalities, fuelling conflict and humanitarian catastrophes. In turn, this would almost certainly trigger migration crises, greater global instability, and spillover effects, even for states which do achieve a green energy transition. Even advances in technologies with a multiplicity of benign applications — such as pathogenic biology and neuromodulation systems — could open new space for conflict.

On a more positive note, states may also respond to disruptions — whether engendered by new technologies or global challenges such as climate breakdown — by taking better advantage of emerging technological tools and capacities to further peace.

It follows from all this that a key to harnessing the power of new technologies for peace, and containing their negative impacts, will be the human capacity to regulate the application of emerging technologies and corresponding robust national, regional and international regulatory systems.

Effective multilateralism that can act at the same pace as technologies evolve will be a vital ingredient to achieving this. It will have to happen in the face of compounding geopolitical tensions. Those states who traditionally dominated in shaping negotiations and negotiated outcomes in multilateral settings such as the United Nations will likely see their influence further diminish, relative to other individual states, groups of states and non-state actors in the geo-political ascendant. This means that the practice of pragmatism, dialogue, and mutual efforts to understand and respond to the interests of others will be essential.

In a rapidly-evolving world subject to shocks and stressors engendered by emerging technologies, and global, systemic challenges such as climate breakdown, it is crucially important that no state — and particularly one armed with weapons of mass destruction — be isolated from the international system.

Given the speed of technological developments, regulatory frameworks will also need to be agile and anticipatory. It is not possible to fully predict the nature of technological evolution over the coming decades. However, a "human-centric" anticipatory approach that uses human behaviour, and the likely utility different individuals and groups will seek to derive from new technologies, is most likely to yield results. To inform regulation, more attention and research is needed on new domains of conflict (such as cyber, cerebral-cortex warfare, and autonomous weapons systems) as well as on new instruments for peace. The interaction of peace-driven transnational youth movements, as of non-state armed groups and organised crime networks, with emerging technologies also merit further attention.

The disruptive impacts of an uneven spread of new technologies (multiplied by the uneven impact of climate, ecological, and demographic challenges) means that increased anticipation, dialogue, strategic planning, and resource transfer between developed and developing countries is crucial for peace. The goal should be to ensure that developing, fragile, and conflict-affected communities can share in the benefits of emerging technologies; and be supported to protect themselves from malign uses and impacts thereof. This will be key to preventing or limiting the proliferation of instability and violence.

Next steps: Making anticipation useful

For anticipation to be useful for conflict prevention, future scenarios ought to be considered through the lens of what needs to happen now, thereby maximising human agency and possibilities for more peaceful outcomes. This task will be the focus on this during future workshops and events under this programme of work.

The first of these is at the 2023 Geneva Science and Diplomacy Anticipation Summit, scheduled for 11-13 October. This meeting will provide a space for dialogue between science, politics, diplomacy, business, and citizens on the application of this anticipatory framework, and how it relates to the anticipation of scientific trends.

The GESDA Science Breakthrough Radar — which provides an overview of 41 science trends and breakthroughs at 5, 10, and 25 years into the future — will be used to further enrich the scenarios developed and should inform future applications of the anticipatory framework.

We gratefully acknowledge support for the New York workshop from the Rockefeller Brothers Fund.

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The Science Lens:
The Human Right to Science

The Brocher Expert Workshop on the Human Right to Science with a Focus on Health, organised by GESDA, was held from 28 November to 1 December 2022 at the Brocher Foundation in Geneva. This report offers a summary of the takeaways from the workshop.

The rapid and intense convergence of the physical, digital, and biological worlds has the potential to transform society and even human beings, for example through genetic modification or human-machine interfaces. To ensure the responsible development and use of these powerful technologies, human rights should be at the forefront of decision-making. Incorporating a human rights framework provides an opportunity for a collaborative, holistic, and inclusive approach that goes beyond the mere mitigation of risks and enables the responsible exploration of the opportunities offered by scientific and technological progress.

Of particular relevance in this context is the human right to science. The right to science has its origins in Article 27 of the Universal Declaration of Human Rights (UDHR, 1948). The right to science is furthermore protected under Article 15 of the legally binding International Covenant on Economic, Social and Cultural Rights (ICESCR, 1966), which has been adopted by 171 States. The right to science is an umbrella term for various legal provisions on science. In essence, the right to science obliges States to:

- recognise the right of everyone to enjoy the benefits of scientific progress and its applications (Art. 15(1)(b) ICESCR)
- conserve, develop and diffuse science (Art. 15(2) ICESCR)
- respect the freedom indispensable for scientific research (Art. 15(3) ICESCR)
- recognise the benefits to be derived from the encouragement and development of international contacts and co-operation in the scientific fields (Art. 15(4) ICESCR).

One area that has not received sufficient attention is that the right to science advocates for the responsible development and use of scientific progress and its applications. This goes beyond the mere mitigation of risks and requires the consideration of opportunities for benefit of scientific and technological progress. The right to science is therefore a crucial tool for anticipating both the benefits and the harms of scientific progress and its application.

Takeaways

The right to science is a living human right.

Although the right to science is a human right dating back to 1948, when it was adopted in the Universal Declaration of Human Rights (UDHR), it is important to interpret this right in a contemporary context. Human rights provisions are deliberately worded in a generic manner, to stay flexible enough to respond to new challenges and developments, and to respond to the evolving needs of society. This ensures that the right to science remains relevant, meaningful, and applicable over time. A contemporary interpretation of the right to science shows that it is indeed a suitable tool for anticipation.

The right to science should include all sciences and should not be limited to natural sciences.

The Committee on Economic, Social and Cultural Rights, in its General Comment No. 25, outlines that the term science, which “encompasses natural and social sciences, refers both to a process following a certain methodology (‘doing science’) and to the results of this process (knowledge and applications).”[1] However, some experts argue that all academic fields, including the humanities, should fall within the scope of the right to science. As such, the protection of the right to science should extend to all academic fields.

To fully bring the right to science into action, the rights and obligations derived from the human right to science need to be comprehensively identified.

To fully bring the right to science into action through its rights and State obligations, further legal research and practice are needed. Judicial and political pathways are particularly relevant for advancing the right to science. This involves lodging legal complaints to invoke the right to science before competent authorities, such as national courts, regional courts, and United Nations treaty bodies. Moreover, this can include submitting reports through the United Nations State reporting procedure or to the United Nations Human Rights Council for the Universal Periodic Review.

Freedom of science is essential for the advancement and flourishing of science. Robust safeguards are needed to protect the rights, freedoms, and independence of scientists, scholars, and researchers.

States must respect the freedom indispensable for scientific research, which is inherent to the right to science (Article 15(3) ICESCR). Scientific progress and growth require an enabling environment for research, free from undue influences of any kind, such as political or commercial interests. The imposition of regulations, such as requiring all research proposals to conform to a particular national objective or subjecting research to public approval, can violate the freedom of science.

The right to science can legitimately be limited within the parameters of human rights law.

In the framework of human rights law, it is possible for States to limit the enjoyment of human rights according to specific criteria. Certain limitations on the right to science may be necessary because science and its applications can, in some contexts, negatively affect or stand in conflict with other human rights and/or the interests of society.

The legally binding ICESCR includes a general limitation clause, as elaborated in Article 4 ICESCR, which allows States to impose limitations under exceptional circumstances only if they are determined by the law and are compatible with the nature of these rights. Furthermore, these limitations must be solely for promoting general welfare in a democratic society.[2]

While, for instance, the freedom indispensable for scientific research must be respected, many aspects of the freedom can legitimately be limited by the State under the parameters of human rights law and among scientists themselves.

2.3
Healthspan Extension
Consciousness Augmentation
2.4
Future Therapeutics
2.6
Human Applications of Genetic Engineering
2.2
Organoids
2.5
Cognitive Enhancement
2.1
Collective Intelligence
1.5
Augmented Reality
1.4
Unconventional Computing
1.3
1.2
Advanced AI
1.1
Quantum Revolution & Advanced AI
Synthetic Biology
The Science of the Origins of Life
5.5
5.4
Complex Systems Science
5.1
5.2
Democracy-affirming Technologies
Future of Education
5.3
Future Economics, Trade and Globalisation
4.2
Advances in Science Diplomacy
Earth Systems Modelling
3.2
3.3
Future Food Systems
Space Resources
3.4
3.6
Solar Radiation Modification

Science should be free from undue influence but conducted in a socially responsible manner. Socially responsible science should, in the first instance, be achieved through scientific self-regulation.

Science should be free from undue influence. However, it should be kept in mind that science is co-produced with society and therefore needs to be carried out in a socially responsible manner. Scientific self-regulation, such as codes of conduct, ethical safeguards, and rules regarding scientific integrity, can, as a first step, help ensure that science is carried out in a socially responsible manner.

Such ethical and professional standards should be consistent with human rights and consider broader societal contexts. Therefore, researchers and experts should have a collective discussion about the potential impact of their work. These experts should not be limited to laboratory scientists, but also include experts from different disciplines, such as science policy experts, social scientists, philosophers, and lawyers. This approach is similar to the Ethical, Legal and Social Issues (ELSI) movement in genetics research.

The enjoyment of the right to science can infringe upon the enjoyment of other human rights. Such conflicts require a balancing of interests and possibly limitations taken within the framework of human rights law.

The exercise of the right to science can lead to conflicts with and violations of other human rights. For example, research on genomic medicine requires large genomic datasets. However, the use of medical data required for research may conflict with the right to privacy (Article 17 of the International Covenant for Civil and Political Rights). In such cases, a proper balance must be struck between the protected interests of the human rights concerned. Therefore, as human rights can affect or conflict with other human rights, they can be limited within the parameters of human rights law.

The right to benefit from scientific progress and its applications, as well as the right to be protected from its adverse effects are both rights under the right to science.

The advancement of science can bring both benefits and potential harms. Under the right to science, individuals have a right to benefit from scientific progress and its applications. They furthermore have a right to be protected against the adverse effects of scientific progress and its applications. Although both rights can co-exist, the protected interests of the rights must be properly weighed and balanced.

States should anticipate the opportunities for benefits and risks of harm of scientific progress and its applications. Under the right to science, such anticipation is composed of prevention, precaution, and due diligence.

Under the right to science, individuals have a right to benefit from scientific progress and its applications while also being protected against its adverse effects. A balancing of both rights is inherent to human rights law and can give rise to a State's obligation to prevent and limit one human right in order to protect another. The obligation to prevent presupposes scientific certainty. Yet, States should also anticipate opportunities for benefit and risks of harm of scientific progress and its applications. Although not explicitly recognised legally, anticipation is encompassed within the current international legal framework, drawing upon the obligation to prevent harm under the right to science, the precautionary principle, and the concept of due diligence.

The precautionary principle involves taking measures to avoid or minimise risks of serious and irreversible harm, and to promote the opportunities for benefit, in cases where the scientific evidence is uncertain. Yet, the precautionary principle evolves with scientific knowledge, moving from precaution to prevention as the risk or benefit becomes scientifically certain. Thus, the precautionary principle can be seen as a trigger for the anticipation of potential harms, but also for the opportunities for benefit of scientific progress and its applications.

When taking preventive or precautionary measures, States should use their best efforts to prevent or mitigate harm in specific circumstances. This is where the standard of due diligence comes in. The assessment of the appropriate standard of conduct consists of a consideration of the likelihood of a risk, legally protected interests, and competing interests. Importantly, the opportunities for benefit of scientific progress and its applications must not be forgotten in the assessment. Prevention, precaution, and due diligence all involve an assessment of the necessity and proportionality of measures. Balancing competing interests and considering the long-term consequences of decisions are key to this process. Consequently, anticipatory measures must be necessary and proportionate to the seriousness of the risks, and ensure they do not result in disproportionate negative impacts on scientific freedom and progress, other human rights, or opportunities for future generations.

Anticipation for effective solutions can be achieved by a systemic integration or cross-fertilisation between different areas of international law.

Different areas of international law, such as environmental law, human rights law and intellectual property law, have different objectives, norms, and procedures when dealing with specific science and technology issues. This fragmentation can lead to challenges in effectively addressing these issues. By fostering a systemic integration or cross-fertilisation between the different domains of international law, effective solutions to address the complex challenges presented by science and technology along with tools for anticipation can be found.

State obligations to anticipate the benefits and harms of scientific progress must be adaptive and projective to include opportunities that benefit scientific progress and its applications.

Anticipation under the right to science goes beyond the prevention or mitigation of risks. It can also facilitate a collaborative and inclusive approach that enables the responsible exploration of the opportunities for benefit of scientific progress and its applications. The current precautionary and risk assessment approaches are insufficient in dealing with adaptive anticipation, which considers unpredictable situations, and projective anticipation, which deals with radically new futures. There is a need for new types of questions, such as "what if" questions, that explore possibilities and probabilities. Therefore, to effectively deal with anticipation, a new risk and benefits governance approach is necessary. This should be adaptive and projective to include opportunities for benefit of scientific progress and its applications.

Anticipation under the right to science can serve as a door-opener to, for example, cautiously lifting existing bans on heritable genome editing or other currently controversial issues that may be beneficial, relevant or necessary in the future.

Anticipation includes a long-term outlook that also considers future generations' interests.

Anticipation means taking a long-term view that considers the interests of future generations. Intergenerational equity in anticipation is essential in the development of new technologies and innovations that may have positive or negative effects. It is important to thoroughly assess the potential impact of our actions on posterity and to approach decision-making processes with a sense of due diligence and responsibility to avoid missing opportunities or causing harm. To illustrate, scientific progress, such as research into transgenic trees (which may not be relevant today but may become highly relevant in the future due to climate change) must be allowed to continue. However, scientific progress must be carried out in a socially responsible manner and with due diligence. It is therefore essential that scientific progress takes place in a socially responsible and intergenerational equitable way.

Institutional capacity building and the use of scientific expert bodies are crucial for anticipation.

To manage risks associated with scientific progress and its applications, appropriate institutions must be established, and their capacities developed. Clear roles and responsibilities for those involved in this process must be defined.

While interdisciplinary bodies may not always be necessary for legal contexts, expert scientific bodies can assist legal procedures by providing expert testimony. Legal entities, such as courts and United Nations Committees, may have limited capacity and expertise in risk management and are obliged to employ legal methods. Therefore, scientific experts play a crucial role in providing scientific input. The establishment of expert bodies or science-policy interfaces, such as the Intergovernmental Panel on Climate Change (IPCC), should be encouraged to effectively assess the danger and potential harm of scientific progress and its applications. However, this does not imply that scientists are the ones making decisions on what is considered appropriate risk management. The decision on the measures that are needed is a shared activity that is determined by society, courts, and other relevant entities.[3]

As a human right, the right to science requires diversity and non-discrimination.

The epistemic strength of science comes from the diversity of individuals, which requires inclusive participation and decision-making. To achieve this, research ought to encompass contributions from and for individuals of varied backgrounds.

The right to science is furthermore reliant on the principle of non-discrimination. According to Article 15(1)(b) ICESCR, all individuals have the right to enjoy the benefits of scientific progress and its applications. Therefore, equity concerns associated with the distribution of risks and benefits linked to innovation must be addressed in advance. Anticipation under the right to science also involves considering potential disparities in access to scientific progress and its applications by potential users and engaging all individuals in participation at both national and global levels.

The right to science includes a right to participate in scientific progress.

All people — not only researchers — are entitled to participate in scientific progress and its anticipation. This involves more than just enjoying the benefits of scientific progress: it also involves actively contributing to and participating in scientific matters. Participation plays an important role in identifying and addressing both the risks and benefits associated with scientific progress. Participation also helps to ensure an equitable and anticipatory co-governance. One way to participate is through citizen science, where individuals provide data and other inputs directly to research studies or participate as research subjects. However, the right to participate in scientific progress does not extend to a right to determine research objectives, as this could potentially impinge upon the necessary freedom for scientific research and progress.

The right to science can serve as a lawful public interest in certain circumstances.

The right to science can be considered a lawful public interest in certain circumstances. As a result, the right to science may be invoked to authorise measures such as the disclosure of private health information in specific situations (in public health emergencies, for example), in order to further scientific advancement. The invocation of the right to science as a public interest may in turn conflict with other human rights, which may lead to a limitation of these rights within the parameters of human rights law.

To ensure the full enjoyment of the right to science as mandated by human rights law, governments have a responsibility to regulate the private sector.

Given that science is a public good, it is important that the private sector involved in scientific research also actively supports and promotes the right to science. However, the private sector has considerable power in areas such as innovation, access to science and its applications, and policy. To ensure the full realisation of the right to science, it is the responsibility of States to oversee and regulate both for-profit and not-for-profit entities. As these entities operate within the framework of State laws, it is in the power of States to encourage or even mandate certain private sector behaviour in relation to the protection of human rights.

The full flourishing of the right to science requires co-operation across all scientific disciplines and knowledge systems.

To ensure the uptake and anticipation of potentially beneficial technologies, it is essential to recognise the importance of collaboration across all scientific disciplines and knowledge systems, particularly at the interface between indigenous knowledge and science. A lack of trust in science can hinder progress and anticipation. To rebuild trust, it is important to respect indigenous cultural norms and protocols and to acknowledge and provide redress for past human rights violations by scientific organisations. Capacity-building is essential to overcome the inequitable distribution of resources and power that leads to the marginalisation of indigenous peoples and other disadvantaged groups.

International co-operation is an essential basis for anticipation, involving collaboration among governments, scientists, and international organisations.

Active co-operation between governments, scientists, and international organisations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO) is necessary for anticipatory measures to be taken. The importance of international co-operation is underlined by Article 15(4) ICESCR, which describes the benefits to be derived from the promotion and development of international contacts and co-operation in the field of science. International co-operation is also inherent in the safeguarding of scientific freedom and the promotion of scientific advancement. Fostering international co-operation requires embracing diversity and non-discrimination to nurture collaborations and partnerships, not only with countries in the global south but also with diverse knowledge systems, including indigenous knowledge.

Written in collaboration with Gérard Escher, GESDA. Thanks to Katja Achermann, Andrea Boggio, Yvonne Donders, Helle Porsdam, and Sebastian Porsdam Mann for their valuable feedback on earlier versions of this report. The final version is the sole responsibility of the author.

Actions & Debates

Taking the Pulse of Society

Mamokgethi Phakeng
Chair GESDA Citizens Forum
Professor of Mathematics Education and Former Vice-Chancellor, University of Cape Town, South Africa

GESDA Digital Pulse of Society

The advances we cover in the Radar are reshaping, or will reshape, how we see ourselves as human beings, the way we interact with each other and our relation to the environment – and that means their applications, potential and implications are discussed broadly.

We monitor public debate using a machine learning algorithm that analyses conversations about the emerging topics presented in the Radar on the world's media and online social platforms. We aim to understand how discussions and sentiments about science and technology issues vary between regions, age groups and topics and to help identify the fields that require a broader societal debate.

New for 2023, we analyse changes in sentiment and demographics across different scientific topics from 2021 onwards. This has allowed us to identify trends in the way breakthroughs are being discussed and debated as technologies evolve.

Who is going further than talk? We extend our analysis with a tool for monitoring civil society and private citizen activity around the scientific emerging topics included in the Radar. We focus on four areas of activity: raising public awareness; entrepreneurial endeavours; policy-orientated action that shapes and drives discussions in society; and direct contributions to science and technology – by biohacking, participation in clinical trials or citizen science endeavours, for example.

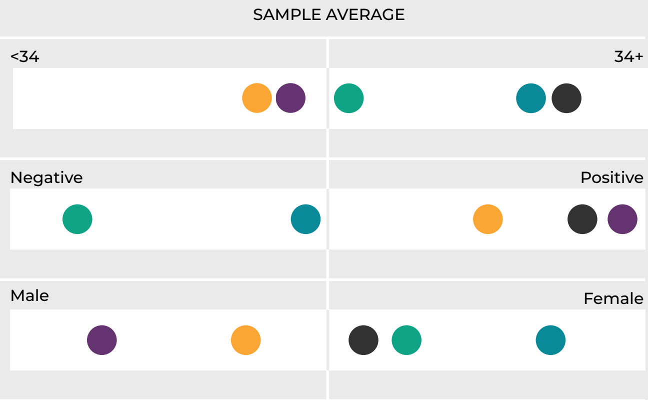
Across all our platforms, we have found that engagement on social media is skewed towards older contributors, with only 42 per cent of contributors younger than 34 years old. There is an average 26 per cent positive sentiment across the Radar's emerging breakthroughs, with male contributors (63 per cent of posts) and North Americans (53 per cent of posts) being the most frequent contributors.

Our analysis shows that it is indeed possible to monitor public opinion and activity; in this section of the Radar, we discuss our findings about what people say and do.

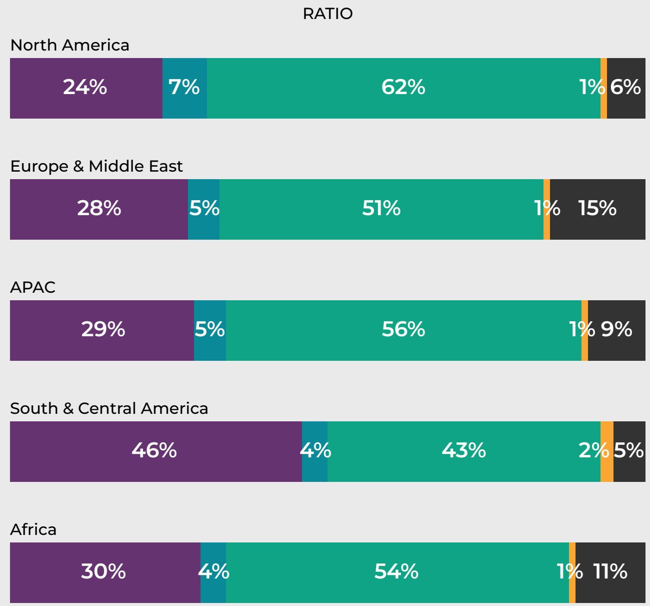
Age
Sample is balanced towards the older populations with <34 at 42%

Net Sentiment
Sentiment is balanced at 26% average net sentiment (63% positive / 37% negative)

Gender
Males dominate the discussion at 63% average share



Age
Sample is balanced towards the older populations with <34 at 42%

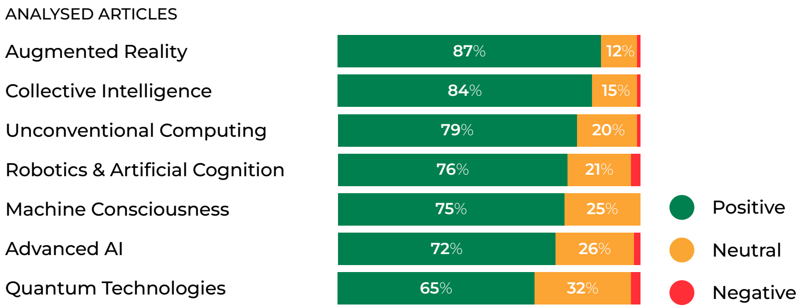


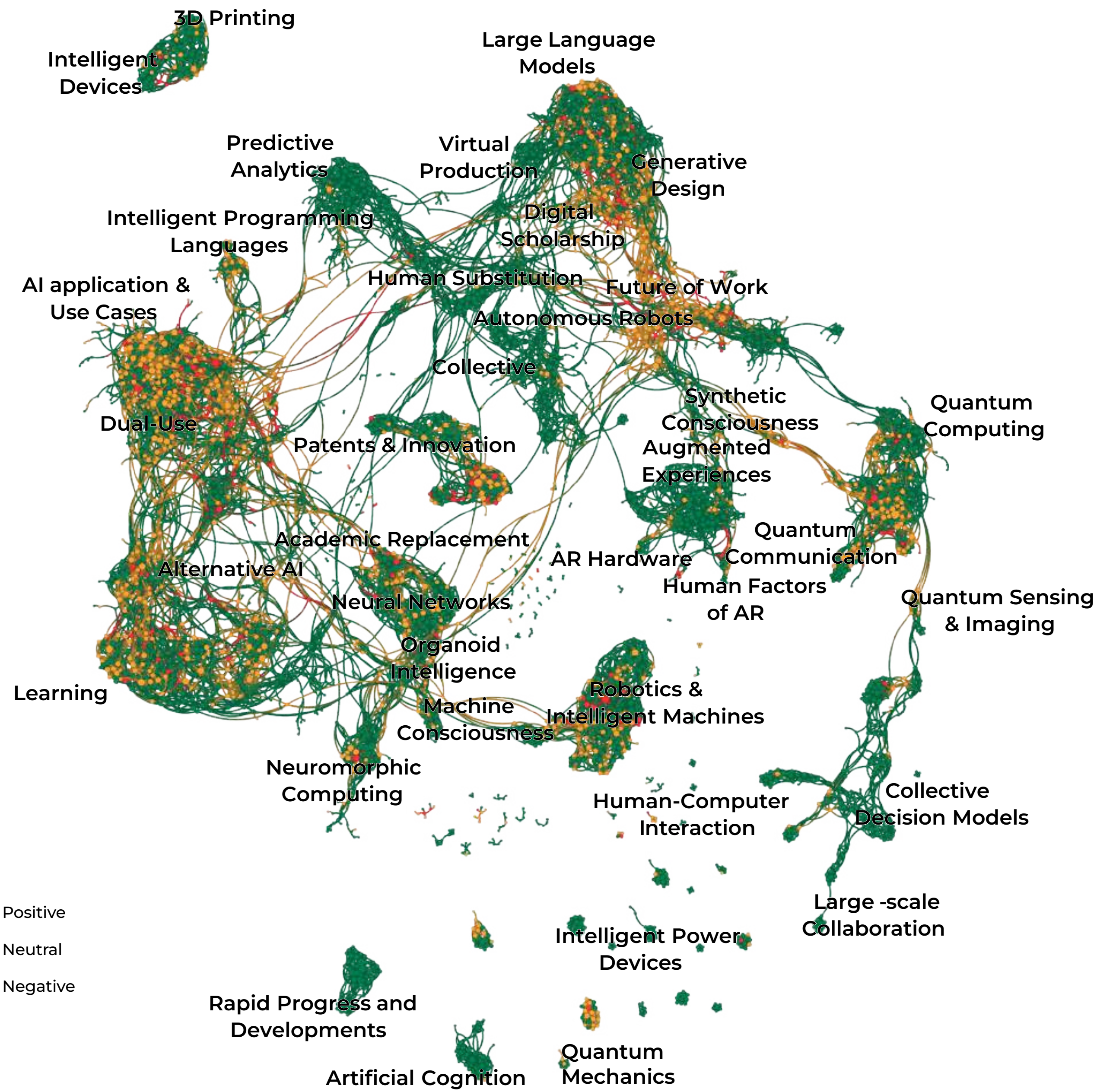
- Advanced AI & Quantum Revolution
- Human Augmentation
- Eco-Regeneration & Geoengineering
- Science & Diplomacy
- Knowledge Foundations

Quantum Revolution and Advanced Artificial Intelligence

What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months reveals that the overall sentiment towards Quantum Revolution and Advanced Artificial Intelligence is very positive.





Sentiment Analysis:

Positive sentiment

The greatest positive sentiment in news, blogs and journals relates to augmented reality (AR) and the application of AI in healthcare. This reflects the excitement and promise of AR as a groundbreaking technology that has the potential to reshape industries and elevate user experiences to unprecedented levels, and the potential of AI to transform healthcare.

Neutral sentiment

While acknowledging AI's productivity-enhancing capabilities and potential benefits in industries like banking, hospitality, tourism, and IT, scientists and experts also highlight concerns about limitations, disruptions to practices, privacy threats, biases, misuse, and misinformation.

Negative sentiment

Negative sentiment with relation to Quantum Revolution and Advanced Artificial Intelligence is predominantly associated with the risks of AI. These include the military applications of AI, such as faster decision-making and autonomous weapons; the risks to society and humanity posed by autonomous AI tools beyond human control, and the potential of AI systems to manipulate and deceive humans, the ability of AI bots to spread misinformation and manipulate social media platforms, for example. Besides AI, negative sentiment is also associated with how quantum technologies may lead to a digital divide, where only certain organisations or countries with adequate resources can harness the power of quantum technology, exacerbating existing socio-economic disparities.

Key Insights:

Augmented Reality is associated with the highest proportion of positive sentiment, reflecting users' rapidly growing enthusiasm for its capacity to transform industries, augment experiences, enable immersive environments, and facilitate superior communication across diverse sectors such as gaming, education, and healthcare.

Collective Intelligence is the next most positively-talked about topic, underlining the optimism surrounding the synergy of collective wisdom and knowledge. Enabled by technology, it is considered to foster innovative problem-solving, enhance collaboration, and support well-informed decision-making across various domains.

Robotics & Artificial Cognition is associated with the highest level of negativity (3 per cent), highlighting concerns about workforce disruption, ethical quandaries, and human interaction changes. Nevertheless, the potential benefits and innovations in manufacturing, healthcare, and logistics are acknowledged and appreciated.

Quantum Technologies are associated with the lowest proportion of positive sentiment and a high proportion of neutral outlook, reflecting cautious perspectives driven by growing apprehensions about security vulnerabilities, economic repercussions, and ethical constraints. Despite these concerns, the promise of solving complex computational challenges and advancing cryptography remains a focal point of interest.

Facts & Figures

Mainstream media

The analysis comprises 343,000 news articles, blog posts or scientific publications in the last year, discussing developments in AI and quantum technologies. Each node in the sentiment analysis opposite represents one article and the linkages between dots show relations between topics in the analysed data.

ANALYSED ARTICLES	VISUALISED ARTICLES
343.6k	**4,052**
OBSERVATION TIME	NET SENTIMENT[1]
2022/06/12 - 2023/06/12	**89**%

Social media

The analysis comprises 2.5 million posts, discussing AI, quantum technologies, computational creativity, unconventional computing, augmented reality, collective intelligence, machine consciousness, and robotics with a net sentiment of 65 per cent and reaching 3 trillion views.

NUMBER OF POSTS	NUMBER OF MENTIONS	IMPRESSIONS
2.5M	**7.3**M	**253.5**B

OBSERVATION TIME	NET SENTIMENT[1]
2 Year	**65**%

The analysis comprises 343 thousand news articles, blog posts or scientific publications in the last year discussing developments in AI and quantum technologies.

Social media: emerging hot topics and discussions

Trust and AI

There is an intense debate surrounding Generative AI on social media, both regarding its potential to transform diverse industries and its risks. Part of this involves discussion of the multitude of strategies and approaches aimed at tackling the problems arising from AI-generated deepfakes, including deep voice fakes and deep image fakes. People are actively discussing the wide-ranging implications for authentication, media integrity, trust in digital platforms, and the potential for cheating in academia.

Quantum technology

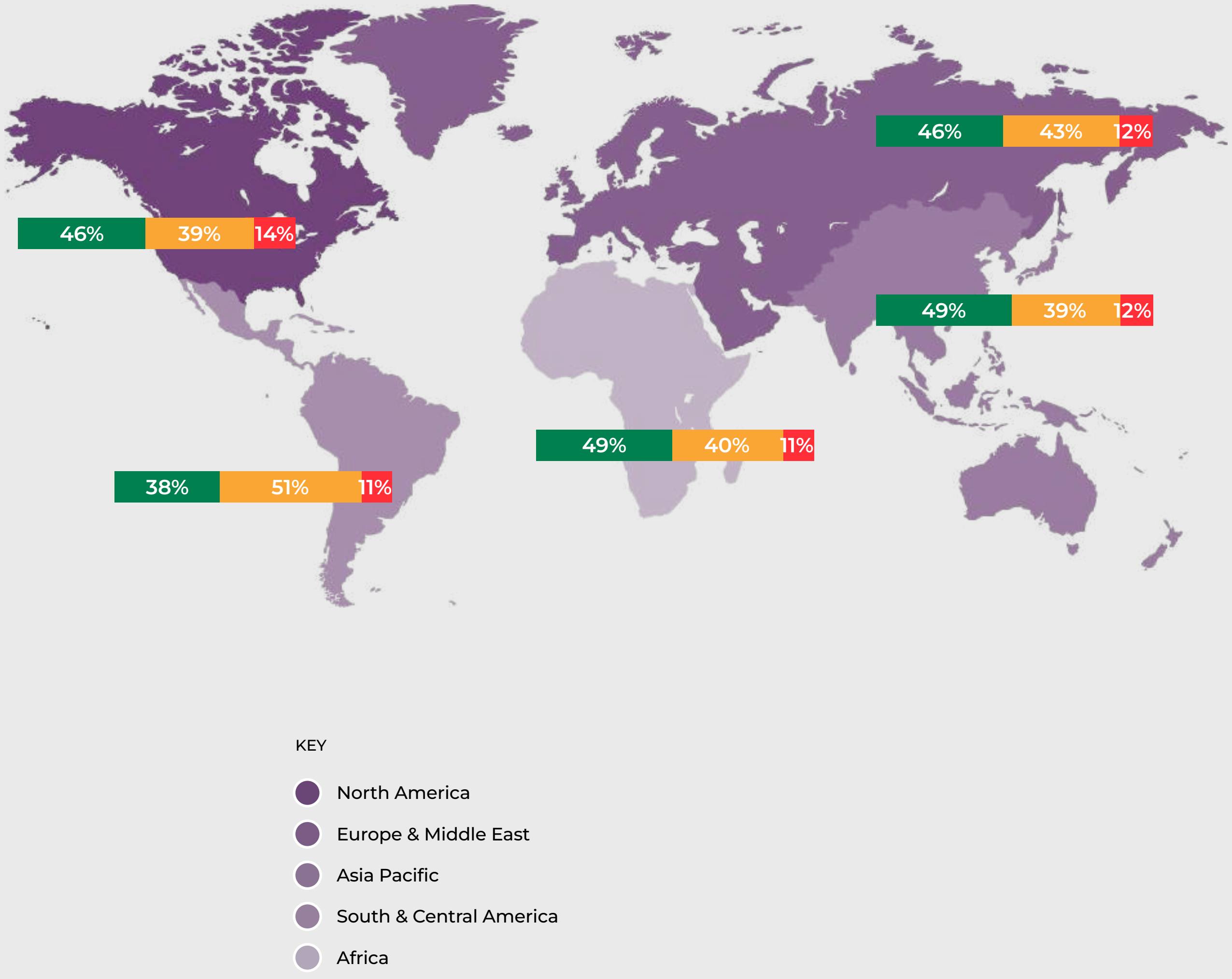
Users on social media have been engaged in lively discussions about recent advancements in quantum technology. Among the key breakthroughs that users are debating are quantum error correction, teleportation, communication, algorithms, and sensors. Additionally, topics like Google's quantum supremacy demonstration and developments in quantum machine learning and post-quantum cryptography are generating substantial interest.

Virtual Reality (VR)

On social media platforms such as Twitter and Reddit, people are increasingly discussing recent breakthroughs in AR and VR technology. Topics include Mixed Reality (XR) experiences, the potential impact of 5G+ connectivity, spatial audio, improved hardware, cloud-based solutions, hand tracking, haptic feedback, and enterprise applications. With the number of AR users projected to reach 90 million in the US by 2023 and 100 million by 2025, along with 68.9 million VR users, interest in these technologies remains strong.

Decentralised autonomous organisations

A trend has emerged on social media discussing the impact of Decentralised Autonomous Organisations (DAOs) on the future of work, powered by self-executing smart contracts and blockchain technology.



Sentiment towards Advanced AI and Quantum Revolution across the world

- In South and Central America, Brazil leads with 32 per cent of all regional social media postings, followed closely by Mexico at 28 per cent. Remarkably, Belize stands out for its per capita posts, surpassing other nations in the region.
- The APAC region demonstrates India's dominance with a 61 per cent share of social media postings, followed by Japan, South Korea, and Taiwan.
- Africa exhibits active engagement with AI and Quantum, led by South Africa (27 per cent), Nigeria (35 per cent), and Kenya (17 per cent).
- Within Europe, the UK holds the largest share of social media postings at 37 per cent, closely trailed by Germany, also at 37 per cent.

How is
sentiment changing?

Mainstream media coverage has increased

In 2022, 239.8k media articles were published relating to Advanced AI and Quantum Revolution, increasing to 343.6k articles by 2023. Alternative AI, biocomputing, human-computer interactions and machine consciousness have shown the greatest increase in media popularity during this time.

Social media reveals changing sentiments and demographic engagement

In 2023, AI advancements witnessed an 18 per cent surge in adverse sentiment compared to 2022. This trend reflects mounting criticism, reluctance, and scepticism among digital audiences. As AI innovation accelerates, apprehensions surrounding ethical consequences, workforce displacement, potential misuse, privacy challenges, and data protection are intensifying uncertainty and fostering more prudent dialogues.

Relative change of media, blog and scientific discussions around developments in Quantum Computing & Advanced AI from 2022 to 2023

What do people do?

Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected close to 63,000 “actions” in the areas covered by the Quantum Revolution & Advanced Artificial Intelligence scientific platform. This is less than for other platforms. However, we see a steady increase of activity related to generative AI over the months across our four indicator categories: raising public awareness; entrepreneurial activities; policy-oriented activities, and contributions to science and technology.

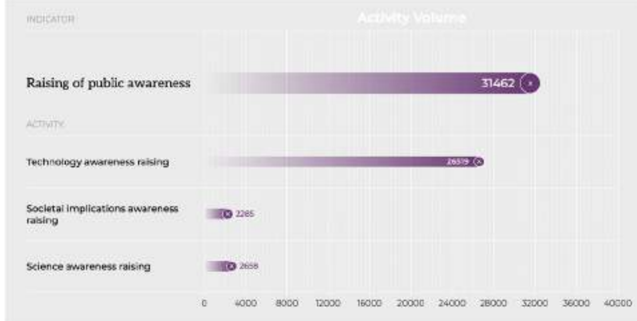
A large increase in activities around advanced AI

Overall, activities monitored focussed mainly around advanced AI, Augmented Reality (AR) – including the metaverse – and quantum technologies. Compared to last year, we observed a large increase in activity around generated AI, especially in the beginning of the year. This is due to a series of announcements about how the technology could be used for new applications and accelerate research and development.

“Technology-awareness raising” – the publications of news and block articles about the latest developments and implications of the technologies – again dominated the share of monitored indicators and variables. Compared to the previous year, we saw a relative increase of the share of activities in indicators “policy-oriented actions” and citizen-led “contributions to science and technology”. This echoes the calls for regulation for AI from different groups but also about indicates how those AI models are applied in different areas of research.

In terms of volume, AR and the metaverse were the areas where most activities were detected in 2022 – followed by quantum. This now has been reversed with advanced AI now being the most active topic.

This data is updated monthly and analysed quarterly on the radar digital platform. Here, we provide a high-level analysis of the most notable features detected by the tool in 2023. Further details on the indicators can be found in this section’s introduction, while information on the tools and its limitations and biases can be found in the appendices.



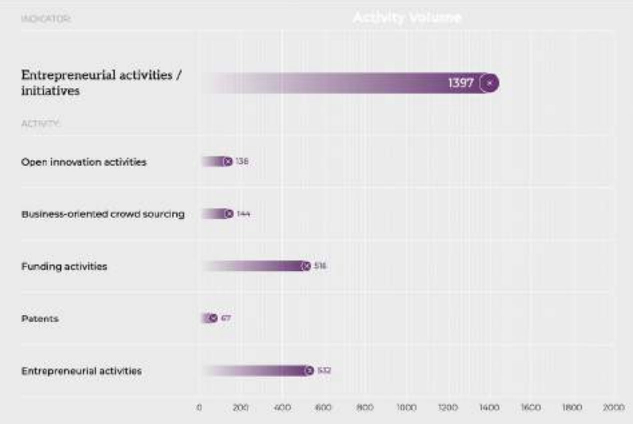
Activities raising public awareness

Comparatively to the other scientific platforms, the share of activity under these indicators was higher. The most active fields were Augmented Reality followed by Quantum Technologies and Advanced Artificial Intelligence.

In the area of Augmented Reality, the strong trend observed previously around the metaverse continued. Awareness-raising activities ranged from companies and brands investing in virtual worlds and communications to military applications. The announcement of Apple’s new augmented reality headset in June further spurred discussion.

Generative AI and more particularly ChatGPT have led many civil society actors as well as companies to release statements about potential applications of the technology, leading to a steady growth of the relative share of the topic in the indicator. Some of these actions raised concern about potential risks associated with generative AI and about monopolistic behaviours if a few players only develop the capacity to develop the technology

1.1 Advanced AI
1.2 Quantum Revolution
1.5 Collective Intelligence

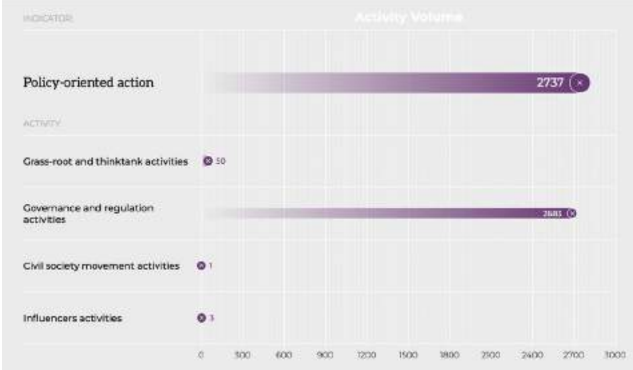


Entrepreneurial activities

Most entrepreneurial actions concerned funding and entrepreneurial activities linked to the creation of startups, fundraising and incubation efforts. For example, one can mention hackathons aimed at developing quantum applications for social good, increasing practical skills and communicating the long-term positive impact of quantum technology on industry and society. There were also many hackathons and contests for the development of enabling ecosystems for metaverse applications. The launch of a Metaverse Standards Forum made quite some headlines and the tool detected the launch of community-based tokenised ecosystems to translate assets between the physical and digital worlds.

Open-source frameworks for generative AI-powered applications, or for the generation of open ecosystems to stimulate the development of AI applications, were often promoted by companies and incubators in order to foster innovation and the uptake of advanced AI by regional actors or to attract creative communities to certain platforms.

- 1.1 Advanced AI
- 1.2 Quantum Revolution



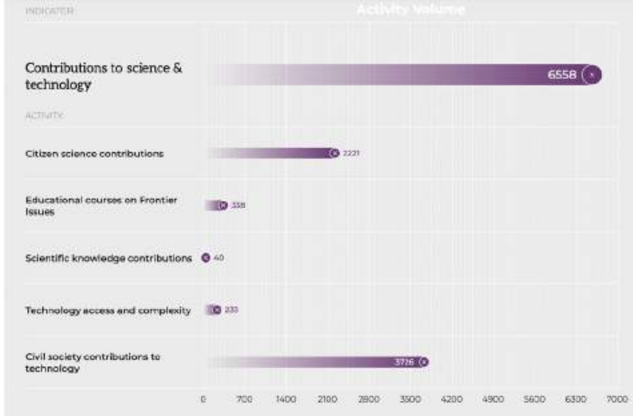
Policy-oriented action

The vast majority of policy-oriented actions were linked to governance and regulation, such as for example concerns about data privacy for healthcare applications in virtual ecosystems, reinforced by advanced AI and augmented reality technologies. Those concerns are likely to grow, as more applications develop and are deployed across society.

Some of the “grass-root and think-tank activities” discussed the implications of a convergence of information technologies (artificial intelligence, quantum computing, blockchain and virtual reality) on law making in a decentralised global economy. The idea of “Lex Cryptographia” was proposed, whereby rules are enforced through code-based systems raising basic questions about accountability, the rule of law and democracy.

In the area of advanced AI, as a result of the release of ChatGPT and other generative AI applications, calls for governance and regulation increased. These concern, for example, the use of these technologies in medical contexts or issues related to copyright and the use of creative materials.

- 1.1 Advanced AI
- 1.2 Quantum Revolution
- 1.5 Collective Intelligence
- 4.4 Democracy-affirming technologies



Contributions to science and technology

One can note the relatively high number of “citizen science contributions” compared to other platform areas, in particular in the field of advanced AI with the provision of a very large number of open source libraries and ecosystems that enable broad group of actors to contribute to new applications or advance research. This also touches unconventional approaches to computing such as cellular or biological computing, albeit marginally. An interesting example is the launch of an open platform for bio-informatics in South East Asia.

In the area of quantum technologies, we detected many educational and awareness-raising activities around quantum physics, quantum computing and quantum communication. We also saw the launch of new open platforms aimed at democratising access to quantum computing.

In the area of Augmented Reality, several initiatives were launched where citizens can contribute by sharing personal and area data about experiences and use of AR systems. These initiatives will speed up the development of AI-based algorithms able to adjust on real-time the AR systems to the real world.

- 1.3 Unconventional Computing
- 1.5 Collective Intelligence

Human augmentation

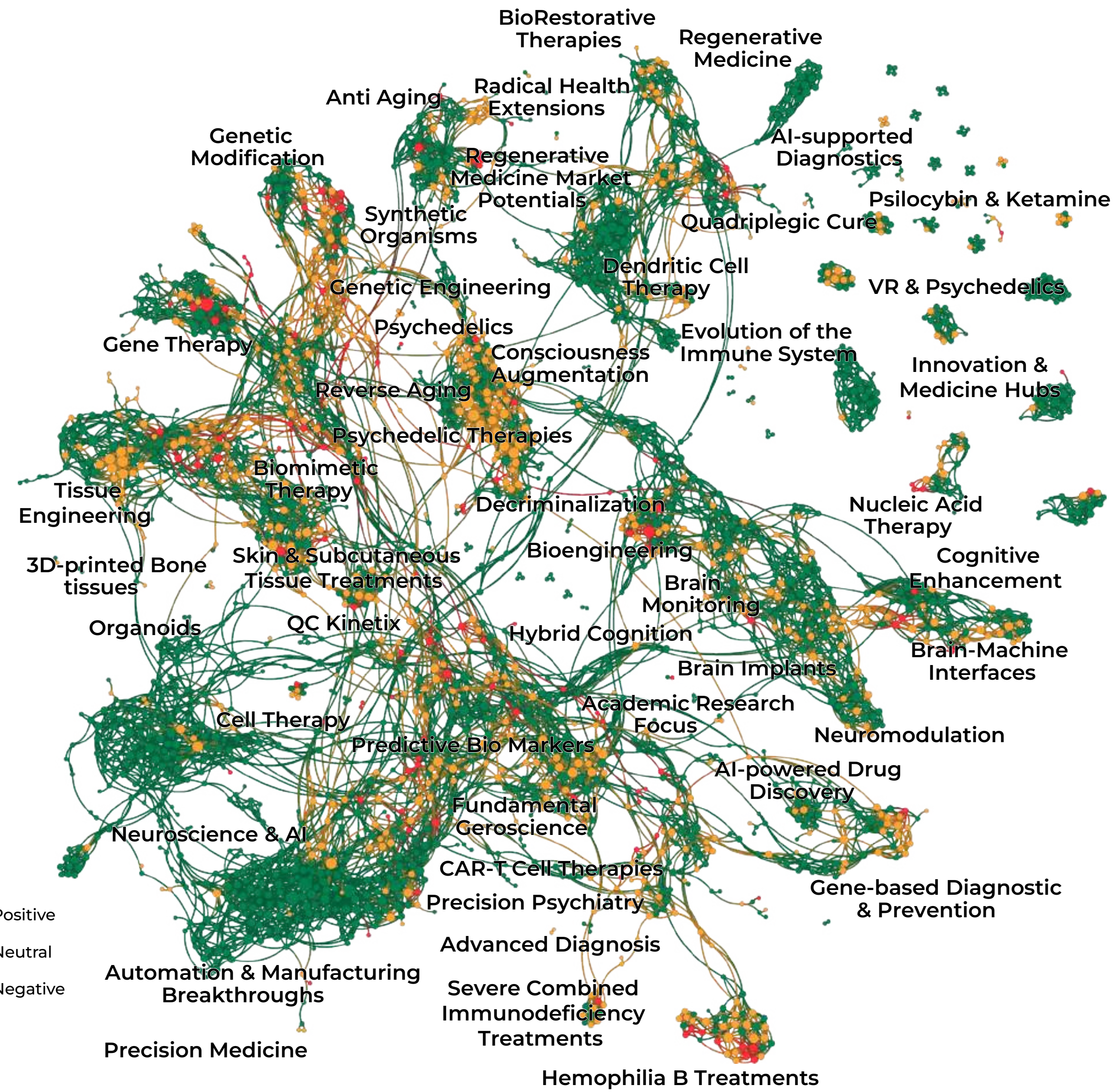
What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months reveals that the overall sentiment towards Human Augmentation is largely positive, although this positive bias is less strong on social media.

ANALYSED ARTICLES

	Positive	Neutral
Cognitive Enhancement	87%	12%
Precision Psychology	78%	18%
Human Genetic Engineering	72%	26%
Organoids	72%	26%
Psychedelics Medicine	71%	26%
Radical Health Extension	68%	30%
Future Therapeutics	68%	27%
Consciousness Augmentation	66%	30%
Neuro-augmentation	66%	30%

Positive
Neutral
Negative



Sentiment Analysis:

Positive sentiment

Precision medicine is recognised to be shaping the future of personalised healthcare, resulting in improved patient outcomes and increased sustainability. A focus on innovation, through advancing technologies such as remote diagnostics, point-of-care testing, and AI, is considered potentially transformative for healthcare delivery and access. Biomedical engineering advancements are also expected to lead to breakthroughs in tissue and bone repair treatments, improving patient outcomes and healthcare. Media associated with the awarding of the Nobel Prize in physiology or medicine for discoveries on human evolution highlight how these insights may have the potential to lead to major advancements in bioengineering and human augmentation.

Neutral sentiment

While support for legalising psychedelic therapy is growing, balancing accessibility concerns with the potential for improving mental health treatment outcomes remains a topic of conversation. Safety concerns around brain-implant technology developed by companies such as Neuralink limits the enthusiasm for the technology's future prospects.

Negative sentiment

Concerns and reservations about human enhancement technologies, particularly brain chip implants, brain-computer interfaces and gene editing for babies, are prevalent among people worldwide, with a majority viewing these as meddling with nature. Non-essential enhancements and the potential use of chip implants to "read people's minds" generate disapproval, highlighting global apprehensions about the ethical and social implications of such technologies.

Key insights:

With an overwhelmingly positive sentiment of 87 per cent, **Cognitive Enhancement** is associated with its application in various fields such as education, professional development, and healthcare.

Healthspan Extension, Future Therapeutics, and Precision Psychology exhibit relative positive sentiment percentages along with varying levels of neutral and negative sentiment. This reflects optimism about extending human lifespan and innovative, well-targeted treatment approaches.

Sentiment about **Consciousness Augmentation** and **Neuro-augmentation**, both with positive sentiment percentages of 66 per cent, indicates growing interest in expanding cognitive abilities and enhancing brain function, while reservations and concerns about ethics, privacy, and potential risks associated with altering human consciousness are also raised.

Stories about **Human Genetic Engineering** and **Organoids** both demonstrate positive sentiment percentages of 72 per cent and 72 per cent respectively, again highlighting the optimism surrounding genetic engineering's potential to address diseases and enhance human capabilities.

With 71 per cent positive sentiment, stories about **Psychedelics** indicate a growing interest in the therapeutic potential for mental health treatments. The positive sentiment recognises their potential efficacy in addressing conditions like depression, PTSD, and addiction, but concerns about misuse, safety, and regulations exist.

Facts & Figures

Mainstream media

In the last year, a comprehensive analysis of 191,000 articles spanning news, blogs, and scientific publications revealed an 86 per cent net positive sentiment while discussing developments in human augmentation.

ANALYSED ARTICLES	VISUALISED ARTICLES
191.6k	2,494
OBSERVATION TIME	**NET SENTIMENT[1]**
2022/06/12 - 2023/06/12	86%

Social media

Over 2 years, 580.4K distinct social media posts covered topics related to human augmentation, such as cognitive enhancement, genetic engineering, health extensions, consciousness augmentation, organoids, therapeutics, precision psychiatry, psychedelics, and neuro-augmentation, with 23 per cent net positive sentiment.

NUMBER OF POSTS	NUMBER OF MENTIONS	IMPRESSIONS
580.5K	1.3M	213.8B

OBSERVATION TIME	NET SENTIMENT[1]
2 Year	23%

In the last year, a comprehensive analysis of 191 thousand articles spanning news, blogs, and scientific publications revealed an 86 net sentiment while discussing developments in human augmentation.

Social media:
emerging hot topics and discussions

Neurorights, mental privacy and free-will

The exponential growth of non-invasive technologies in neuro-augmentation and brain monitoring has amplified concerns about privacy. As our innermost thoughts and mental states become vulnerable to external surveillance and manipulation, concerns are centred around significant implications for personal autonomy and the potential for neuro-technological abuses.

The ethical dilemma surrounding advancements in precision psychiatry reveals the potential for unprecedented manipulation of human behaviour, raising concerns over blurring the line between choice and manipulation.

Neuro-manipulation technologies and warfare

Advances in technology that enable manipulation of human thought and behaviour, such as brain-machine interfaces and neuropharmacology, offer potential for optimising human performance. However, oversight and governance concerns arise from the dual-use of these technologies. Neuroweapons, fuelled by neuroscience advancements, raise misgivings about their widespread implications for warfare, intelligence, and national security.

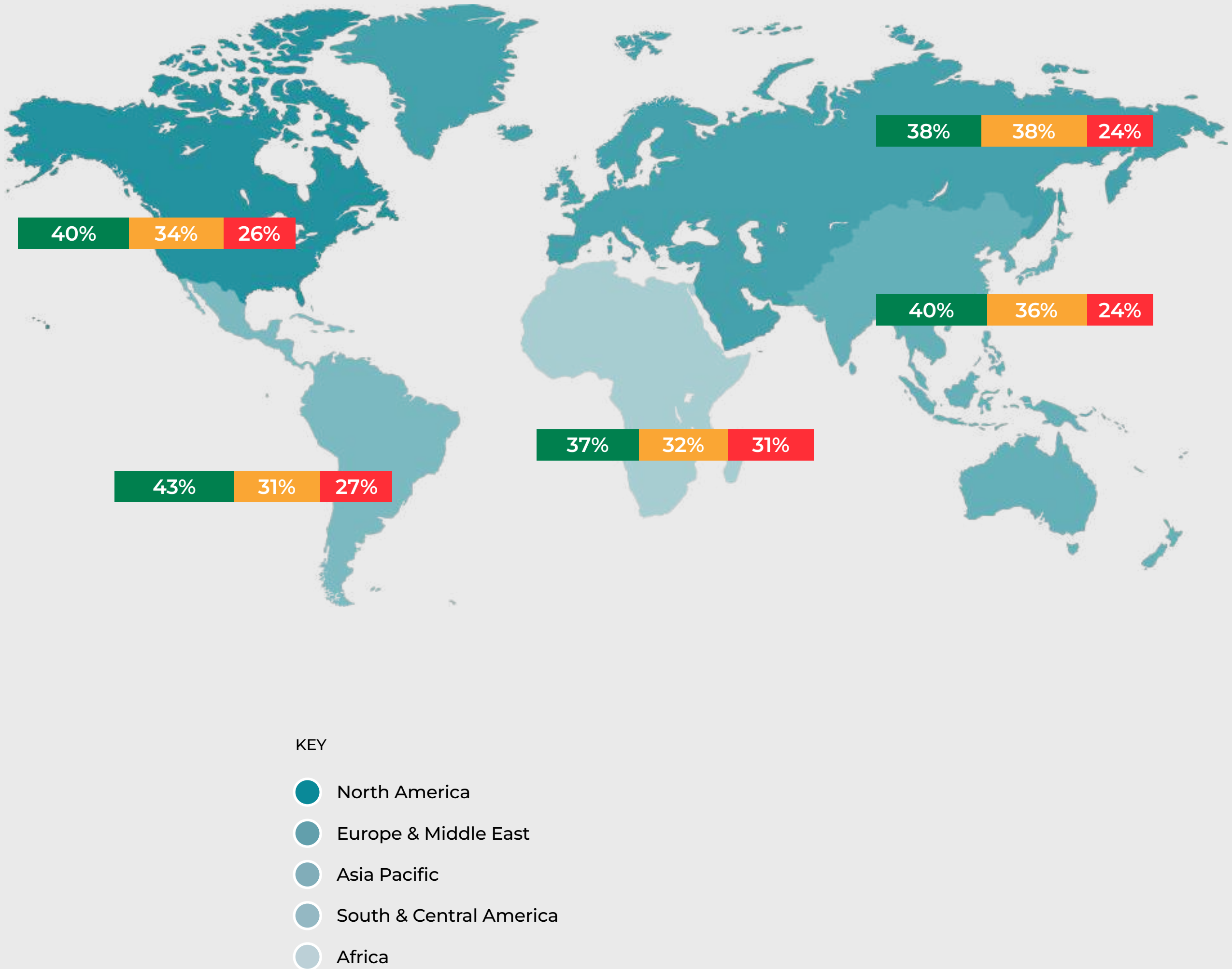
Memory, consciousness and identity

Advances in memory modification and cognitive enhancements present a future where personal memories can be manipulated, raising questions about identity, authenticity, and control. The prospect of memory modification technologies as commodities is considered to have implications for individual autonomy and the potential for societal control.

Emerging technologies in consciousness augmentation and hybrid cognition have implications for the future of humanity, as they reshape our understanding of consciousness and open new possibilities for cognitive enhancement: what does it therefore mean to be human?

Gene editing as a driver of inequality

While somatic human genome editing is considered to show promise for curing once-incurable diseases, concerns about accessibility and genetic inequalities exist. The use of CRISPR/Cas9 technology could inadvertently exacerbate societal divides due to its cost, availability, and ethical implications; the unequal access to its benefits could lead to significant disparities in health, longevity, and genetic enhancement, thereby deepening pre-existing inequalities.



Sentiment towards Human Augmentation across the world

- Users in Nigeria, Kenya, and South Africa contribute to more than 80 per cent of English language posts originating from Africa. Additionally, an upward trend in discussions surrounding human augmentation can be observed in Ghana, Zimbabwe, and Namibia.
- In APAC, the majority of discussions around human augmentation takes place in Australia and New Zealand, followed by South Korea, Malaysia and India.
- In Europe and the Middle East, Montenegro leads the post per capita ranking, followed by the Netherlands, UK and Germany.
- In Latin America, users are most frequently talking about human augmentation in Costa Rica, Colombia, Guyana and Chile.
- The US is still the leader when it comes to total postings worldwide, even when normalised to their population density.

How is sentiment changing?

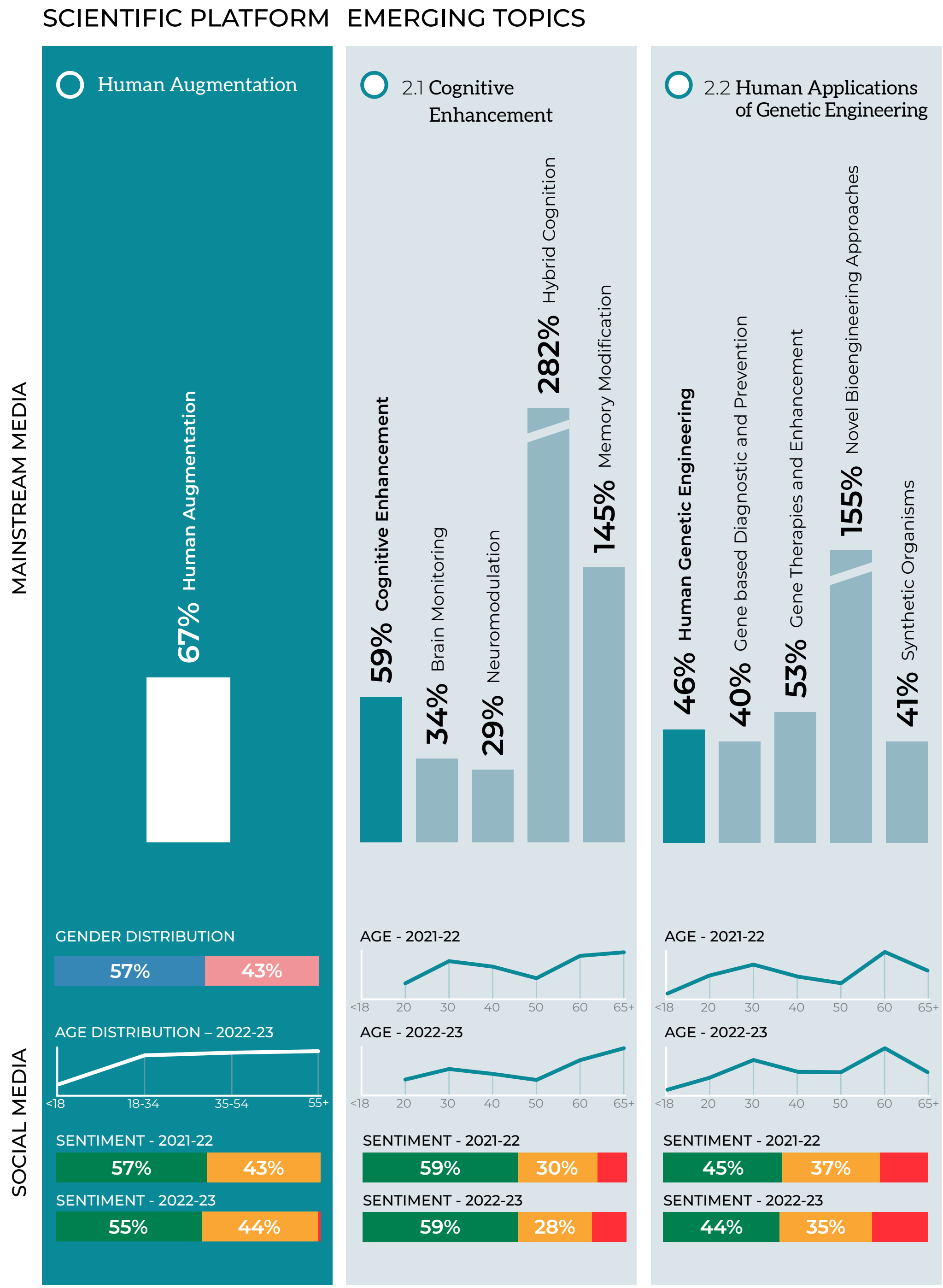
Mainstream media coverage has increased

In 2022, 115,000 media articles were published relating to Human Augmentation, increasing to nearly 192,000 articles by 2023. Hybrid cognition, memory modification, novel bioengineering approaches to human genetic engineering, organoid research, personalised organoids and tissue engineering have shown the greatest increase in media popularity during this time.

Social media reveals changing sentiments and demographic engagement

There has been a substantial 100 per cent increase in popularity of neuro-augmentation over the past two years. This highlights the growing interest and social media traction surrounding Neuralink and related advancements in the field.

The rise in discussions and scrutiny regarding the feasibility, safety, fairness, and broader implications of healthspan extension, along with the increased frequency of posts related to neuro-augmentation, reflect a shift towards scepticism and an increased diversity in the range of perspectives on the effectiveness and implications of these advancements in human augmentation.



Relative change of media, blog and scientific discussions around developments in Human Augmentation from 2022 to 2023

What do people do?

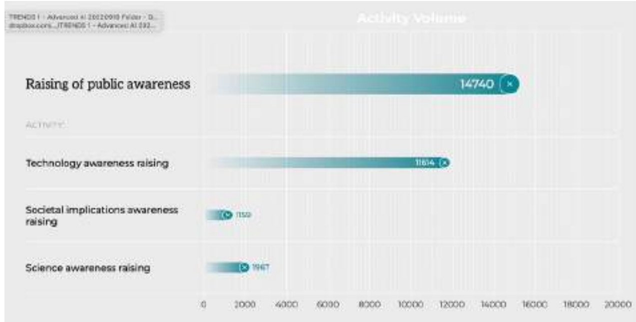
Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected around 30,000 “actions” in the areas covered by the Human Augmentation scientific platform, making this the least active domain of the Science Breakthrough Radar. This is due to technical nature of the field, which requires more advanced knowledge and is more niche than the other areas surveyed.

The third International Summit on Human Genome Editing caused large increase in volume

Radical Health Extension and issues related to longevity and ageing covered almost half of the activities detected. Neurotechnologies (related to the Cognitive Enhancement and Consciousness Augmentation emerging topics), Human Application of Genetic Engineering and Future Therapeutics followed with an almost equal share of actions.

The Third International Summit on Human Genome Editing that took place in March at the Francis Crick Institute in London caused upwards of 30 per cent increase in the volume of awareness activities over the preceding month. Most issues raised concerned the ethical implications of heritable genetic modifications and the associated governance needs.

Other notable topics concern the application of new genetic engineering techniques to crops, advances in immunotherapies and approaches to longevity such as diet and lifestyle changes.

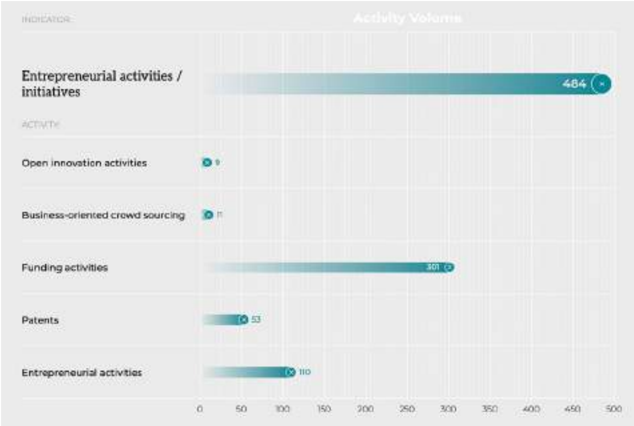


Activities raising public awareness

Concerns and hopes linked to practical applications of new advances in technology drove the indicator. This trend is shared across all areas surveyed. This concerned, for example, the potential of brain implants to tackle neuro-degenerative diseases or the announcement of a successful brain-machine interface that allowed thought-controlled walking again after spinal cord injury.

Awareness-raising about the societal implications of advances in human augmentation dealt mainly with questions about unequal access to the most advanced therapies, the impact of deep-brain stimulation on cognitive functions such as learning and memory, and the implications of a longer healthy lifespan on the economy and society. “Science-awareness activities” aimed to communicate fundamental science advances to a broader public.

2.1 Cognitive Enhancement
2.3 Healthspan Extension



Entrepreneurial activities

This indicator is divided into funding activities, entrepreneurial activities, patents, business-oriented crowd-sourcing and activities fostering open innovation. Most of the entrepreneurial and funding activities monitored centred around immunotherapy and gene therapies.

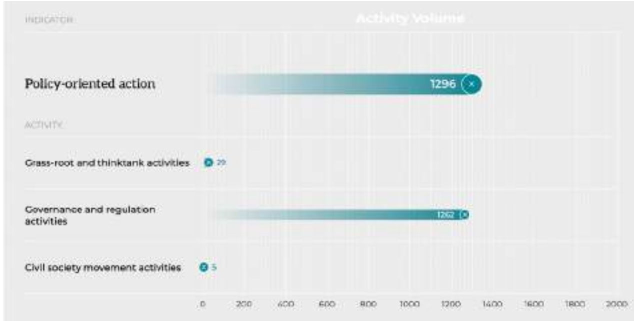
We also observed citizen-led crowd-funding campaigns for research on genetic therapies for ultra-rare diseases. Radical Health Extension is less present in this indicator, partly because the field saw fewer investment rounds compared to other topics analysed.

Finally, start-ups and young companies developing neural interfaces and neuro-modulation technologies to tackle neuro-degenerative diseases saw an increase in funding activity compared to the past.

2.1 Cognitive Enhancement

2.2 Human Applications of Genetic Engineering

2.3 Healthspan Extension



Policy-oriented action

Our monitoring tool detected very few activities of civil society movements, grass-roots organisations or think tanks and the vast majorities of actions concerned governance and regulation. This is surprising given concerns voiced about genetic engineering and reactions to the mRNA vaccines during the pandemic.

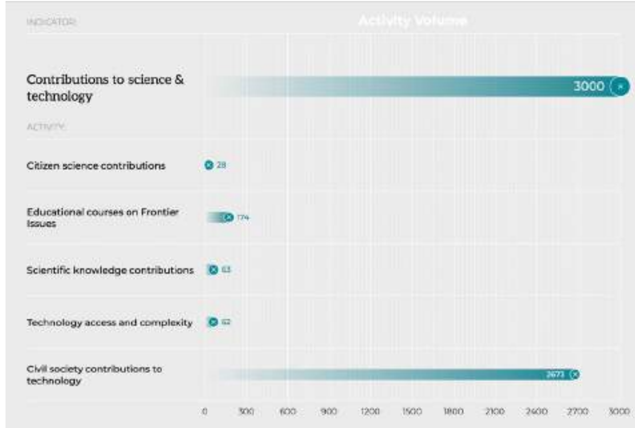
More interesting are the activities of grass-roots organisations and think tanks, who discussed the implications of increased human lifespan on society at large. They debated which measures and strategies governments should take to foster inclusive development and maintain an intergenerational peace. Various civil society actors mobilised around the necessity to provide adequate funding for the development of genetic therapies for rare diseases.

Finally, in the area of cognitive enhancement and neurotechnologies more broadly, we detected calls for more transparency and regulation about how those technologies are used in the military domain.

2.1 Cognitive Enhancement

2.2 Human Applications of Genetic Engineering

2.3 Healthspan Extension



Contributions to science and technology

Most activities for this fourth indicator dealt with contributions to science and research by non-traditional academic actors. There were also quite a few "do-it-yourself" or "bio-hacking" activities detected, including people attempting to improve their health or slow their ageing by consuming metformin, or experimenting with drugs to enhance cognitive functions such as memory and concentration (nootropics).

Finally, a few open databases and protocols for the sharing of brain-data,EEG recordings and individual genetic data were launched, with the hope of speeding up research and discovery.

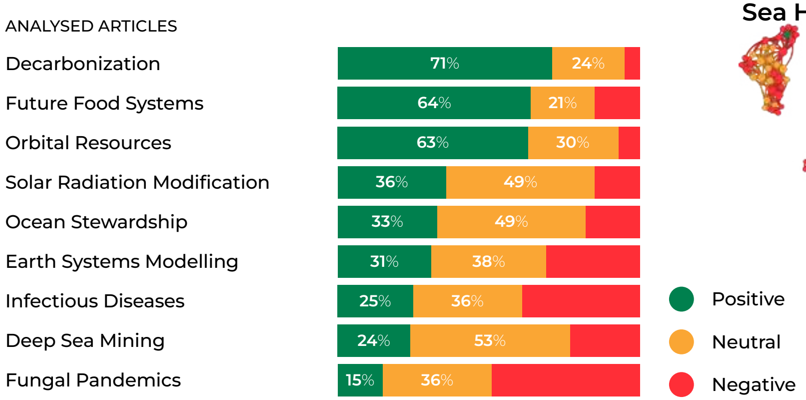
2.4 Consciousness Augmentation

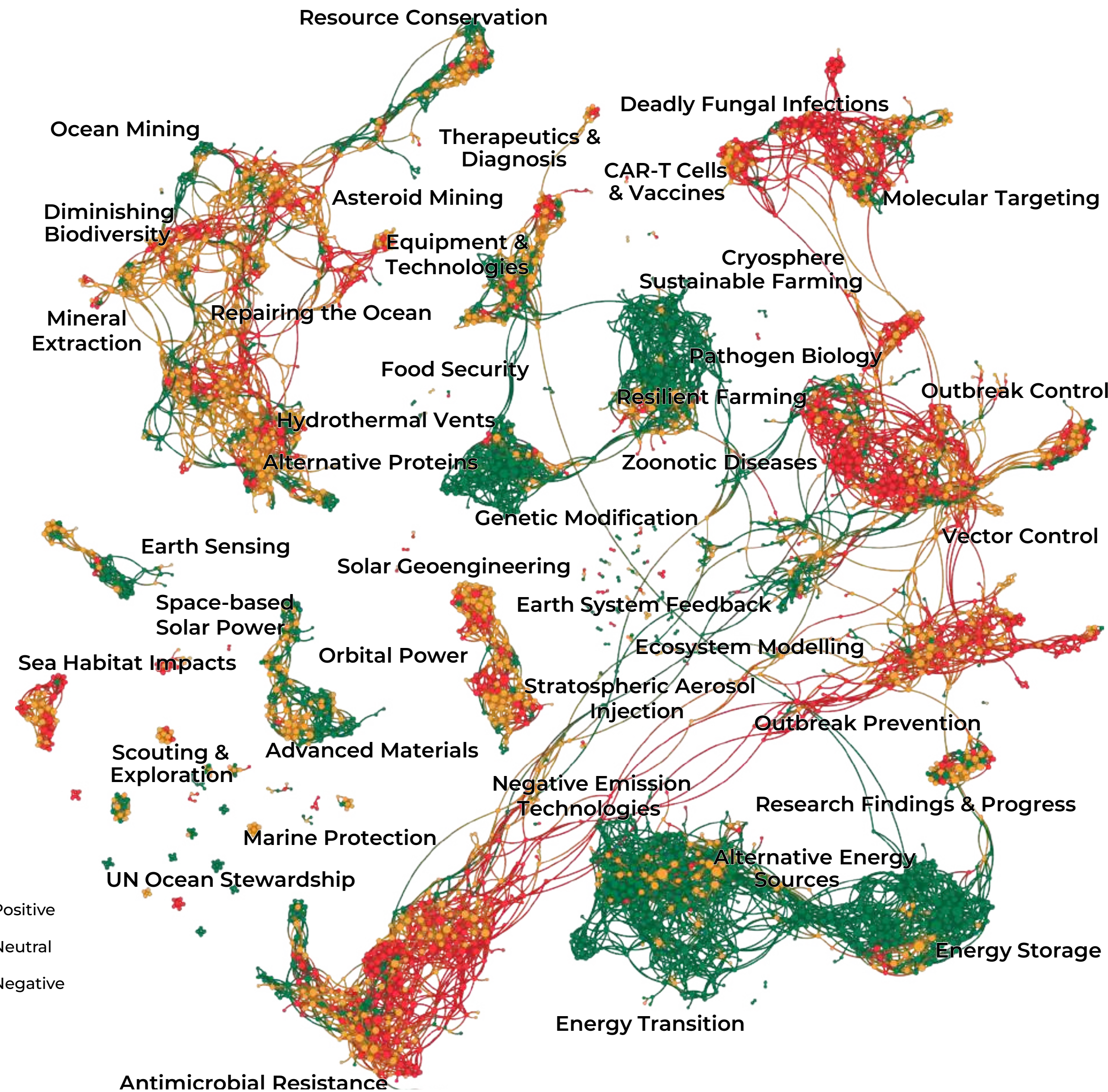
5.5 Synthetic Biology

Eco-regeneration and geoengineering

What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months reveals that the overall sentiment towards Eco-regeneration and Geoengineering is mixed, with nearly as much associated negative press as there is positive.





Sentiment Analysis:

Positive sentiment

There is a generally positive trend in discussions about sustainable agriculture. Measures that prioritise environmental protection, economic viability, and social benefits are highlighted, and it is generally discussed that the production of alternative proteins is at the forefront of innovation in the food and beverage industry. News discussions and blogs about space-based solar power reflect growing optimism for the technology.

Neutral sentiment

The surge in demand for metals needed for electric vehicle batteries has thrust seabed mining into the spotlight. While seen by some as an attractive solution, studies point to the serious ecological impacts, particularly on marine life. Public opinion varies, but the consensus favours developing robust regulations and conducting further research before commencing seabed mining. Population disruption stemming from the energy transition is under discussion: the pivot towards clean energy and the consequent increase in demand for Energy Transition Metals (ETMs) may disrupt more communities globally than the reduced production of thermal coal.

Negative sentiment

Negative sentiment surrounds the emerging issue of pharmaceutical pollution. The issue of antimicrobial resistance (AMR) continues to generate significant negative sentiment in the media. Stratospheric aerosol injection (SAI), a proposed climate intervention method, is often viewed with negative sentiment due to the unknown and potentially harmful consequences on the global climate system.

Key insights:

Opinion towards **Decarbonisation** and **Future Food Systems** both show optimism for creating sustainable ecosystems and embracing innovative food solutions. It is also recognised that existing challenges and uncertainties still need to be addressed for successful implementation.

Orbital Resources and **Earth Systems Modelling** stories express interest in advancing space exploration and resource use. However, concerns persist regarding the ethical aspects, accuracy, and limitations of these scientific advances, particularly in understanding environmental changes.

Ocean Stewardship and **Deep-Sea Mining** stories emphasise the necessity of preserving marine ecosystems while addressing economic opportunities in deep-sea exploration. Both themes include the potential environmental impacts and implication for marine life that come with such exploration.

Stories about **Solar Radiation Modification** and **Infectious Diseases** exhibit mixed sentiments regarding the potential of geoengineering techniques and the development of improved prevention for diseases. Concerns over side effects and global preparedness for these changes underline the need for cautious optimism.

The negativity associated with **Fungal Pandemics** highlights growing unease about the possible impact on global health, emphasising the importance of taking proactive measures and conducting more research.

Facts & Figures

Mainstream media

In the last year, a comprehensive set of 224,200 articles spanning news, blogs, and scientific publications, revealed a 20 per cent net positive sentiment while discussing eco-regeneration and geoengineering.

ANALYSED ARTICLES	VISUALISED ARTICLES
224.2k	2,896
OBSERVATION TIME	NET SENTIMENT[1]
2022/06/12 - 2023/06/12	20%

Social media

Over a 2-year period, 5.6 million unique social media posts across various platforms, including Twitter, Reddit, and other channels focusing on language and text, addressed a wide range of topics such as decarbonisation, future food systems, deep-sea mining, and more, contributing to an overall net positive sentiment of 8 per cent.

NUMBER OF POSTS	NUMBER OF MENTIONS	IMPRESSIONS
5.7M	13.4M	2,808B

OBSERVATION TIME	NET SENTIMENT[1]
2 Year	8%

In the last year, a comprehensive set of 224 2 thousand articles spanning news, blogs, and scientific publications, revealed a 20 net sentiment while discussing eco regeneration and geoengineering.

Social media: emerging hot topics and discussions

Social media: emerging hot topics and discussions

On social media, discourse on urgent sustainability topics such as decarbonisation, the use of biodiversity, negative emission technologies and energy transition is often polarised. Narrative extremes between anthropocentric views (climate change denialism) and ecocentric viewpoints (advocation for the rights of nature) reflect the ideological struggle influencing discussions on climate change and environmental rights. The simplistic binary perception of anthropocentrism and ecocentrism is gradually being seen as insufficient, and a growing dialogue advocates for promoting a balanced view that respects both human necessities and environmental preservation.

Humanity's treatment of outer space

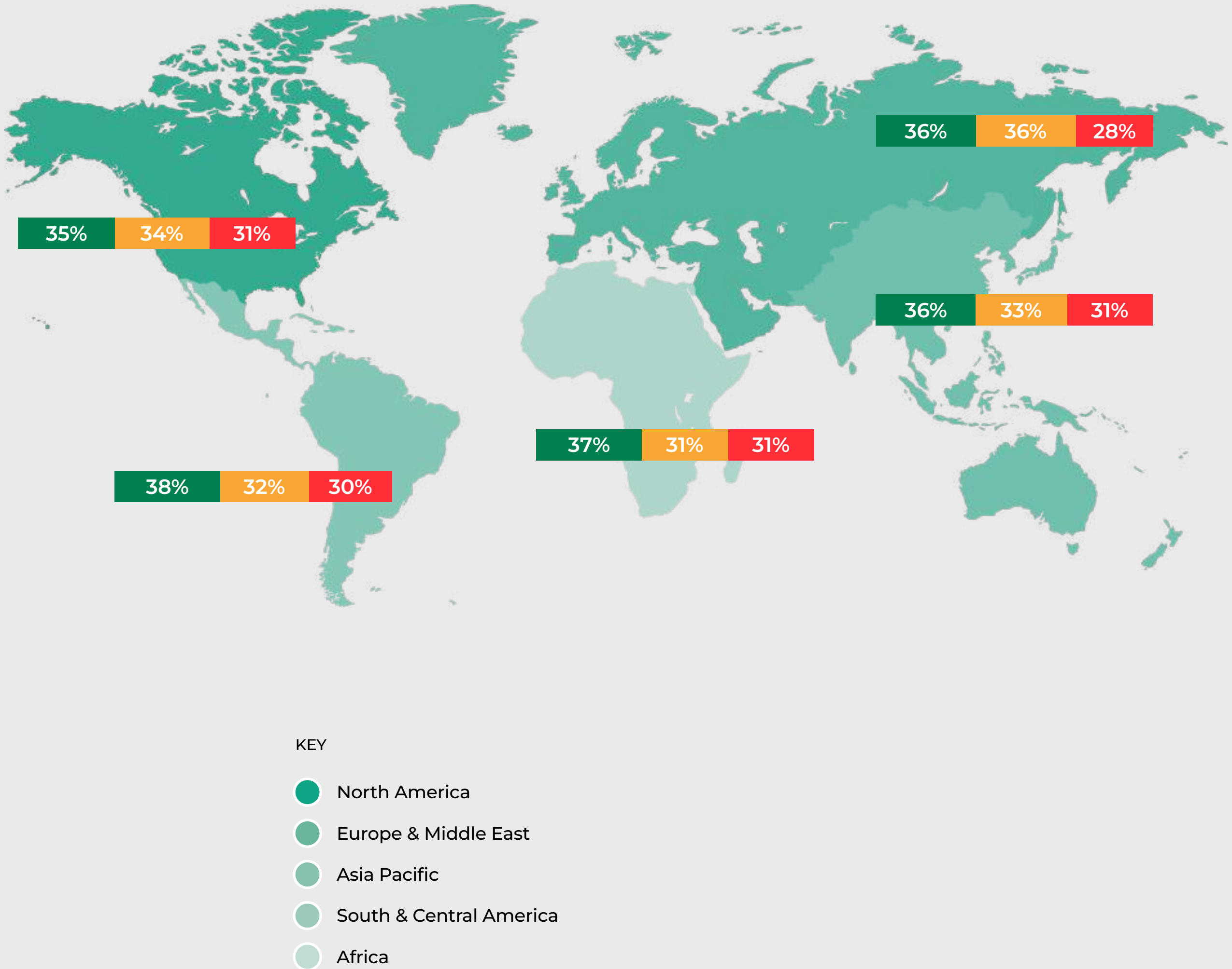
In social media discussions on space exploration and resource extraction, topics like orbital powers, planetary exploration and the accompanying legal implications are frequently discussed. The debates often oscillate between viewing space as humanity's ultimate frontier and a potential site for resource exhaustion. These discussions extend to innovative concepts like solar radiation modification and Earth systems modelling, signifying increasing concern about earthly environmental challenges. Agreements like the Artemis Accords in global space governance are commonly highlighted, particularly as private entities venture into this domain.

Fungal threat

Social media platforms have become a hub for discussions on infectious diseases and fungal pandemics, raising philosophical questions about the balance between societal well-being and individual liberties. The popularity of the HBO show, The Last Of Us, depicting a fictional fungal pandemic, is fuelling these discussions, aligning with scientific research suggesting that climate change could make certain fungi more dangerous to humans.

Energy breakthroughs

As the energy landscape evolves, certain cutting-edge energy sources and delivery mechanisms have taken over the imagination in social media. Space-based solar power emerges as a visionary concept, envisioning satellites capturing abundant sunlight in space and wirelessly transmitting it to Earth. Artificial photosynthesis, inspired by nature's efficient processes, is also popular, aiming to directly convert carbon dioxide into clean fuels using sunlight. Quantum energy, leveraging advancements in quantum technologies, is thought to hold promise for revolutionising energy production and storage through enhanced efficiency and novel materials. Piezoelectric energy, derived from vibrations in infrastructure and human movement, is considered to hold promise as a unique and supplementary power source. Antimatter energy ignites imaginations with the boundless possibilities it presents. These forward-looking energy solutions have captured attention and are inspiring anticipation for the transformative energy landscape of the future.



Sentiment towards Eco-regeneration and geoengineering across the world

- Libya, the Central African Republic, and Namibia are active contributors in Africa's mixed sentiment discussions on eco-regeneration and geoengineering, reflecting a growing interest in sustainability and climate solutions.
- In the Asia Pacific region, Australia, New Zealand, the Philippines, and South Korea are notably engaged in discussions surrounding eco-regeneration and geoengineering.
- In Latin America, the discussions surrounding eco-regeneration and geoengineering have been particularly prevalent in Colombia, accounting for 50 per cent of all regional posts.
- In Europe, conversations about eco-regeneration and geoengineering have been particularly active in the UK, Ireland, the Nordic and Baltic countries, and Germany.
- In the Middle East, discussions on eco-regeneration and geoengineering have been largely concentrated in the United Arab Emirates and Turkey.

How is sentiment changing?

Mainstream media coverage has decreased

In 2022, nearly 387,000 media articles were published relating to Eco-regeneration and Geoengineering, decreasing to just over 224,000 articles in 2023. Negative emissions technologies, infectious diseases and seabed extractions exhibit the greatest decreases in coverage, with ocean biodiversity, stratospheric aerosol injection and fungal outbreaks receiving the highest increases.

Social media reveals changing sentiments and demographic engagement

Social Media traction amplified considerably for Fungal Pandemics, Ocean Stewardship, and Deep-Sea Mining over the past biennium, with a tenfold surge specific to Fungal Pandemics. Conversely, the focus on Infectious Diseases and Orbital Resources diminished. Infectious Diseases, however, continue to be the most prevalently discussed topic within this cluster, primarily due to their close association with the globally disruptive COVID-19 pandemic. This implies a sustained high level of public interest and concern in pandemic scenarios.

Relative change of media, blog and scientific discussions around developments in Eco Regeneration & Geoengineering from 2022 to 2023

What do people do?

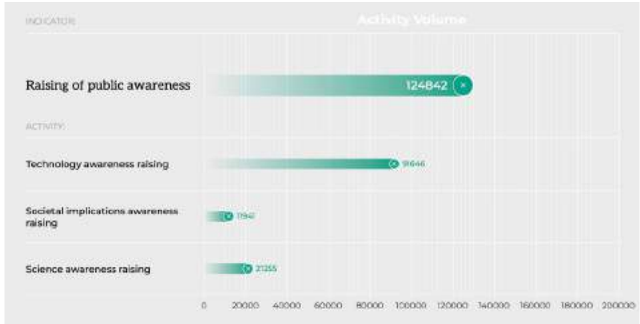
Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected close to 250,000 “actions” in the areas covered by Eco-regeneration & Geoengineering, making this by far the most active domain for this section of the Science Breakthrough Radar. This is due to the nature and breadth of the topics covered – decarbonisation for example – but also the importance of climate-related issues for the civil society actors surveyed.

The energy transition dominates actions by civil society actors

The energy transition, renewable energies (in particular wind and solar), climate technologies and the activities of NASA (space exploration) were some of the areas where most of the activity was detected.

Looking at the volume of detected “actions” across all four indicators, and in comparison with the other scientific platforms, the share of awareness-raising activities was lower. This is explained by a rise in the share of entrepreneurial activities and citizen science contribution.

Two-thirds of actions happened in the field of decarbonisation and, compared to last year, the share of volume attributed to infectious diseases diminished strongly as the COVID-19 pandemic ended. The volume was constant across the surveyed months.



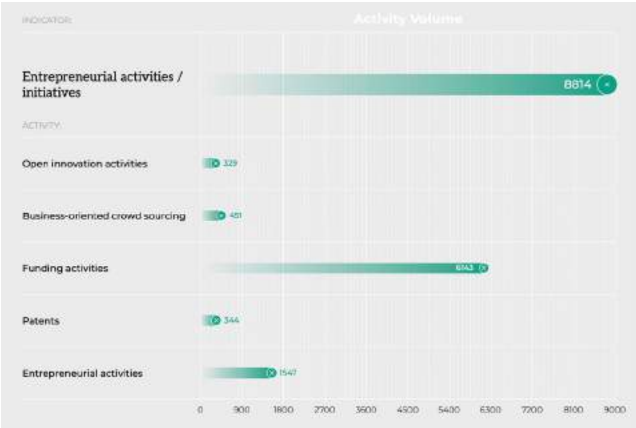
Activities raising public awareness

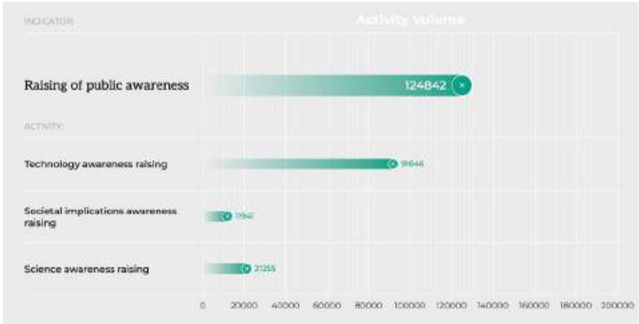
Almost 60 per cent of all technology awareness activities were linked to Decarbonisation, with a focus on renewable energy development, batteries and electricity storage. In contrast, very little activity was detected around carbon capture technologies.

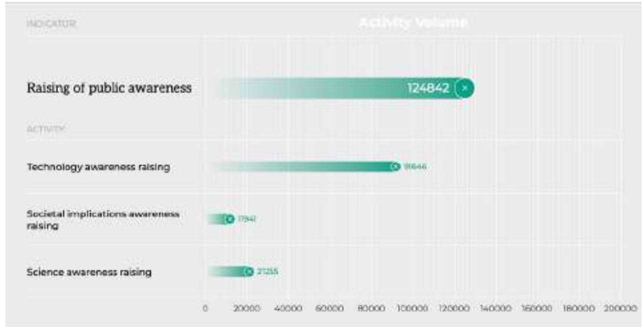
Science awareness-raising activities focused much more on the research enabling space exploitation and exploration, in the interplay between climate change and health, or in relation with the Sustainable Development Goals and climate change more broadly. The implications of the Artemis Accords for space exploration also featured prominently.

Finally, awareness-raising activities about societal implications discussed, among others, the effects of pollution and climate change on biodiversity loss, the rise of antimicrobial resistance, how to ensure better pandemic preparedness or the impact of synthetic fuels on land.

- 3.1 Decarbonisation
- 3.4 Space Resources
- 3.7 Infectious Diseases
- 5.3 Future Economics, Trade and Globalisation







Entrepreneurial activities

This indicator monitors activities like funding announcements, start-up creations, seed investments or actions that enable access to funding opportunities.

Almost all detected activities were related to decarbonisation, especially in the area of electric vehicles, renewable energies (wind and solar) and hydrogen. This is happening globally, with more investments in projects in Africa for this area compared to others.

Zooming in on other topics, we detected significant activities related to urban digital twins, aiming at modelling and simulating socio-ecological systems. In the area of space, beyond the big announcement related to the regain of interest in Moon exploration, open data initiatives appeared to stimulate investments in young companies and the development of new applications.

- 3.1 Decarbonisation
- 3.2 Earth Systems Modelling
- 3.4 Space Resources

Policy-oriented action

Most of the monitored activities targeted governance and regulatory issues around decarbonisation and ways to reach the national net-zero targets.

Still, a significant amount of studies released by think tanks and other civil society associations tackled the economic costs of the energy transition and which measures should be taken by governments to reach their climate pledge in an equal, just and inclusive manner.

In the area of Space Resources, space debris, remote sensing, and the consequences of the Artemis Accords on space exploration and exploitation remained high on the agenda, with calls for more global coordination and legal clarity as the US-China space race ramps up. More concretely, the issue of ownership of extraterrestrial territories and resources was frequently raised.

Finally, related to Infectious Diseases, various actors published recommendations of alternatives to tackle anti-microbial resistance, such as regulatory approaches to reduce veterinary anti-microbial use.

- 5.3 Future Economics, Trade and Globalisation
- 3.4 Space Resources
- 3.7 Infectious Diseases

Contributions to science and technology

Here too, decarbonisation-related activities dominated. One example is the vast number of studies about technology requirements and societal incentives needed to reach to 2050 carbon targets. Beyond the publication of new knowledge, smaller scale citizen science activities such as the launch an open public biofuel laboratory in Argentina, were also taking place.

However, the relative share of citizen science activities was stronger in the other topics surveyed. A typical example is the use of remote sensors to monitor environmental quality and therefore enhance various models of Earth systems.

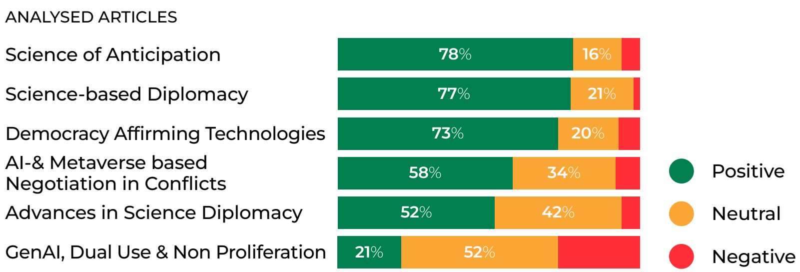
Several educational and outreach activities took place to relay information about space programmes and mission linked to various launches and announcements in the first half of the year. There was also an increased effort to inform about mosquito control and explain the concept of the “exposome” – the impact of environmental exposure on the human body over a lifetime.

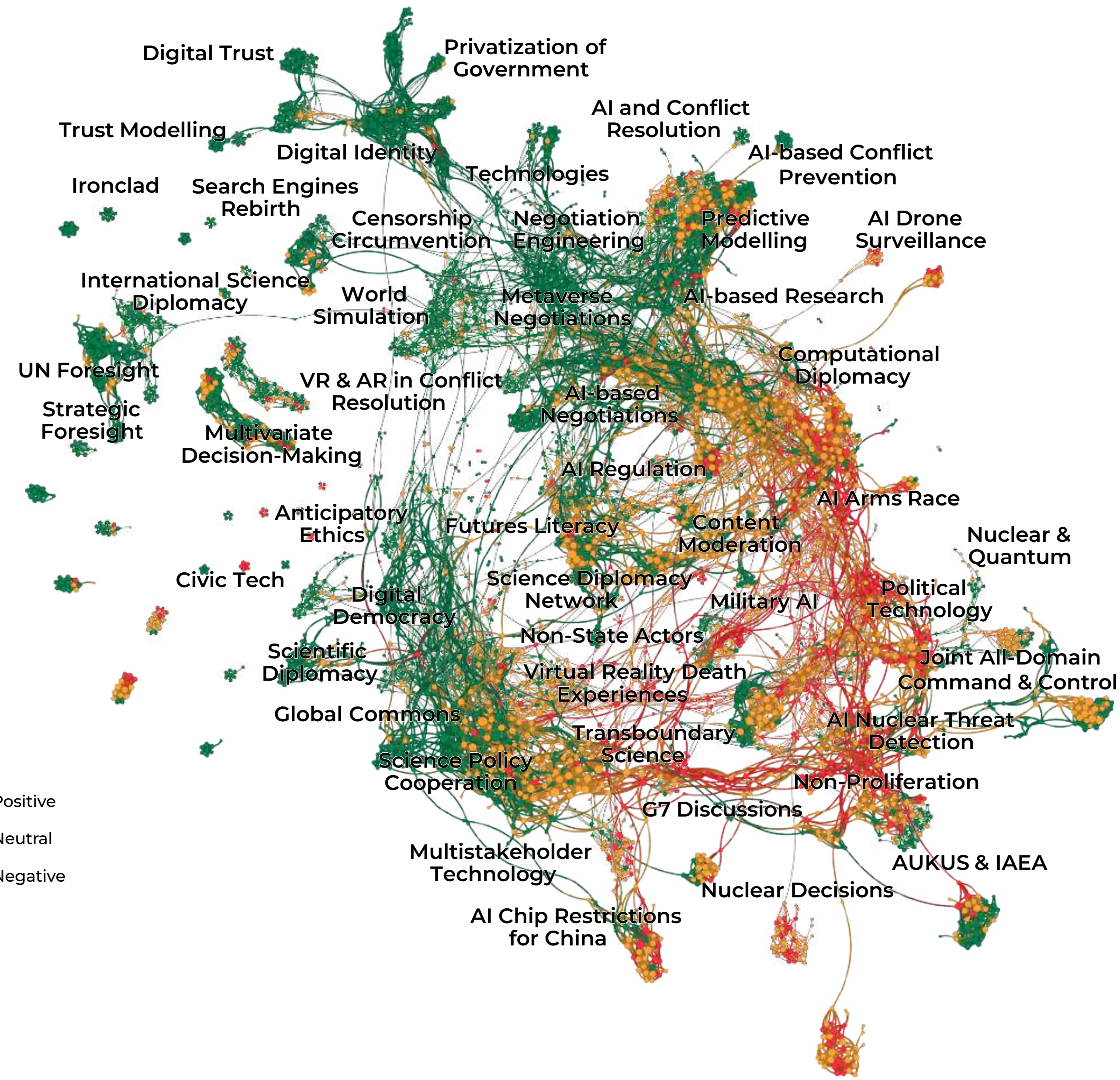
- 5.3 Future Economics, Trade and Globalisation
- 3.2 Earth Systems Modelling

Science & Diplomacy

What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months reveals that the overall sentiment towards Science and Diplomacy is largely positive.





Sentiment Analysis:

Positive sentiment

Positive sentiment is associated with initiatives emphasising the enormous potential of digital technologies in reducing greenhouse gas emissions and driving sustainable practices, focusing on "ethical AI". The European Parliament committee's AI Act has also received positive public sentiment, for factors including its ban on facial recognition in public spaces, predictive policing tools, and new transparency requirements for generative AI applications such as ChatGPT. Additional positive sentiment surrounds the European Union and the United States reaffirming their strong partnership and commitment to advancing transatlantic cooperation in various key areas through the EU-US Trade and Technology Council (TTC).

Neutral sentiment

The need for diplomacy in the face of global challenges, such as climate change and international security concerns, is treated with a neutral sentiment in the media. While environmental protection increasingly takes centre stage, discussions also focus on how nations are grappling with health emergencies and the need for equitable vaccine distribution. Attitudes towards international relations are evolving, with a focus on creating a common shield against shared threats, and fostering economic, strategic, and cultural integration.

Negative sentiment

The rapid advancement of AI is raising concerns about potential dangers, including the risk of weapons automation and AI systems outpacing human control. In Europe, concerns have also arisen regarding the future of global security and the role of the United States, especially in the context of nuclear warfare. Doubts are emerging about the US's reliability in guaranteeing European security.

Key insights:

Prediction and Foresight and **Science-based Diplomacy** display favourable sentiments of 78 per cent and 77 per cent respectively, reflecting optimism for future-readiness and diplomatic advancements driven by scientific insights. Although there is also recognition of existing challenges, such as scientific limitations and potential data validity issues, these subjects are considered significant pillars for global development.

Democracy-Affirming Technologies harbouring 73 per cent positive sentiment underline the potential of technology-enhanced democratic processes. Its 7 per cent negative sentiment underlines concerns about security, misuse, and information manipulation, which underscores the need for robust regulatory measures.

AI- & Metaverse-based Negotiation in Conflicts and **Advances in Science Diplomacy** show balanced sentiments. While optimism is apparent, with 58 per cent and 52 per cent positive sentiments respectively, the significant neutral and negative views reflect tentative confidence amidst concerns over technology's capacity to comprehend complex human interactions and potential risks in international collaborations.

GenAI, Dual-Use & Non-Proliferation are associated with mixed sentiments with 52 per cent neutral, and 27 per cent negative. This dispersion indicates the complex emotions tied to the promise of revolutionising applications that come with associated ethical dilemmas.

Facts & Figures

Mainstream media

Over the past year, an exhaustive collection of 431 thousand pieces spanning news, blogs, and scientific journals unveiled a 62 per cent net positive sentiment within the discourse on Science and Diplomacy.

ANALYSED ARTICLES	VISUALISED ARTICLES
431.0k	2,273
OBSERVATION TIME	NET SENTIMENT[1]
2022/06/12 - 2023/06/12	62%

Social media

Over a 2-year span, 619.6K unique social media posts on platforms such as Twitter, Reddit, and other text-centric channels were screened. Subjects ranged from computational diplomacy, negotiation engineering, predictive peacekeeping, and cooperation modelling, to topics like privatisation of governance and content moderation, contributing to an overall net positive sentiment of 43 per cent.

NUMBER OF POSTS	NUMBER OF MENTIONS	IMPRESSIONS
619.9K	1.2M	86.2B

OBSERVATION TIME	NET SENTIMENT[1]
2 Year	43%

Over the past year, an exhaustive collection of 431 thousand pieces spanning news, blogs, and scientific journals unveiled a 62 net sentiment within the discourse on Science and Diplomacy.

Social media: emerging hot topics and discussions

Inclusive global diplomacy

There is a growing consensus in social media discussions: while predictive models for responsibly preventing conflict can provide essential insights for pre-emptive action, it is crucial to approach them ethically, considering potential data misuse, privacy rights violations, and algorithmic bias. Social media discussions spotlight prominent academic voices and civil society groups as valuable contributors to achieving global consensus on issues such as climate change and cybersecurity, reflecting a transformation towards more inclusive and cooperative international diplomacy. However, concerns about these actors undermining state sovereignty or being manipulated for destructive purposes are also prevalent.

Unity for sustainability

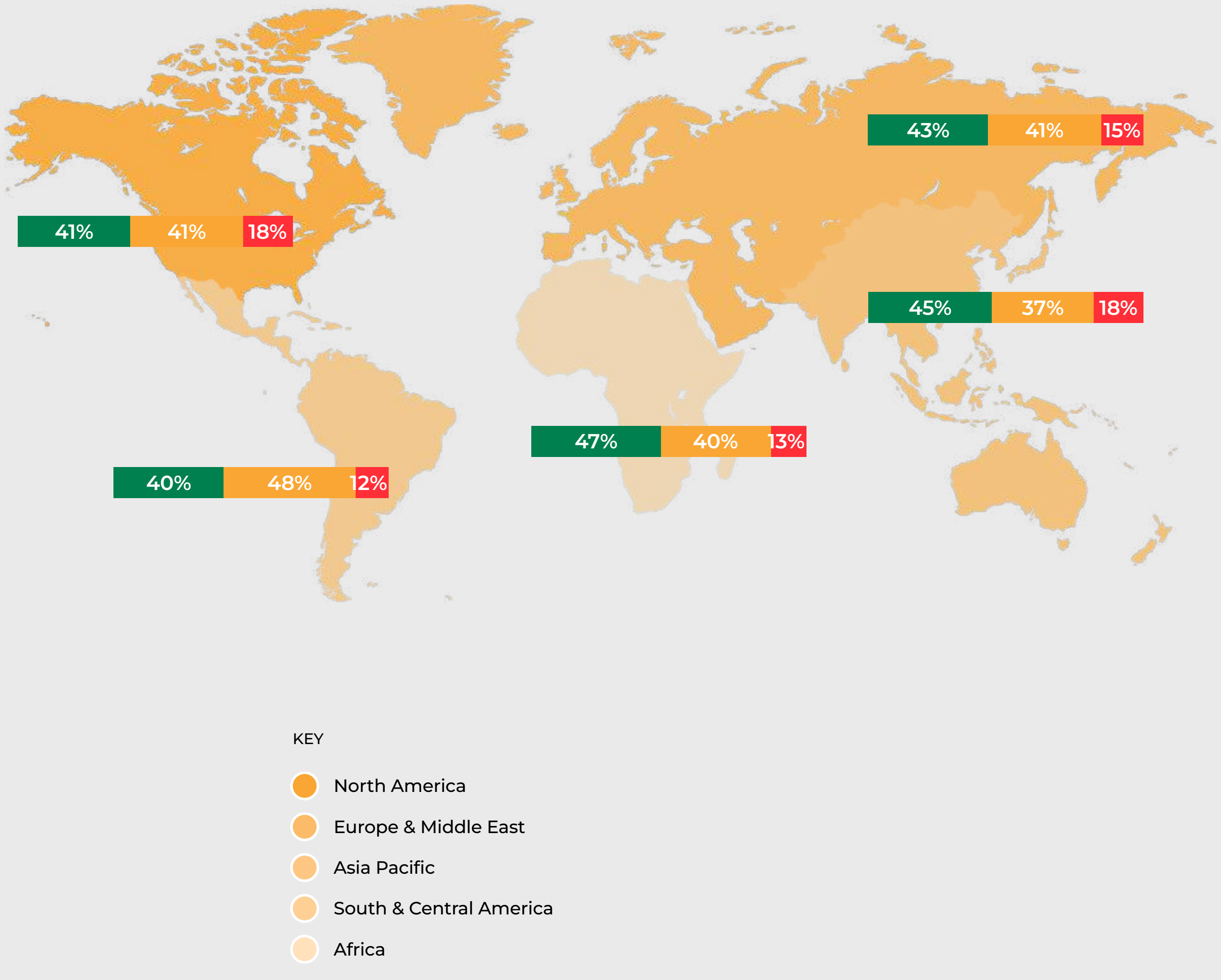
Social media discussions on the sustainable management of global commons such as the oceans, the internet and outer space call for universal norms to ensure internet security, non-militarisation of outer space, and marine biodiversity conservation. Amidst ongoing geopolitical shifts and climate crises, the need for proactive approaches towards sustainable development and climate change mitigation is eagerly debated. The discourse also underscores the importance of multilateral diplomacy in addressing socio-economic disparities and collective responsibilities, encouraging a unified approach to global sustainability.

Free speech, censorship and misinformation

Online discussions on censorship circumvention and content moderation reveal a tension between the protections for free speech and the necessity to prevent harm and misinformation. Advocates propose concepts like social circuit breakers and improved moderation practices. Proponents of free speech express concerns regarding potential misuse of content moderation to suppress dissenting voices, demanding legal safeguards and transparency. In restrictive societies, circumventing censorship via technology is viewed as essential for preserving freedom of speech.

AI and dual-use concerns

Discussions on social media about AI often revolve around how technologies can be regulated to prevent misuse in both military and civilian contexts. Representing diverse standpoints, people are increasingly interrogating the ethical ramifications of dual-use AI technologies and the need for comprehensive regulatory strategies to curb their potential misuse. Highlighted is the importance of human control in the use of AI, the prevention of premature technology usage, and the necessity for an inclusive, multilateral perspective in formulating AI governance norms.



Sentiment towards Science and Diplomacy across the world

- South Africa is the primary hub within Africa for social media discussions intersecting science and diplomacy.
- Central and South American discourse is predominantly within Uruguay, French Guiana and Costa Rica.
- The US maintains a leading role with 56 per cent of global posts on the science diplomacy interface.
- The sentiment analysis of global posts discussing the intersection of science and diplomacy reveals a relatively even distribution across various regions. This uniformity suggests that the impact of scientific advancements on diplomacy and policymaking is a topic of equal interest worldwide, cutting across regional and cultural boundaries.

How is sentiment changing?

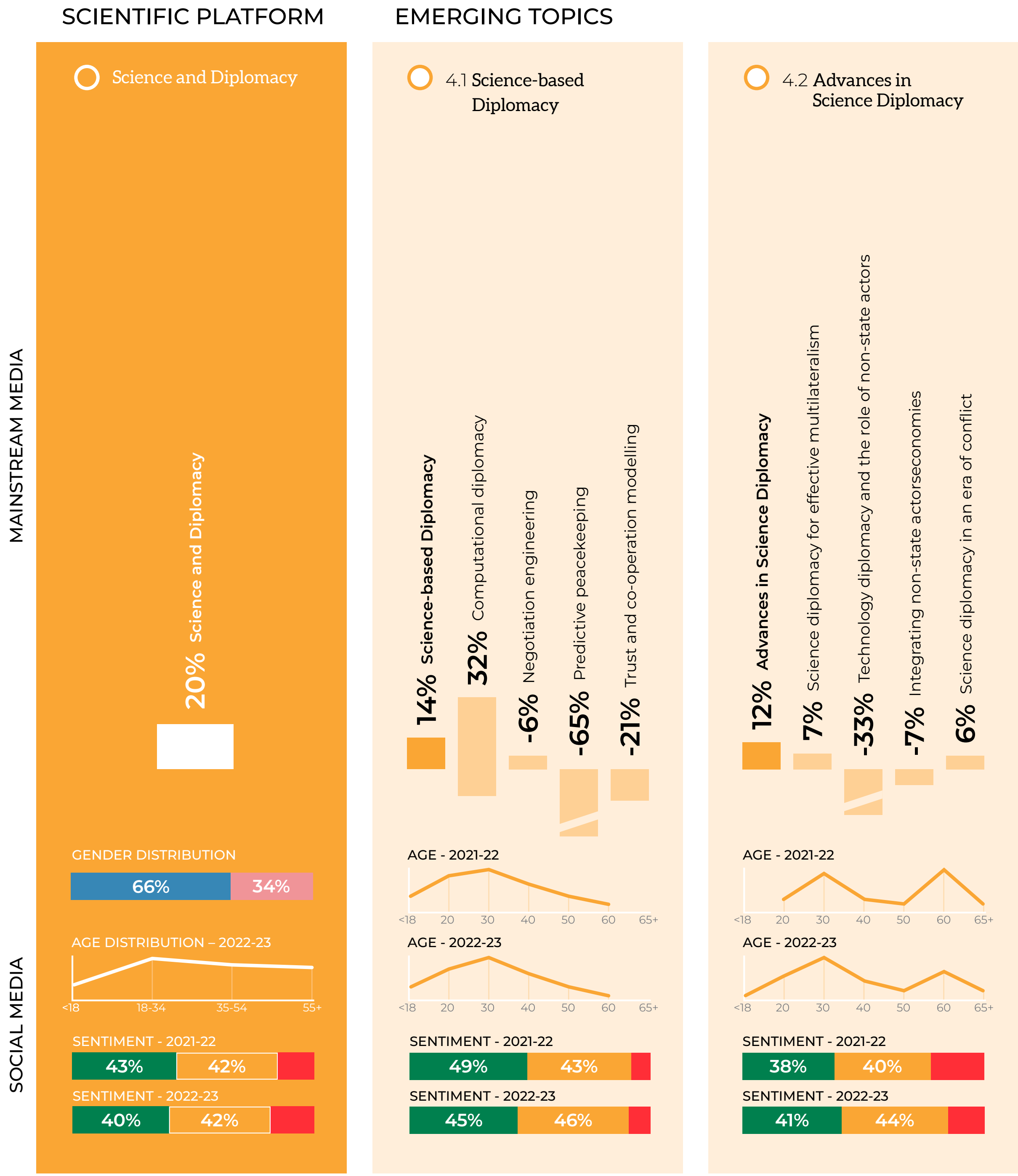
Mainstream media coverage has increased

In 2022, 358,200 media articles were published relating to Science and Diplomacy, increasing to 431,000 articles by 2023. AI's impact on nuclear disarmament and threat detection, as well as AI and dispute resolution, have shown the greatest increase in media popularity during this time, while coverage of predictive peacekeeping, concerns around dual-use technology and multistakeholder technology diplomacy have decreased.

Social media reveals changing sentiments and demographic engagement

While overall popularity and engagement concerning science and diplomacy have been on the rise, Science-based Diplomacy and related keywords have experienced a slight decline. Contrarily, AI-based and VR-augmented negotiation in conflicts have tripled their annual post mentions, showcasing a stark shift in public interest and engagement towards these technologically advanced negotiation methods.

A sentiment analysis of the posts on science and diplomacy-related topics, including metaverse, augmented reality, and AI-aided conflict resolution, uncovers a slight upsurge in negativity between 2022 and 2023.



ASSOCIATED TOPICS

Relative change of media, blog and scientific discussions around developments in Science & Diplomacy from 2022 to 2023

What do people do?

Our monitoring tool detected just over 72,000 "actions" by civil society actors (citizens, small groups and NGOs) in the areas covered by the Science and Diplomacy scientific platform. Compared to the other 3 scientific platforms analysed, we observe a larger share of citizen science contributions and policy-oriented actions. This is explained by the nature of the emerging topics considered, with, for example, the detection of many citizen-led projects in the area of democracy-affirming technologies.

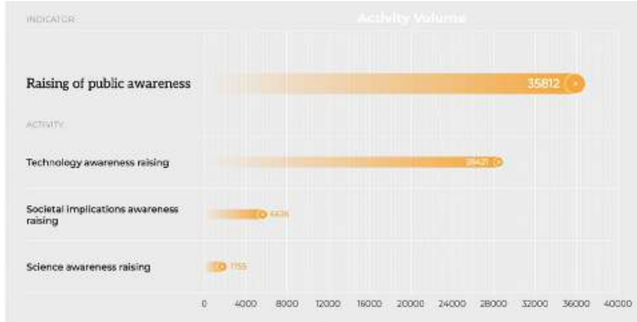
Censorship in the cyberspace (and ways to avoid it) and cybersecurity dominate

Of all the emerging topics considered, we observed the largest share of activities in Democracy-Affirming Technologies. They mainly concerned activities aimed at strengthening privacy, circumventing censorship measures in the digital space and issues related to digital trust and security.

Blockchain was continuously mentioned as a technology that could be used to enhance privacy, transparency, security and trust, and saw significant activity by a whole range of actors (citizen groups, small business and so on) over the four indicators.

Approaches to science-based diplomacy rooted in game theory and data-driven decision-making also saw significant activity.

On science diplomacy itself, the field also seemed to have gained traction here, with different awareness-raising and capacity-building activities across the globe. Actors and communities in Turkey and India have been reaching out to their science diasporas in views to tackle common regional challenges and strengthen ties, for example.



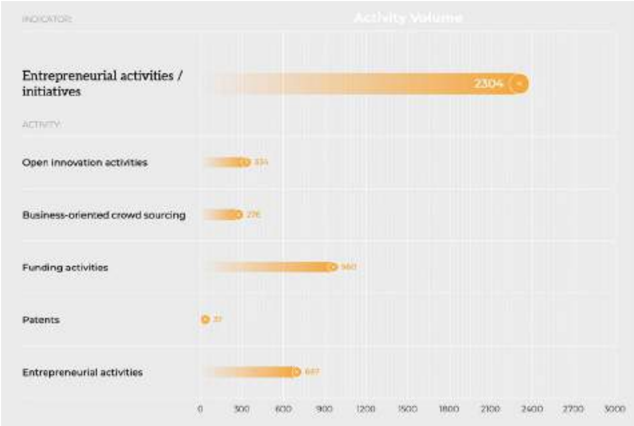
Activities raising public awareness

Most awareness-raising activities dealt with the consequences of cyberattacks and data breaches, and what needs to be done to protect cyberinfrastructure, especially in the context of political processes increasingly relying on digital tools (digital democracy).

While "technology awareness raising" remained by far the stronger variable for this indicator, awareness-raising about societal implications of developments in this area were relatively higher. This concerns among other how new (digital) technologies affect society, governance and geopolitics, and shape conflicts. Misinformation, manipulation and deepfakes – in the context of the war in Ukraine – was a domain that saw significant activity under this indicator.

4.4 Democracy-affirming technologies

5.1 Complex Systems Science



Entrepreneurial activities

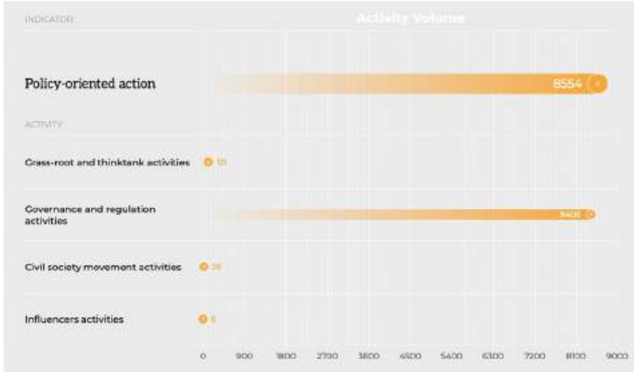
Most entrepreneurial activities were linked to democracy-affirming technologies; more specifically, they concerned funding activities linked to open government initiatives (open data) or the deployment of blockchain-based solutions.

In the areas covered by science-based diplomacy, entrepreneurial activity was less intense and focused on the development open ecosystems to explore data-driven collaborative decision-making approaches.

The hackathon on quantum computing for social good, jointly organised by GESDA and New York University Abu Dhabi, was identified as one of the entrepreneurial activity linked to science and diplomacy that bridged quantum computing communities across the world with international organisations.

4.1 Science-based diplomacy

4.4 Democracy-affirming technologies

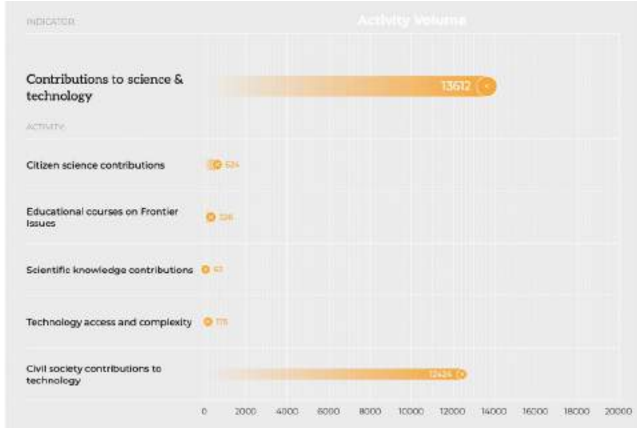


Policy-oriented action

Compared to the three scientific platforms monitored, the area of Science and Diplomacy saw the largest share of policy-oriented activities. They mostly focused on governance and regulation activities in relation to misinformation – we observed a sharp increase in the early part of the year, linked to the deployment of generative AI tools, cyberwarfare and the role of open source intelligence, and cryptocurrencies.

We detected relatively few activities of civil society movements. They dealt among others with the creation of Decentralised Autonomous Organisations build on blockchain technology and tackling different challenges linked to sustainable energy and the climate.

4.4 Democracy-affirming technologies



Contributions to science and technology

Close to a quarter of all monitored activities for the Science and Diplomacy platform were linked to contributions of non-traditional academic actors to science and technology. This is a larger share than for the other scientific platforms analysed.

As an example of activities this concerned, we can mention tools such as Virtual Private Networks (VPNs) for anonymous web browsing or to evade digital censorship mechanisms, information about next-generation blockchain-based applications or about the latest thinking about science diplomacy: for example, the outcomes of the China International Forum on Science and Diplomacy.

Finally, labelled as "citizen science activities" we monitored a number of community-driven open source initiatives to foster cybersecurity and detect threats. We also observed a series of initiatives experimenting with various form of decentralised networks for more transparent governance.

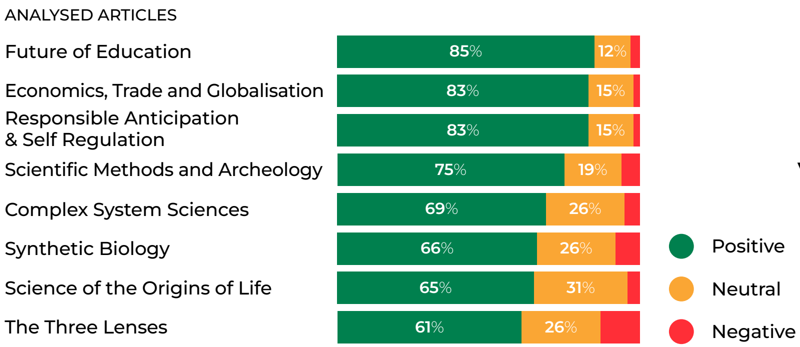
4.2 Advances in Science Diplomacy

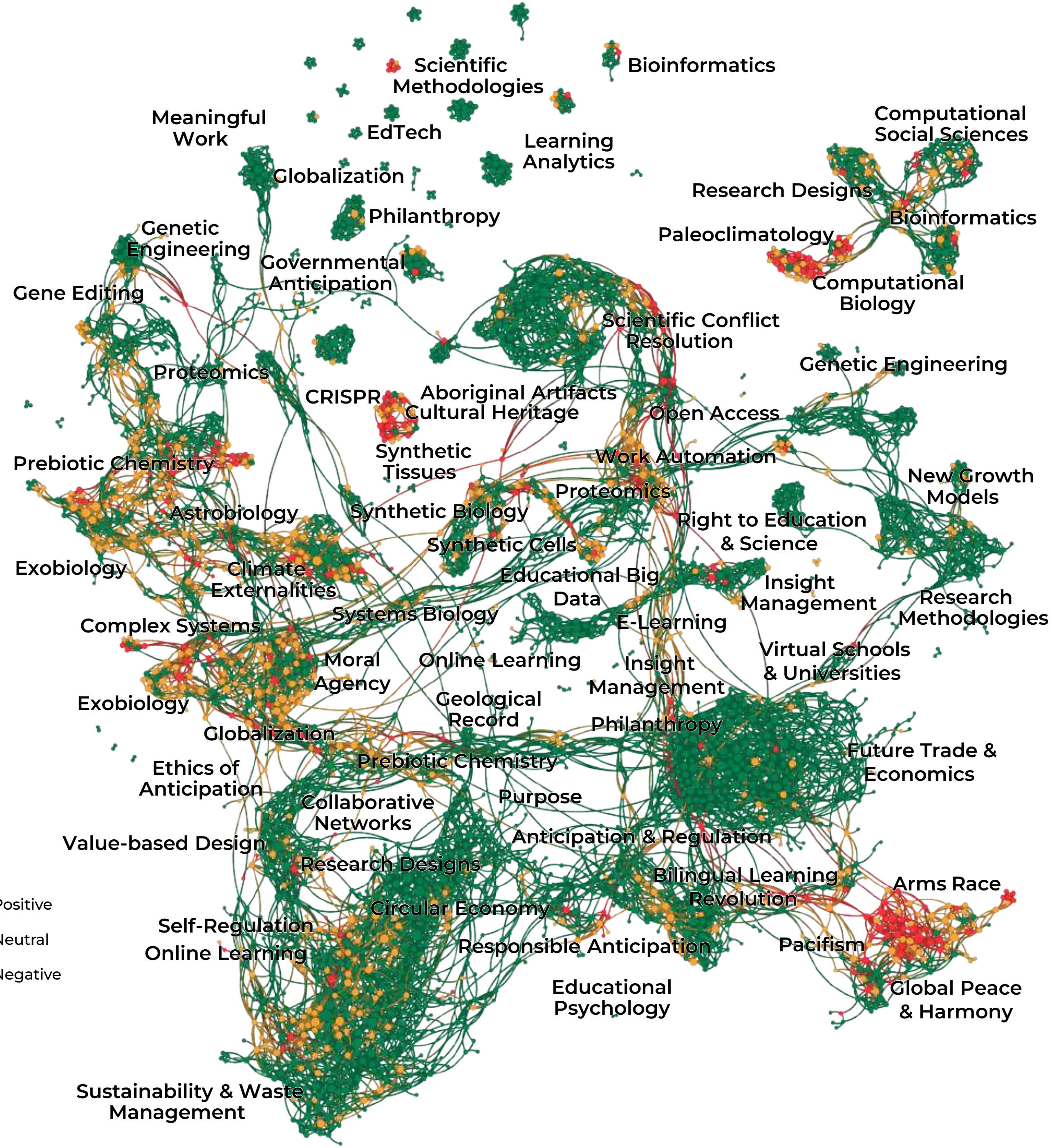
4.4 Democracy-affirming technologies

Knowledge Foundations

What do people say?

Analysis of mainstream media articles, blog posts and scientific articles over a period of 12 months reveals that the overall sentiment towards the topics covered under Knowledge Foundations are largely positive.





Sentiment Analysis:

Positive sentiment

The transformation of education through EdTech, providing personalised and collaborative learning experiences, is received positively in news and blogs. There is also a growing positive sentiment towards purpose-driven actions: high school students championing chosen causes, and businesses shifting their models to better serve societal and global needs. Furthermore, the advocacy for purpose-driven work cultures, bringing increased productivity and satisfaction, further underlines this overarching trend of purpose shaping personal and professional identities.

Neutral sentiment

The mystery surrounding life's origin generates mixed sentiments in news and blogs, as does the ground-breaking progress in synthetic biology. While advances in synthetic biology tools are considered to vastly improve therapeutic capabilities and expedite the creation of novel treatments, concerns about ethical implications, long-term effects, and potential risks are echoed in the discourse. On the topic of economics, the circular economy model is positively viewed as a solution for sustainable development, but changes to the global waste trade fuel both optimism and concern.

Negative sentiment

Significant advancements in gene editing technologies such as CRISPR are stirring up controversies and negative sentiments, including debates about the safety and regulation of inheritable genetic modifications. In terms of the geopolitical climate, global reports reflect rising apprehension and negative sentiments due to escalating conflicts and unresolved geopolitical tensions. There is a call for an urgent, new world order based on human morality, with a focus on ensuring global peace and solidarity amidst escalating discord.

Key insights:

The **Future of Education, Economics, Trade and Globalisation**, and **Responsible Anticipation and Self-Regulation** are associated with high positive sentiments of 85 per cent, 83 per cent, and 83 per cent respectively, reflecting the general optimism in opinion towards these themes.

Other topics such as **Scientific Methods and Archaeology**, and **Complex System Sciences** also carve out a relatively high positivity at 75 per cent and 69 per cent, suggestive of societal appreciation for foundational scientific methodologies. The small amount of negative sentiment associated is reflective of inherent complexities and accuracy concerns shared across the various topics.

Synthetic Biology and the **Science of the Origins of Life**, with a positive sentiment of 66 per cent and 65 per cent, reflect the profound interest in life's mysteries and bioengineering innovations. The observed negativity is caused by shared apprehensions over ethical and safety implications pervading various cutting-edge scientific fields.

The Three GSDA Lenses, although overall displaying 61 per cent positive sentiment, also shows a comparatively higher negativity at 13 per cent, highlighting society's cautious approach when it comes to overarching perspectives or philosophical meta-analyses, a sentiment echoed across multifaceted subject areas.

Facts & Figures

Mainstream media

In the last year, an analysis of 150,000 articles spanning various platforms revealed an 84 per cent net positive sentiment in the discourse on knowledge foundations, touching upon a broad array of topics from Complex Systems Science to the Future of the Scientific Method.

ANALYSED ARTICLES	VISUALISED ARTICLES
149.8k	**3,157**
OBSERVATION TIME	NET SENTIMENT[1]
2022/06/12 - 2023/06/12	**84**%

Social media

Over a 2-year period, 722K unique social media posts from platforms such as Twitter, YouTube, and various other text-based channels were analysed. These covered an extensive range of themes, from Complex Systems Science and Digital Democracy to Synthetic Biology and the Future of Peace and War, culminating in an overall net positive sentiment of 58 per cent.

NUMBER OF POSTS	NUMBER OF MENTIONS	IMPRESSIONS
722.6K	**1.5**M	**121.4**B

OBSERVATION TIME	NET SENTIMENT[1]
2 Year	**58**%

In the last year, an analysis of 150 thousand articles spanning various platforms revealed an 84 net sentiment in the discourse on knowledge foundations, touching upon a broad array of topics from Complex Systems Science to the Future of the Scientific Method.

Social media: emerging hot topics and discussions

Balancing the role of technology in education

The role of technology in education has sparked vibrant debates on social media about whether it enhances learning or compromises the interpersonal skills and community ethos in traditional classrooms. Social media dialogues emphasise how technology can pave the way for inclusive, personalised education. Yet discussions also caution against excessive reliance, which could risk overshadowing the benefits of traditional classrooms. The challenge underscored in these online debates is about finding the right balance where technology can augment learning without compromising the social interactions and sense of community inherent in a traditional classroom setting.

Innovation embedded in ethics

On social media platforms, there are many discussions focused on balancing innovation stimulation with ensured ethical conduct in science and technology. Often highlighted is the desire for a holistic approach to tackle ethical dilemmas in the tech industry, integrating ethical principles into the innovation framework itself.

Synthetic and extra-terrestrial life

Advances in synthetic biology, particularly the use of the CRISPR/Cas9 genome editing tool, have been picked up and amplified across social media, with a focus on the potential of synthetic biomolecules across sectors. The revolution in producing synthetic biomolecules is generating discussion about a sustainable and efficient future. Recent efforts to search for extra-terrestrial biosignatures and simulate life's origins have also been a hot topic of future-centric debates.

Sustainable economic practices

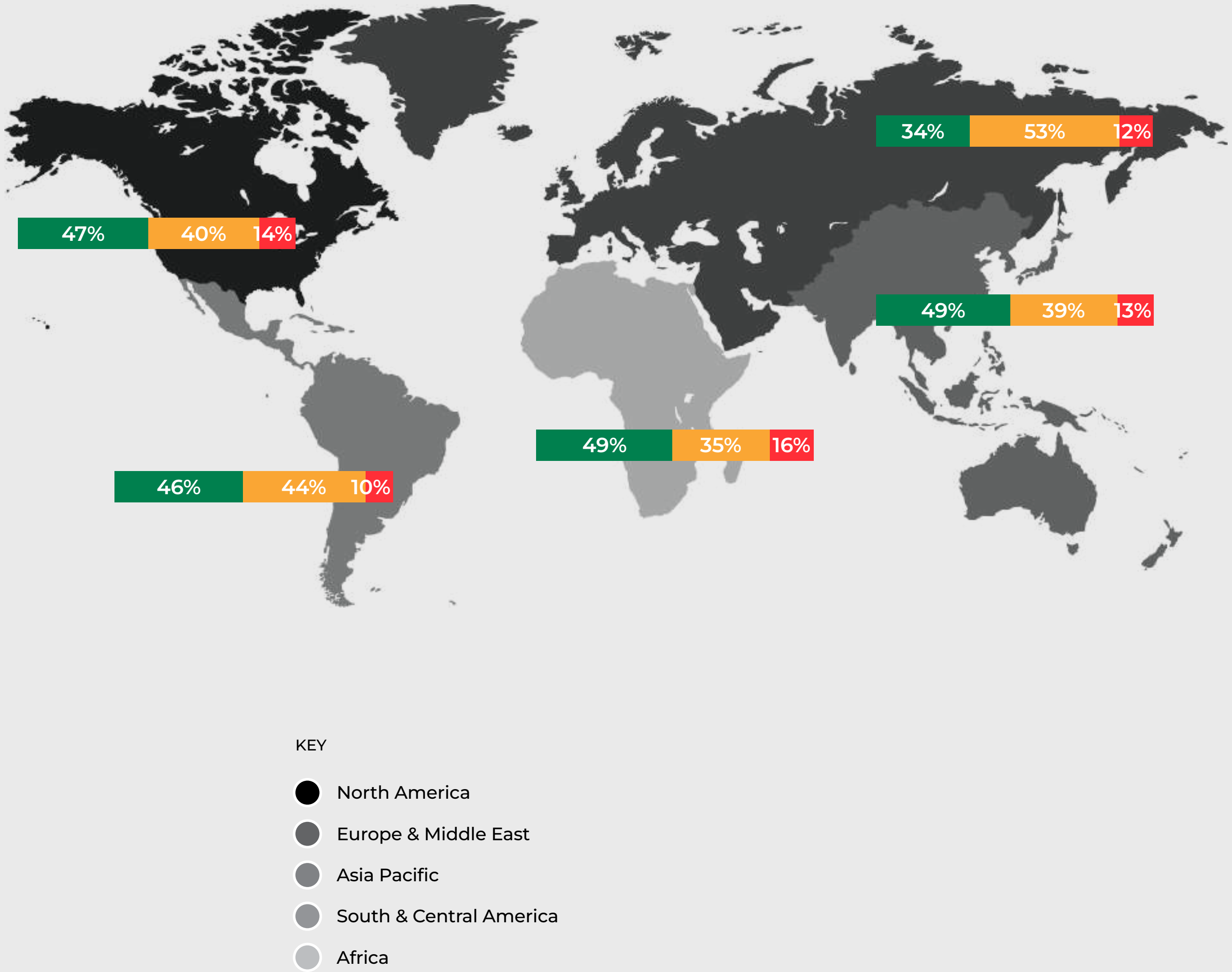
Public discourse is increasingly focusing on the pivot from extractive to regenerative economic models, including the future sustainability and fairness of global economies. The exploration of indigenous practices to foster an understanding of sustainable, reciprocal relationships with natural systems, and integration of these practices into future policies and initiatives, is discussed.

The digital divide and distribution of power

The struggle towards achieving widespread digital accessibility is stirring debates on social media. Digitisation's potential to democratise or concentrate wealth and power features prominently in social media discussions. Social media dialogues emphasise that while digitalisation can create sustainable, innovative economies, it risks exacerbating existing inequalities if not distributed equitably.

Technology in peace and war

The role of technology in peace and war is a recurring topic of discussion in online platforms. The debate hinges on whether technology can act as a catalyst for peacebuilding, or whether it merely presents new mechanisms to instigate conflict. Social media discussions highlight how digital tools can foster connectedness, empathy, transparency, and accountability, all critical to maintaining peace but simultaneously useful for cyber warfare, disinformation, and societal disruption. A prevailing theme in these discussions is the need to use technology to promote peace while addressing the potential risks it can pose to global security.



Sentiment towards Knowledge Foundations across the world

- 90 per cent of discourse relating to the Knowledge Foundations in African nations takes place in Ghana, Kenya, Nigeria, South Africa, Namibia, and Botswana. The influential sentiments involved in these discussions showcase a mix of extreme positivity and negativity, implying strong feelings regarding these subjects.
- Within Europe and the Middle East, countries like Montenegro, Estonia, and Ireland see the most discussion per capita concerning knowledge foundations. Conversations generally display a neutral sentiment.
- In South America, the majority of social media discussions (75 per cent) can be attributed to Colombia, Brazil, and Mexico.
- Within the APAC region, India is the leading contributor to dialogue regarding knowledge foundations, with a particular focus on discussions about technological advancements.
- North America contributes the most to global English language discussions about knowledge foundations.

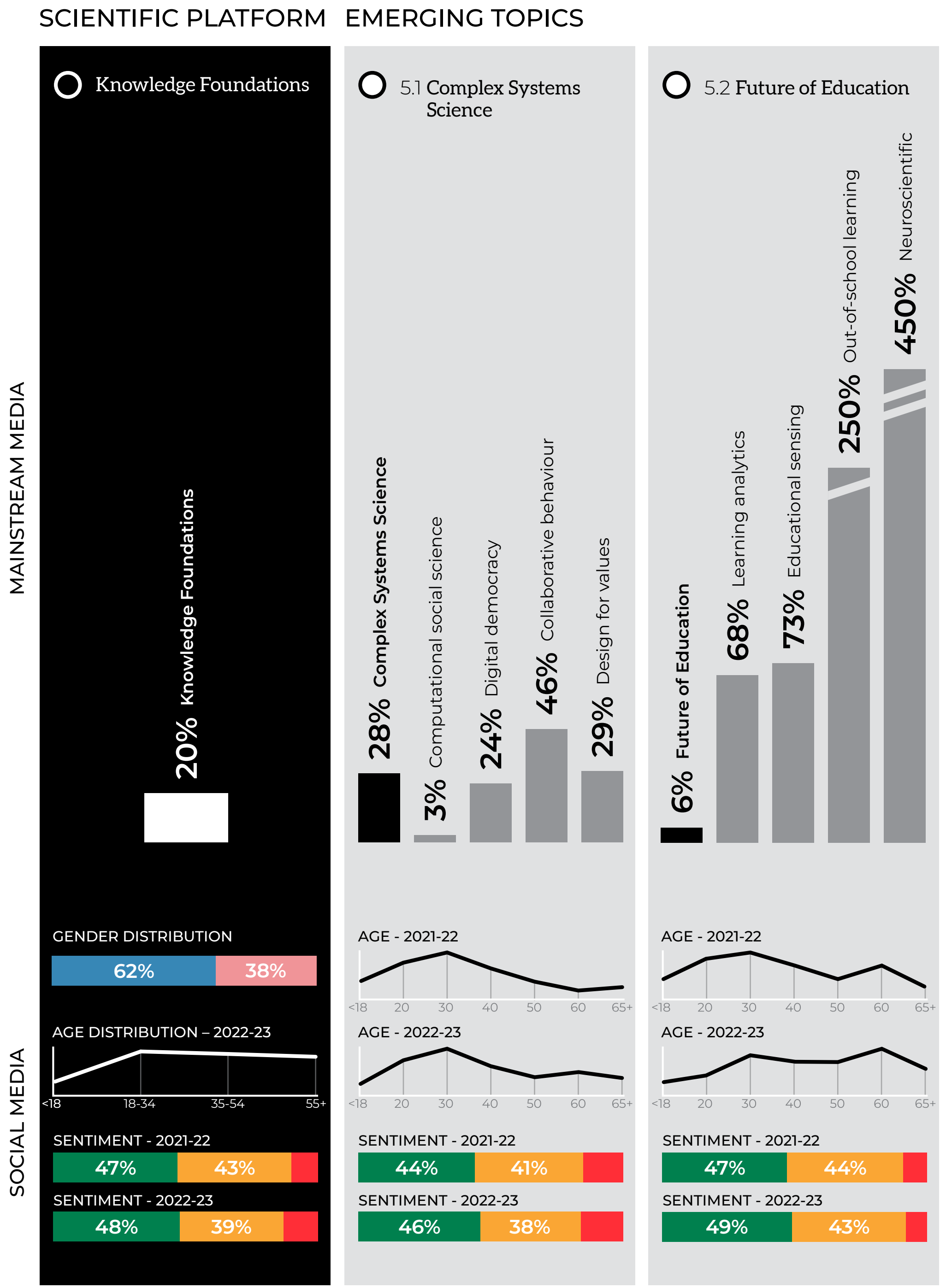
How is sentiment changing?

Mainstream media coverage has increased moderately

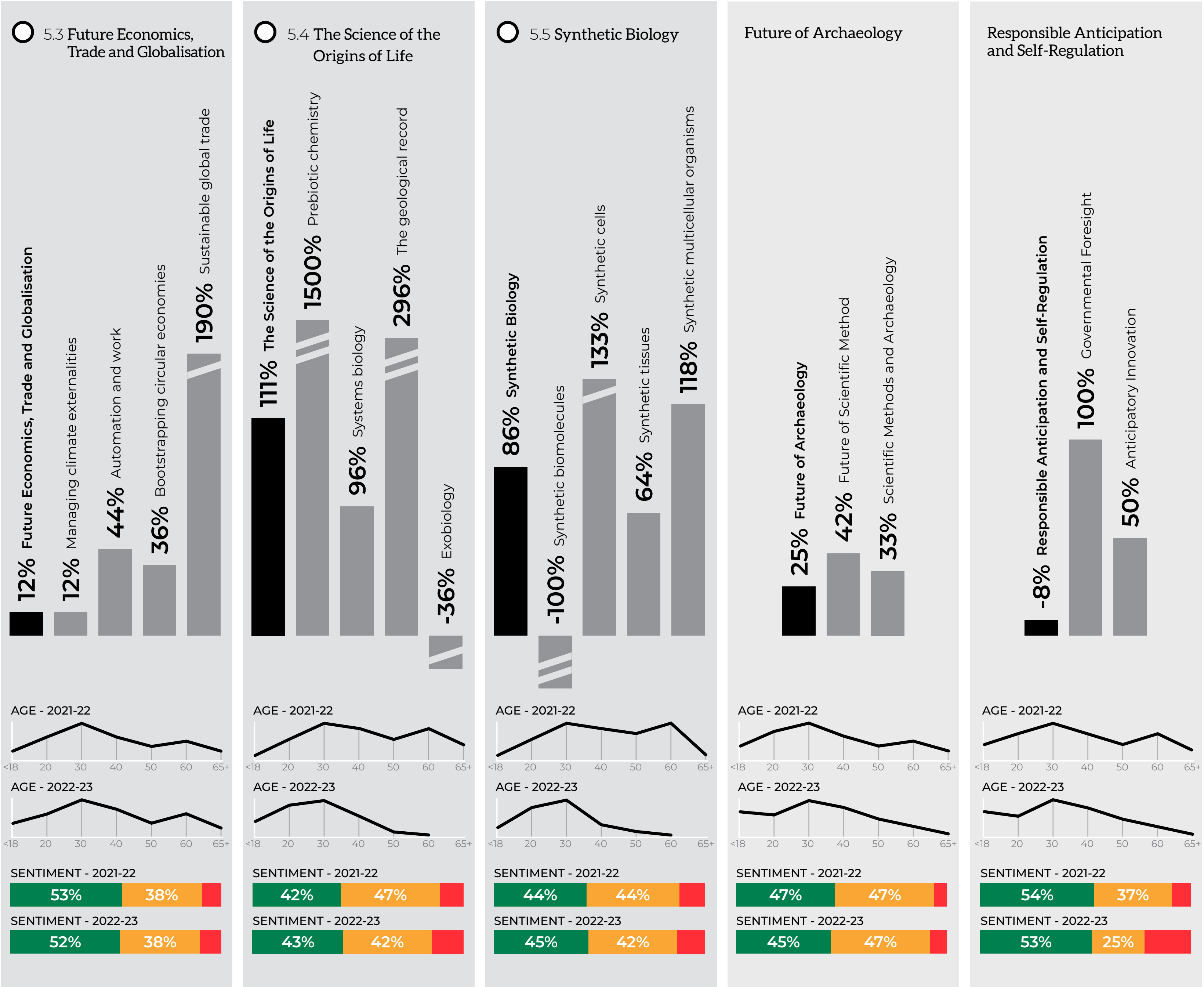
In 2022, 124,500 media articles were published relating to topics within Knowledge Foundations, increasing to 149,100 articles by 2023. Out-of-school learning, neuroscientific aspects of learning, prebiotic chemistry and the geological record have shown the greatest increase in media popularity during this time, whilst mentions of synthetic biomolecules have decreased the most.

Social media reveals changing sentiments and demographic engagement

Across the spectrum of topics classified under Knowledge Foundations, the overall social media sentiment leans towards positivity, averaging at 58 per cent. The majority of analysed posts revolve around Scientific Methods, Archaeology, and the Future of Education, which have increased in popularity over the past two years, reflecting growing public engagement and interest.



ASSOCIATED TOPICS



Relative change of media, blog and scientific discussions around developments in selected Knowledge Foundations from 2022 to 2023

Opportunities

Taking the Pulse of Diplomacy

Alexandre Fasel
Outgoing Chair of the GESDA Diplomacy Forum,
Swiss State Secretary for Foreign Affairs,
Former Swiss Special Representative for Science Diplomacy

Opportunities
Introduction

The GESDA Science Breakthrough Radar presents an overview of some of the world's most anticipated scientific disruptions and how the world's citizens are discussing, perceiving and acting in response to them. These breakthroughs and the related discussions contribute to our evolving understanding of what makes us human and how we relate to each other and to our ecosystem. GESDA was developed to anticipate those future breakthroughs and their impacts. The key question now is what can and should be done about it. By leveraging the Geneva International ecosystem and the diplomacy community at large, GESDA aims to accelerate the ways in which we can derive collective benefits, making the most of opportunities to translate proposals into concrete initiatives, and creating new ways for different stakeholders to contribute to a better future. In doing so, we can move from scientific anticipation to anticipatory science diplomacy in order to:

- respond more effectively and more quickly to emerging and future challenges, always keeping the huge costs of non-anticipation and missed opportunities in mind.
- help — as an honest broker — multilateralism adapt to the acceleration of science, ensuring that its benefits are co-developed and enjoyed by all of the world's inhabitants equally.
- offer a platform for joint deliberation across all communities on possible solutions to the emerging challenges In this spirit, the annual Geneva Science and Diplomacy Anticipation Summit examines the most anticipated scientific disruptions in order to build consensus around potential initiatives for addressing practical problems.

This is why this last section of the Science Breakthrough Radar, in analogy to GESDA's Anticipatory Situation Room Methodology, is reflecting on the necessary ingredients to move from the knowing to the acting, or in GESDA's words, from Think Tank to Do Tank. The essays, acting as a honest broker, the cost of non-anticipation and the ethics of anticipation presented in the past edition and available on the digital edition of this report provide additional essential reflections about the required essential ingredients and how to understand the key summit takeaways presented in the following pages. It contains a report on the incubation phase of the Open Quantum Institute, and a summary of the 2022 GESDA Summit, with an introduction to the event, and a selection of proceedings and takeaway messages serving as a basis for the collective solution development process.

Marieke Hood
Executive Director Impact Translator, GESDA

The Opportunities of Quantum: The Open Quantum Institute Incubation Report 2023

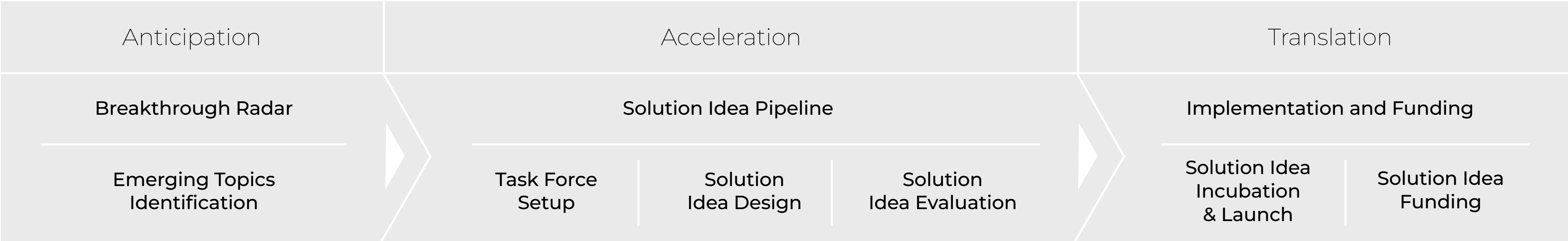
The Geneva Science and Diplomacy Anticipator (GESDA) is a Swiss independent private non-for-profit Foundation, established as a global Public Private Partnership by the Swiss and Geneva governments in 2019.

GESDA's mission is to develop an instrument of anticipation and action to provide solutions to current and future technological challenges, turn them into opportunities and widen the circle of beneficiaries of advances in science and technology.

Beyond a think-tank, GESDA is also a do-tank. GESDA is committed to ideate and design Solution Ideas for effective multilateralism with its science diplomacy community. GESDA then incubates and implements the most globally relevant and transformative of these Solution Ideas with its partners.

GESDA does not aim to host and manage the initiatives beyond an initial incubation phase. Its goal is to hand over the initiatives with proven viability which are ready to be fully deployed, so that implementation partners with the institutional capacity and the operational means can build them at scale. This includes securing the funding of the first years of operation of the initiative.

Think Tank to Do Tank



Quantum technologies is the most advanced in the Anticipatory Situation Room pipeline. The related solution idea — the Open Quantum Institute (OQI) — reached the incubation phase in 2023.

From the 42 emerging scientific topics covered by GESDAs Science Breakthrough Radar, quantum computing has been identified by GESDA's Academic and Diplomacy Forum as a technology with great transformative capability requiring a science and diplomacy mobilisation to ensure global access and benefits.

The main considerations justifying the selection of quantum computing as a priority domain for GESDA are:

- If the unprecedented computational speed-ups enabled by quantum computing are directed towards the right issues — such as materials science, chemistry, energy, or logistics — the technology could enable scientific and technological breakthroughs that could transform the lives of millions.
- Since quantum computers are hugely expensive and hard to build, ensuring broad access to them is difficult. Until now, their development has been concentrated in a handful of nations and large multinational corporations, with a risk of widening the digital divide.
- Little work has been done to investigate how quantum computing could help accomplish the UN's Sustainable Development Goals (SDGs), for example, on challenges related to climate, food security or health. Quantum computing could reveal many such benefits if sufficient resources were dedicated to exploring use cases that have so far been neglected due to the lack of an obvious business case.

Based on these considerations, GESDA set up a Task Force on Quantum Computing to imagine a science diplomacy solution tackling these global challenges. This international multistakeholder group, composed of academic researchers, diplomats, and industry leaders both from corporates and start-ups, worked until October 2022, when their proposal of an Open Quantum Institute was made public.

Located in Geneva, the OQI is intended as a novel multilateral and multistakeholder anticipatory science diplomacy instrument, with the following objectives:

- **Accelerating the exploration of use cases of quantum computing** geared towards the achievement of the SDGs and other beneficial applications for humanity, linking industry and academic researchers and developers to SDG experts and UN organisations.
- **Widening the circle of beneficiaries and users of quantum technologies** by providing global, inclusive and equitable access to a pool of public and private computers and simulators available via the Cloud.
- **Levelling the playing field** by developing the capacity building instruments for all bright minds across the world to contribute to the development of the technology, notably those in currently underserved geographies.
- **Providing a neutral forum for diplomatic discussions** to frame the future quantum computing multilateral governance enabling the technology to be leveraged for the SDGs.

Once at full speed, the OQI and its partners aim to deliver a pipeline of disruptive innovations enabled by quantum computing.

The OQI proposal unveiled at GESDA's summit in 2022 gained significant traction in the quantum community and with diplomacy stakeholders, as illustrated in the table of supporting partners below. The Summit enabled gathering comments on a Solution Idea from all GESDA communities: academic, diplomatic, impact and citizens. A further call for such comments followed, feeding the final evaluation by the quantum task force.

Academic

Supporting letters from

CERN, EPFL, ETH zürich, JÜLICH Forschungszentrum, Imperial College London, NITheCS National Institute for Theoretical and Computational Sciences, Quantum Delta NL Centre for Quantum & Society, RRI, University of Calgary, University of Copenhagen, Université de Genève, University of KwaZulu-Natal Inyuvesi YakwaZulu-Natali, جامعة نيويورك ابوظبي NYU Abu Dhabi, Bibliotheca Alexandrina مكتبة الإسكندرية

Diplomacy

Permanent Representatives from a number of countries are actively helping shape the multilateral relevance of the future Open Quantum Institute

Australia	Japan	Netherlands
Austria	Malta	Pakistan
Brazil	Mexico	Singapore
France	Morocco	Switzerland

Intergovernmental Organisations and **NGOs** have been actively helping in defining possible Quantum for SDG use cases

gain Global Alliance for Improved Nutrition, ICRC, Periodic Table of Food Initiative, SDG Lab, UN-Habitat For a Better Urban Future, UNFCCC, WFP World Food Programme, World Health Organization, WIPO World Intellectual Property Organization

Impact

Supporting letters from

AQT, aws, IBM, IQM, Microsoft, OQC, PASQAL, Strange Works

Impact

Strategic partners

Fondazione Compagnia di San Paolo, XPRIZE

GESDA's Board of Directors decided early in 2023 to fund and incubate the OQI, with a 2024 launch target to be followed by a pilot implementation phase that runs until December 2026. GESDA's objective with the incubation phase is to hand over an initiative with the best chances of success to a strong operating partner, which is already on the move, can demonstrate positive initial results and has sustainable governance in place.

During the incubation, OQI stakeholders from all four communities were engaged with the process, helping to shape the progress, status, results and offering of the OQI initiative. While the GESDA OQI Team managed OQI's incubation progress, a group of senior advisors formed the OQI Incubation Advisory Board which lead the strategic work within the different work packages.

Members of the Advisory Board are listed below:

Alberto Anfossi
Secretary General, Fondazione Compagnia di San Paolo

Anousheh Ansari
CEO, XPRIZE Foundation

Özge Aydoğan
Director, SDG Lab

Stéphane Decoutère
Secretary General of the Board, GESDA

Stéphane Duguin
Chief Executive Officer, CyberPeace Institute

Ambassador Alexandre Fasel
Swiss State Secretary for Foreign Affairs, outgoing GESDA Diplomacy Forum Chair, former Swiss Special Representative for Science Diplomacy

Rosario Fazio
Head of the Condensed Matter and Statistical Physics Section, International Centre for Theoretical Physics (ICTP)

Anna Fontcuberta i Morral
Associate Vice President for Centers and Platforms, EPFL

Cornelius Hempel
Group head, ETHZ-PSI Quantum Computing Hub

Sana Odeh, Professor
New York University, Curator NYU Abu Dhabi Quantum Hackathon

Barry Sanders
Scientific Director, Quantum City

Urbasi Sinha
Professor, Quantum Information and Computing Lab, Light and Matter Physics group, Raman Research Institute

Matthias Troyer
Technical Fellow and Corporate Vice President, Microsoft

Incubation plan

The incubation plan set deliverables for the OQI community to achieve by October 2023 and by December 2026 (see below). These deliverables constitute the "minimum viable product" (MVP) for the OQI to test its offering with future users, learn by doing and improve its methods of action.

Work Package	Aim	Incubation milestones by the GESDA Summit (Oct 2023)	Incubation status	Deliverables by December 2026
1 "Go to" place for quantum SDG use cases	Establish the OQI as the "go to" place to find scientifically robust knowledge on the use cases of quantum computing serving the SDG, as well as experts to collaborate with to develop impactful applications	• Four outlines of SDG-focused use cases developed • GESDA-PRIZE Quantum for SDG contest prepared • Impact X feasibility review developed	ACHIEVED	• Proof of concept of 4-6 use case projects • Repository of use cases visited and fed by users • Pipeline of new use cases for OQI to support
2 Pool of quantum computers	Create a broad pool of state-of-the-art quantum computers and make it globally accessible. The pool is representative of all geographies and technological modalities	• MoUs with providers to secure sufficient and state-of the-art level of access • Modalities to access the OQI pool of computers clarified • Mock-up of a unified access portal not built as an assessment concluded that it was too early to select a technical solution	RE-CALIBRATED	• Working interface / portal making quantum computers (and emulators) easily available to OQI users
3 User empowerment – educational capacity	Develop OQI educational tools for two core target groups: researchers from quantum underserved geographies and diplomats. Partner with other organisations for complementary offerings	• Hackathon pilot, OQI prize winners returned on experience; there work will be showcased at summit. • Quantum geopolitics online game (MVP model) is designed	ACHIEVED	• Best practices on how to involve players from quantum underserved regions in use case projects • Initial playbook of OQI training instruments

4 Multilateral governance of quantum for SDG	Activate diplomacy to frame the future multilateral governance that will enable quantum computing to be leverage for the SDGs	• Relevant multilateral governance themes are prioritised by diplomatic group • Communication of initial considerations of DEEG are presented in an Intelligence Report	ACHIEVED	• >1 Diplomatic Engagement Process started • >20 countries involved in discussions
5 Strong OQI governance	Establish the institutional governance for OQI that will ensure its core values and independence from specific interests are guaranteed	• Governance scenario validated Individuals approached to join governing bodies once the OQI starts operations • Discussion are ongoing to formally confirm governance: At the time of release of this incubation report, GESDA is about to finalise the negotiations with the prospective implementing partner	ON WAY TO CONFIRMATION	• Statutes plus corporate & organisational regulations confirmed • Key organisational procedures guaranteeing values and independence of OQI are respected
6 Financial sustainability	Secure solid funding for OQI in the longterm, notably by including novel sustainable finance vehicles in its business model	• Financing needs of incubation and pilot phase are being secured	ON WAY TO CONFIRMATION	• Stable business model • Financing needs for 2026-2028 secured
7 Stakeholder engagement	Expand OQI's community to make it consistent with OQI's overall mission. Ensure the community actively supports OQI's mission, and uses its services	• Community of over 130 experts to pilot OQI's future offering proved concrete engagement in initial activities and demonstrated scientific excellence	ACHIEVED	• Active committed community in place • Fully functional matchmaking platform

Outcomes

The outcomes of the seven incubation phase work packages are laid out below:

1 "Go To" place for quantum SDG use cases

OQI aspires to become the hub for robust scientific and translational knowledge on the applications of quantum computing conducive to the SDGs (and their future succeeding framework).

In this early stage of technology development, it is still speculative whether quantum computing will deliver a clear advantage over conventional computing. The function of the OQI as a knowledge hub will counteract hype effects, create a sound basis for confirming where there is real potential of quantum computing to progress towards the SDGs. It will also de-risk the investment for such applications and establish an equitable multilateral governance of the field.

The OQI will achieve this through:

(1) an **OQI-coordinated pipeline of collaborative SDG use case projects** involving each at least one academic, one industry and one intergovernmental organisation partner. The OQI will thus curate and support the initial exploration of a vast scope of application domains with impact on the SDGs, aiming to provide scientific evidence of potential benefits of quantum computing. This will prepare the ground to inspire new stakeholders (researchers, UN orgsanisations, NGOs) and form a growing community of best practices to take over the exploration and solve these problems.

(2) a joint **GESDA-XPRIZE "Quantum for SDGs" Contest**, for a global bottom-up generation of additional use cases.

(3) **scientific and impact validation of use cases** submitted by quantum stakeholders willing to showcase their commitment to the SDGs.

SDG use cases

During the incubation, outlines for use cases were developed. Each of them consisted of a description of proposed quantum computing solutions in terms of:

- the problem and its context (including specification who is impacted, clarification on relevance and why does the use case matter to look at it);
- the existing (classical) computational approaches to the problem and their bottlenecks;
- the potential quantum computing solution (type of algorithms, methods that will be used, steps to achieve the proposed project, expected benefits over classical approaches (e.g. accuracy);
- the societal impact, in terms of SDGs and addressed challenges. All outlines are complemented by a resource assessment for a proof of concept and a description of the team.

Applications of quantum computing outlined during the incubation focused on SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy) and SDG 13 (climate action). Below are examples of use cases that the OQI partners are working on:

- **Food security:** Quantum computing-based optimisation of the food supply chain, in particular in the route planning of food delivery in underserved regions impacted by climate change or other crises (SDG2).

  Team: Ernst & Young, ForeQuast and potentially Oxford, FAO

- **Food production:** Quantum computing-based optimisation solutions to produce more nutritious food locally in less land, taking into account key components in food and environmental parameters (SDG 2).

- **Antimicrobial resistance:** Quantum computing solution to improve current AI models and predict more quickly and accurately patterns of resistance and identifying new chemical compounds with low resistance on more targeted bacteria (SDG 3).

  Team: University of Copenhagen, Alphanosos, GARD-P

- **Medical imaging:** Quantum machine learning solutions to improve accuracy of imaging and early diagnosis of diseases (SDG 3).

  Team: Raman Research Institute (RRI), CERN, Cleveland Clinic

- **Renewable resources:** Quantum computing simulations to design new catalysts to break down lignin in order to turn waste products into fuel alternatives (SDG7).

  Team: Microsoft, ETH Zurich, UN Habitat

- **Carbon reduction:** Quantum Computing simulation to improve catalysis process responsible for the fixation of carbon on the surface of materials, and thus reducing CO2 in the atmosphere (SDG13).

  Team: ETH Zurich, EPFL, UNFCCC

  Biodiversity: Quantum computing simulation to predict the impact of climate change on biodiversity, improve current models and processing more complex biological and environmental data (also relevant for SDG 14 and SDG 15).

  Team: University of Sherbrooke

Other topics currently in discussion include: tackling antibiotics in wastewater, eco-friendly fertiliser production, optimisation of vaccine distribution, genomics, novel batteries, photocatalysis, and agri-tech.

2 Pool of quantum computers

OQI will provide access to a broad pool of quantum computers, representative of all geographies and technical modalities (superconducting, trapped ions, photonic, neutral atoms, annealing so far). It is essential that this capacity is state-of-the-art and it should be accompanied by other mechanisms (simulators, strict selection processes, onboarding and mentoring etc.) to ensure effective use of the resources granted by the partners.

During the incubation period, the adequacy of the initial pool of computers was re-assessed. The assessment confirmed the need to include simulators and emulators in the pool and new partners were approached for this purpose. The commitment of these partners is being confirmed by a Memorandum of Understanding (MoU) where they confirm what resources they are willing to grant to OQI, and other above-mentioned modalities of support they can provide.

List of partners involved in the OQI:

Alpine Quantum Technologies (AQT), AWS, IBM, IQM Quantum Computers, Microsoft, Oxford Quantum Circuits (OQC), PASQAL, Strangeworks

3 User empowerment for educational capacity

OQI has two priority target groups for its educational offering: 1) researchers, developers and entrepreneurs of quantum underserved geographies and 2) diplomats.

For the first group, OQI aims to equip researchers, developers and entrepreneurs of quantum underserved geographies with the capacity to submit ideas of use cases leveraging quantum computing for the challenges that concern them. In a second step, the OQI educational offering should provide efficient training to enable them to participate in the teams addressing the use cases. This way, OQI should become a source of best practices on how to involve players from quantum underserved regions.

The offering to diplomats is aimed at providing solid understanding of the state of quantum computing, its impact on economies and populations and its geopolitical ramifications. These are conditions to enable informed policy making at a multilateral level.

During the incubation, the first group was addressed by a partnership with New York University Abu Dhabi for a “quantum for social good”. GESDA’s role in the partnership involved anchoring the 2023 edition into the SDG framework by involving its UN and OQI science diplomacy community. GESDA also supported participants from its target geographies to attend. In total 14 teams of 8 to 10 members were formed, each mixing students of world leading quantum academic institutions and of quantum underserved geographies.

For the diplomats, the incubation enabled the completion of a beta version of an online role-play anticipating the geopolitics of quantum technologies. Resource constraints limited the development of the game to its introduction but feedback on the tool was positive. The next phase of the development involves simulation of scenarios.

4 Multilateral governance of quantum for SDGs

Diplomatic engagement is necessary to ensure that future multilateral governance enables quantum computing to be leveraged for the SDGs. During the incubation, OQI held a series of meetings with representatives of more than 20 countries to raise awareness and inform about quantum computing itself and the state-of-play of the multilateral governance relevant for quantum computing.

Themes addressed with diplomatic and multilateral stakeholders included clarity on SDG potentials, digital divide, security and dual-use, standardisation initiatives, environmental impact and human agency. This work led to the publication of an Intelligence Report launched at the GESDA Summit 2023.

At the time of the publication of this report, OQI was the only forum where countries, with or without quantum capacity, have an equal voice on how the technology could be governed in the future.

The discussions confirmed the importance of reflecting on the potential impact of these technologies before they are built or as soon as possible during their development (for example by understanding where is the potential dual use, and/or including core principles, such as human rights, by design). For many of the themes addressed, enforcing regulation is premature in the current stage of the technology. Nonetheless, anticipation is necessary for human agency to be fostered.

During the incubation, OQI also continued to bridge the foreign affairs approaches with those of industry, research and innovation ministries, as well as those focused on SDG/development aid. In future, the themes could be addressed with formal diplomatic processes as a result of the discussions informally started within the OQI.

5 Strong OQI governance

The objective of the incubation was to set up a governance framework of the OQI that allows the initiative to gain the necessary speed, critical mass and institutional stability to make an impact, while ensuring that its values (inclusivity; global scope; focus on benefits to humanity) are respected. OQI governance must also guarantee its independence from specific national or corporate agendas. In particular, as a novel science diplomacy instrument, the OQI must have:

- the legitimacy to manage common goods internationally
- the capacity to engage in public-private partnerships
- mechanisms to ensure the active participation of the countries with less quantum capabilities
- the structure to ensure the effectiveness of implementation (time to delivery, global network and programmes, governance and oversight processes etc.)

Based on the above criteria, an evaluation of three alternative scenarios was conducted during the incubation. The most suitable was considered to be the sister/daughter affiliated organisation of an existing UN organisation that has relevant competence. Implementation partners were consequently approached to test their interest in hosting the OQI. At the time of release of this report, GESDA is about to finalise discussions with the prospective implementation partner.

Based on first responses, hypotheses for the governance bodies of the OQI were defined and prospective members contacted to pre-confirm their willingness to engage in such bodies.

Finally, the incubation also clarified key organisational procedures and workflows, to be reconfirmed by the implementation partner in due course (e.g. selection criteria; open criteria; mechanisms to grant resources).

6 OQI financial sustainability

During the incubation phase, GESDA has approached a variety of prospective funding partners from philanthropy, industry and finance. At the time of release of this report, GESDA is about to finalise the negotiations with a prospective funding partner to secure the resources needed to finance the incubation (2023) and pilot implementation phase of OQI (2024-2025-2026). This funding will enable an independent progressive ramp-up during the pilot phase.

7 Supportive stakeholder engagement

From October 2022 to October 2023, the OQI engaged over 130 experts in the five continents to pilot OQI's future offerings and to build a best-in-class governance and a science and technology knowledge hub.

During the incubation, the OQI followed an engagement strategy which clustered external stakeholders by their level of participation (informative, consultative or collaborative) to guide their contribution towards the four objectives, as follows:

1. UN Organisations and NGOs, quantum algorithmic scientists and classical computer scientists from academia and industry, domain experts and engineers. These were among the most actively engaged stakeholders as they co-created outlines for potential quantum computing use cases (collaborative participation through multi-stakeholder teams to develop SDG use cases of quantum computing).
2. Tech providers, private companies, entrepreneurs, and philanthropy. These were included in decision making and planning process of the OQI pilot. With the information, opinions, and ideas they provided, they had an impact on the shape and content of the OQI initiative (consultative participation to make quantum hardware available through the cloud).
3. Leading quantum education providers. These were engaged in partnership exploration to further develop the offering and geographical outreach of OQI.
4. Nation state representatives. These examined questions such as technology access, relevant applications for the SDGs, standardisation initiatives, security and oversight considerations through inputs of experts from industry or relevant international organizations. (WIPO, ISO).

Next steps and perspectives for GESDA

The incubation demonstrated the feasibility of the implementation plan. All the milestones initially set were either reached or recalibrated for operational reasons, with no significant consequences on the objectives assigned for 2026. Constructive feedback from users has been gathered to enhance the initiative's chances of success. The incubation saw increased support of the quantum community for the initiative, which confirmed the uniqueness of its value proposition.

OQI is already globally relevant, and the partnerships reaffirmed in action during the incubation will give it even more critical mass to gain the impact it was designed to achieve. Key to the value proposition are the synergies between the OQI 3 pillars: inclusive access to use the technology, focus on applications conducive to the SDG, and global diplomacy as enabling condition.

2022 Geneva Science and Diplomacy Anticipation Summit: **Introduction**

The GESDA Foundation's second annual gathering — the Geneva Science and Diplomacy Anticipation Summit, or GESDA Summit — took place on 12-14 October 2022 in Geneva, Switzerland, at Campus Biotech, where GESDA is headquartered. It consolidated its standing as a new force for global multilateral action based on anticipatory science and diplomacy. This hybrid event expanded participation from all of GESDA's collaborative pathways including the first assessments from a high-level political panel and from a youth cohort.

The four main objectives were to:

- debate the yearly update of the GESDA Science Breakthrough Radar;
- introduce GESDA's new Pipeline of Solution Ideas, which are prototypes of possible avenues of action that could accelerate the beneficial uses of emerging scientific and technological breakthroughs for humanity;
- gain a preliminary assessment by political authorities on whether and how these actions could be politically endorsed in a broad manner and, as a result, be set in motion at a global diplomatic level;
- start to set up innovative impact funding instruments that could provide the resources that would be needed to incubate these solution ideas.

In addition, a Public Plenary session focused on advances in genetic engineering and synthetic biology organised in partnership with the Geneva Graduate Institute.

Summit highlights

High-Level Political Segment

A new political element was introduced with an inaugural panel that included Swiss President Ignazio Cassis and ministers from Estonia, Mexico, Morocco, Singapore and the United Arab Emirates. It was moderated by Alexandre Fasel, Switzerland's first Special Representative for Science Diplomacy. President Cassis pointed out that a Western assumption that the world is "automatically increasing towards democracy" no longer seems to be the case, with the rise of authoritarians and wars in Asia, the Middle East and now Europe telling a different story. He emphasised the need for citizens living in democracies to be willing and able to include all viewpoints in public debates, not just those from like-minded people, and "this is a topic where science, science diplomacy can help us to do the right thing."

The Swiss President, Ignazio Cassis conveyed that his dream is for GESDA to become "a powerful tool in enabling a diverse world, through science, to make some steps together in a peaceful way," and for science diplomacy to become the theme of the 21st century among Geneva's hub of international organisations and multilateralism, much like human rights in the 20th century and international humanitarian law in the 19th century.

Opening High-Level Plenary

The summit opened with a demonstration of GESDA's firm support from the Swiss and Geneva governments, including an explanation from Swiss President Ignazio Cassis about why the authorities extended GESDA's mandate for 10 years after its successful three-year pilot phase. Speakers cited the need for multilateral governance in a world grappling with climate-linked droughts and flooding; widespread hunger; pandemics; armed conflicts in Europe and much of Asia and Africa; human rights abuses; inflation, and disrupted supply chains. As GESDA Board Chairman Peter Brabeck-Letmathe emphasised, GESDA has no time to waste.

GESDA Board Member Mamokgethi Phakeng, Vice-Chancellor of South Africa's University of Cape Town (UCT), oversaw a new Youth and Anticipation Initiative as a partnership between UCT and GESDA to engage young people.

During a high-level panel on the topic of "The New Geopolitical Landscape for Science", GESDA announced a new collaboration with the Geneva Centre for Security Policy (GCSP) and Columbia University that links emerging science to future challenges of peace, war and international security. This has materialised in the future of peace and war deep-dive discussed in this edition of the Science Breakthrough Radar.

The 2022 GESDA Science Breakthrough Radar®

Presented during the Opening High-Level Plenary, GESDA's flagship product involved 774 scientists from 73 countries, a 43 per cent increase in the number of scientists from last year's inaugural edition. The number of emerging topics identified also rose to 37, up from 24. A fifth area of emerging sciences — Knowledge Foundations — was added to the four main areas in which the scientists anticipate developments.

GESDA's Academic Forum has expanded its network of participating scientists because "we have to keep engaging with the scientific community," said Martin Vetterli, President of the Swiss Federal Institute of Technology Lausanne (EPFL), who oversaw the forum's development of the Radar for two-and-a-half years with Joël Mesot, President of the Swiss Federal Institute of Technology in Zurich (ETHZ).

Since the Radar affects everybody, Phakeng said, the new Youth and Anticipation Initiative will "get the voices of young people into the conversation", helping to reduce inequalities. The Radar's new philosophical and geopolitical lenses also include a "very necessary dialogue" involving social scientists, said Geneva Graduate Institute Director Marie-Laure Salles.

The GESDA Pipeline of Solution Ideas

GESDA presented a new tool for accelerating the conversion of solution ideas from the Radar and Summit into concrete actions. This year, those were a pair of proposals to create an Open Quantum Institute (OQI) in Geneva and the first Global Science and Diplomacy Curriculum. The purpose of the OQI — which drew lengthy discussion and was well-received — is to widen global access to quantum computers and develop use cases for quantum computing that could help accelerate the accomplishment of the UN's 17 Sustainable Development Goals (SDGs) for 2030. The Global Science and Diplomacy Curriculum will help to train current and future science and diplomacy leaders to effectively tackle emerging global challenges through anticipatory science and diplomacy. It is being developed with a large number of partners.

The GESDA Youth Cohort

This year's summit gained fresh perspective from 12 young people whose participation was based on the nominations and support of GESDA partner institutions, including South Africa's University of Cape Town, Swissnex, Swiss Young Academy of Scientists, Villars Institute and XPRIZE Foundation. Among them were three participants chosen from the Youth and Anticipation Initiative led by Phakeng. Throughout the summit, these young people were invited to share their thoughts about what they heard, learned and reflected on during the sessions, and to share their views on the future of science and diplomacy and on GESDA's efforts and vision.

During a panel discussion, several of the young and aspiring leaders, who are just setting out on their chosen educational and career paths, emphasised the need to sustain hard work and hope in the service of science anticipation. "We are constantly reminded that there is a lot that we are struggling to cope with as a society, as a world and as a species. There are a lot of challenges that we have to overcome," said Jordan Naddaf, an American student at SOAS University of London. "I think that GESDA has left me very hopeful."

In a keynote message, Phakeng congratulated all of the youths for their selection because it meant they are all working hard and doing things that are important for everyone to hear about. "You will inherit the world," she told them. "And so it is important that you become part of the conversation and that you, as young people, become part of leading the action into a better future."

Launch of the Impact Forum and Fund

With financing for international impact continuing to be a challenge, GESDA confirmed its ambition to launch an Impact Forum and related Impact Fund led by GESDA Board Vice-Chairman Patrick Aebischer, who is President-emeritus of EPFL. Their purpose is to provide the resources necessary to implement the most promising solutions and initiatives that use emerging science for the benefit of humanity.

The Forum and Fund aim to target the same global inequalities and nationalism that hampered recovery from the COVID-19 pandemic. In a keynote message, Aebischer noted that we are living through anincredible time of scientific disruption that is occurring at a pace never seen before. A new Impact Forum and Fund can help us respond better, break down inequalities and bring the scientific community to the table of multilateralism. "Everybody needs to be around the table, and that is what we have decided to do at GESDA," he said. "We are going to rely on innovating new financing, which is going to be public-private by definition."

This section provides a description of the sessions related to the scientific emerging topics discussed in the Science Breakthrough Radar 2022, as well as their main conclusions. They provide the basis for the concrete solutions and initiatives currently in the making in GESDA's pipeline of solution ideas, that will be presented and discussed in more depth at the next GESDA Summit from 11–13 October 2023. The full summit proceedings, including programmes and speakers is available at: https://gesda.global/ summit/.


LEGEND
PUBLIC AWARENESS
CITIZEN SCIENCE
POLICY ORIENTED ACTION
ENTREPRENEURIAL
Taking the Pulse of Society
What people are saying
The Science of the Origins of Life and Synthetic Biology
Taking the Pulse of Society
What people are saying
Democracy-affirming Technologies and Digital Technologies & Conflicts
Taking the Pulse of Society
What people are saying
Infectious Diseases and Solar Radiation Modification

Conference proceedings: Building an Open Quantum Institute

Quantum technology is an issue of geopolitical importance, becoming a critical infrastructure relevant to national security and innovation capability. To make sure the technology can be used with purpose in 5-10-25 years, new R&D collaboration and governance models that consider both technology security and equity of access need to be put in place now.

1.2 Quantum Revolution

More information

https://https://gesda.global/solutions/
https://www.youtube.com/watch?v=U9lStAWHrnw
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580613744425672707

Quantum capabilities could impact key sectors of the economy including pharmaceuticals, materials, chemistry, energy, finance, security, and logistics. If applied to the right set of issues, quantum computing has the potential to become a world-improving technology, directly applicable to implement the Sustainable Development Goals (SDGs) outlined by the United Nations. Quantum computers are tremendously expensive and hard to build so ensuring broad access to them will be difficult.

- How can we make sure this new technology benefits all of humanity, focusing on impact on the planet and society, and not just be used for the greatest profits?
- With so much on the line, how can scientists and policymakers make sure to maintain a spirit of open collaboration?

Participants

Moderated by:

Anousheh Ansari
Chief Executive Officer, XPRIZE Foundation

With:

Graham Alabaster
Head, Geneva Office, UN Habitat

Alberto Anfossi
Secretary-General, Compagnia di San Paolo

Tommaso Calarco
Director, Institute for Quantum Control, Peter Grünberg Institute, Forschungszentrum Jülich

Fabiola Gianotti
Director-General, CERN; Board Member, GESDA, Italy

Sana Odeh
Clinical Professor of Computer Science;
Faculty Liaison, Global Programs of Computer Science, New York University

Urbasi Sihna
Professor, Quantum Information and Computing Lab, Raman Research Institute Lab, Raman Research Institute

Matthias Troyer
Technical Fellow and Corporate Vice President, Microsoft, Austria

Takeaway messages

"As the most advanced proposal in GESDA's pipeline, the creation of an Open Quantum Institute (OQI) is being proposed to identify important quantum breakthroughs, figure out what to do about them and bring ideas to fruition."

"The proposal for a new institution in Geneva promises access to quantum computers to those who lack it and a forum for diplomatic discussions. The proposal already has strong support."

"OQI is envisioned as a centre of expertise for all quantum applications that could get the world closer to fulfilling the United Nations' 17 Sustainable Development Goals for 2030."

"A decision was taken early on to have OQI focus on facilitating collaborative research to ensure open access to quantum technologies among the world's population that lacks access to the technology, science or education."

"OQI will not perform its own R&D but will work to identify areas of interest for partner research institutions to investigate. In recent years, there has been a huge increase in investment in quantum research."

"Quantum is real, quantum is coming, and the impact is real. It will help us solve some of the planet's most important challenges."

"XPRIZE Foundation is working closely with GESDA and its Quantum Task Force on a quantum competition, which will award incentive-based cash prizes for innovation that expands quantum technologies."

"OQI is a good fit for GESDA because it has an anticipatory role and is well-placed to ensure that quantum will be used in the best possible way."

Conference proceedings: Reshaping Reality in Tomorrow's Society

Augmented and extended reality technologies, which blend our digital and physical experiences, are beginning to transform industry, work, education, and social platforms. With tens of billions of dollars being invested today to lead to a transition in the way people use their smartphones, consume information, and interact with each other, the extended reality ecosystem could be a $1.5 trillion opportunity by 2030.

1.4 Augmented Reality

More information

https://www.youtube.com/watch?v=z_wVyeV4iRk
https://twitter.com/i/flow/login?redirect_after_login=%2Fi%2Fevents%2F1580232544368447489

The blurring of boundaries between realities holds enormous implications for how citizens, communities, and leaders comprehend the world around them.

- How will a blended reality existence transform social and economic policies, and how long will it be before these two worlds become indistinguishable?
- What should be done on the multilateral level to prevent undesirable consequences from becoming pervasive and entrenched in our hybrid physical-digital realities?

Participants

Moderated by:

Azeem Azhar
Founder, Exponential View

With:

David Chalmers
Author of Reality+; Professor of Philosophy and Neural Science, New York University; Co-director, NYU's Center for Mind, Brain and Consciousness

Cordel Green
Executive Director, Broadcasting Commission, Jamaica

Sarah Kenderdine
Professor of Digital Museology, EPF Lausanne

Charlotte Lindsey
Chief Public Policy Officer, CyberPeace Institute

Marc Pollefeys
Computer Vision and Geometry Lab, ETH Zurich

Takeaway messages

"At their best, such technologies can improve one's work or education by speeding up lessons or handiwork, for example by bringing in an expert to communicate information in 3D.

"Trust in technologies like augmented reality (AR), mixed reality (MR), virtual reality (VR) and the metaverse is a critical aspect as we move from one tech era to another without fully understanding the implications and challenges."

"Trust in technologies like AR, MR, VR and the metaverse is a critical aspect as we move from one tech era to another without fully understanding the implications and challenges."

"Large-scale immersive VR and AR systems can help preserve and share reservoirs of knowledge in the form of cultural heritage and materials, including scientific data, for the museums of the world."

"The idea of virtual reality has antecedents through millennia of philosophy, but the meaning in our lives ultimately comes from community, not from playing games."

"Through avatars, people tend to experiment with new identities, including gender and culture."

"For communities of disabled people who have limited access to the physical world, virtual and digital worlds provide new possibilities for accessibility and for expression of identity."

"The impacts of electronic media on mental health and memory formation in children are a concern for regulators because of the potential for deep immersion and synthetic experiences."

"Regulatory innovation in governance is needed to effectively manage these challenges in a way that keeps pace with how society is changing."

Conference proceedings:
How can we Prepare for Collaborative Human-Machine Intelligence

In many fields, such as healthcare applications, economic modelling, and social robotics, the mix of human experience and computational capabilities combine to generate breakthroughs in understanding population dynamics, climate cycles, and even management processes. Collaborative human-machine intelligence ranges from combining data analytics with decision-making humans to interactive knowledge developed through interconnected biological and technological systems.

1.5 Collective Intelligence

More information

https://www.youtube.com/watch?v=j_ZYIEypUbs
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580621506433978369

As Human-Machine collaborative technologies advance, the future of knowledge economies hangs in the balance.

- What will be required to responsibly integrate sprawling varieties of data, computing systems, and AI methods with human agency and experience?
- How will we live, work and socialise in a world where machines do more than analyse data, they make knowledge?

Participants

Moderated by:

Geoff Mulgan
Professor of Collective Intelligence, Public Policy and Social Innovation, University College London

With:

David Harel
President, Israel Academy of Sciences and Humanities

Wendy Mackay
Research Director, Classe Exceptionnelle, Inria

Illah Nourbakhsh
Executive Director, Center for Shared Prosperity, The Robotics Institute, Carnegie Mellon University

Eric Salobir
Chairman, Executive Committee, Human Technology Foundation; President, OPTIC

"The Russian invasion of Ukraine has shown the enormous disruptive potential of collaborative human-machine intelligence, from drones to satellites to fundraising platforms."

"New combinations of human-machine interactions are blurring the way we define ourselves.

"A fundamental problem is that we use the word autonomy as if it's good for technology to gain independent decision-making."

"The systems we create are not autonomous; that word semantically inflates terms like thinking and wisdom and decision-making that connote intentionality that just isn't there."

"The best human-machine designs increase personal human agency, rather than concentrating power in the hands of an already powerful corporation."

"We have to find technical ways of building systems that can use both artificial intelligence (AI), which can for example recognise traffic signs or lighting conditions, and classic software, which doesn't have the ability to learn."

"Verification in human-computer systems is an important issue because, as AI enables computers and machines to perform human-like decisions and automate tasks, it can be used to automate cybersecurity portals to prevent identity theft at a scale used by financial institutions."

"The design of many AI systems is based on an algorithm's quality and not on how well they interact with humans; this is perhaps because they're designed by computer scientists trained in math and engineering but not in how people think."

"The answer may be found in a movement towards "human-centred" AI, which combines psychology, sociology, anthropology, design, engineering and math to design effective systems that can continuously improve from human input and collaboration."

Conference proceedings: Navigating the NeuroTech Compass

Recent technological advances in electronic miniaturisation, brain signal detection, and the use of AI for data analysis pave the way to a better understanding of neurological and mental health disorders. Anticipated developments offer potential for health, communication, mood regulation, and memory enhancements, generating huge financial investments from the public and private sectors.

- 2.1 Cognitive Enhancement
- 2.4 Consciousness Augmentation
- Neuro-augmentation Deep Dive

More information

https://gesda.global/solutions/
https://www.youtube.com/watch?v=YaeTpDXATxg
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580619817790410774

While investment will bring the technologies to patients and consumers more quickly, applications outside the medical field are developing rapidly for neuromarketing, gaming and entertainment, and military purposes. With the scientific and technological landscapes rapidly accelerating, a global and inclusive approach enabling their development remains a challenge.

- Why is this a topic policy makers should be interested in?
- What are the challenges they face preventing them to take action?

Participants

Moderated by:

Daria Robinson
Executive Director, Solution Accelerator, GESDA

With:

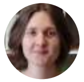
Olaf Blanke
Professor of Neurosciences, EPF Lausanne

Lidia Brito
Regional Director, Southern Africa, UNESCO

Ricardo Chavarriaga
Head, Switzerland Office, CLAIRE Initiative for Excellence in AI

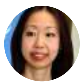
Stephanie Herrmann
Staff Attorney, Perseus Strategies; Lawyer, NeuroRights Foundation

Jürg Lauber
Ambassador, Permanent Representative of Switzerland to the United Nations and other international organizations



Estelle Nakul
Postdoctoral Researcher, LNCO, EPF Lausanne

Olivier Oullier
Co-founder, Inclusive Brains; Professor Aix Marseille University, France



Ayaka Suzuki
Director, Strategic Planning and Monitoring Unit, Executive Office of the Secretary-General, United Nations

Takeaway messages

"GESDA began exploring the promise of neurotechnology as a result of the 2021 Science Breakthrough Radar and Summit and formed a task force to explore the topic further."

"Scientists have long made use of neurotechnology but, with recent advances, there has been an explosion of new methods and devices."

"Engineering, computer science and artificial intelligence will be used to process the massive amounts of data obtained from people's brains and to decode it, raising questions of governance."

"Only a few governments have the capacity, time and resources to deal with the governance questions, which is why GESDA can help by bringing diverse communities together."

"Countries tend to have national laws regulating the data that's collected by this technology, but consumer devices that use brain data may not be regulated."

"The UN is mapping existing human rights treaties and surveying other information for the implications of future neurotechnology scenarios, some of which could occur soon."

"The next stage in 2023 would be to develop and test the prototype for a new centre or "NeuroTech Compass" where scientists, policymakers and industry can gather."

"Neurotechnology is a hotbed of legal concerns in the field of international human rights law."

Conference proceedings: **Defining Usage Frameworks for Organoids**

Organoids are three-dimensional cell cultures that replicate some of the complexity of human organs. They are already providing insights into diseases pathologies, drug development, transplantation options, behavior and genetics, brain research and even learning networks.

2.5 Organoids

This rich field of research agendas and commercial needs could usher in a revolution in innovative diagnostics, therapeutics, and commercial ecosystems connected to personalised medicine.

- What challenges affect developing organoids openly and transparently?
- What ethical and moral issues are there, especially around brain and interspecies organoids?

Participants

Moderated by:

Effy Vayena
Professor of Bioethics; Founder, HealthEthics and Policy Lab, ETH Zurich

With:

Matthias Lütolf
Professor of Life Science, EPF Lausanne; VP, Scientific Director, Roche Institute for Translational Bioengineering

Alysson Muotri
Professor, Department of Pediatrics and Cellular & Molecular Medicine, University of California

François Rivasseau
Senior Consultant Technology & Diplomacy, World Intellectual Property Organization

More information

https://www.youtube.com/watch?v=nJ7SHULhVqY
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580236348916699136

Takeaway messages

"Most of the biomedical sciences have been reliant on animal models, which is unsatisfactory for understanding the human brain."

"Human organoids open a new window in science, including gaining more understanding of the human brain, but they present ethical and moral issues that should be examined. Several groups are working on generating synthetic human embryos in culture, which raises important questions."

"High costs mean that research tends to overlook diseases in the Global South, where there's less of a developed market."

"The issue of autonomy and consent – whether a patient should have a say in how their samples are used or lingering rights to them in these new applications – is a looming problem."

"Organoids are not seen as morally neutral; tissue donors may perceive enduring personal connections with their organoids."

"The issue of patient confidentiality can be easier for researchers to deal with if they don't know where the samples came from."

"Eventually, organoids sending neural oscillations similar to an EEG may acquiresomeself-awareconsciousness."

"More communications outreach is needed to help the public understand what's going on in the labs; a member of GESDA's youth cohort recommends incorporating the research into school curricula."

"Some soft regulation may be needed, and the UN Human Rights Council in Geneva and a UNESCO bioethics committee could be involved in governance discussions."

"The issue of remuneration involves intellectual property, and these problems may be the first issue for global governance to address with discoveries involving organoids because IP and ethics are closely linked."

Conference proceedings:
Deciphering the Human Immunome with AI for Better Therapeutics

The biggest difference between two individuals lies in the set of genes and proteins that constitute their immune systems. This complex ecosystem — the immunome — may hold the key to the biggest health breakthroughs in the 21st century. Like the sequencing of the human genome, mapping myriad immunomes across diverse populations will advance immunology, enabling significant innovation in health diagnostics and therapeutics.

2.6 Future Therapeutics

With the new help of machine learning (AI), immunome therapy breakthroughs will likely materialise in the next decade and could even lead toward human enhancement technologies.

- How can medical professionals, scientists, and policymakers manage the enormous transformation a mapped immunome will bring?
- Can such a project remain open and coordinated among representative stakeholders?

More information

https://www.youtube.com/watch?v=iHybrM9kTAI
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580631966268940289

Participants

Moderated by:

Samia Hurst
Professor of Ethics, University of Geneva

With:

Jacques Fellay
Co-director Health Genome Centre, EPF Lausanne/ University of Geneva

Wayne Koff
President & Chief Executive Officer, Human Vaccines Project

Jürgen Schmidhuber
Director & Professor, The Swiss AI Lab IDSIA; Co-founder & Chief Scientist, NNAISENSE

Soumya Swaminathan
Chief Scientist, World Health Organization

Chorh Chuan Tan
Chief Health Scientist, Ministry of Health of Singapore; Board Member, GESDA

Takeaway messages

"The potential of decoding the human immune system – the genetic underpinnings of people's ability to respond and adapt to a range of diseases – is a major frontier in science."

"Researchers have an unprecedented amount of data and need artificial intelligence (AI) and machine learning to understand it and, using AI, create a model of the human immune system."

"If successful, the model could be used on infectious diseases, including AIDS, tuberculosis, and malaria, and noncommunicable diseases like Alzheimer's, cancer and multiple sclerosis."

"Researchers need partnerships with academia, industry, NGOs and governments to be able to work in labs worldwide in ways that benefit the people most vulnerable to a range of diseases."

"Data privacy is an important issue in a system that collects data from lots of different people, including data-sharing across jurisdictions."

"International standards and guidelines are needed on the ethics of immunome research and data."

Conference proceedings: Assessing Solar Radiation Modification

Solar Radiation Modification (SRM) has been scientifically, politically and societally divisive. Some experts don't even want to discuss proposals to go on with fundamental research in the field, while others believe that interventions such as cloud brightening, aerosol injection, and creating more reflective surfaces must be part of a possible intervention portfolio — especially if other measures fail.

3.6 Solar Radiation Modification

More information

https://www.youtube.com/watch?v=vxN2eK5WdBc
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580235074875817989

Regardless of position, all experts agree that the planet's future is in peril and people and governments must act — while asking the difficult questions:

- With the consequences of climate change rising, should we be doing fundamental research on SRM, or at least verifying the feasibility of these technologies?
- How can we deal with the risks and consequences that some actors will deploy SRM techniques unilaterally?
- How do we create an inclusive multilateral process to make sure that no country is left out of any possible decision on using SRM technologies?

Participants

Moderated by:

J Milica Momcilovic
Professor of Ethics, University of Geneva

With:

Frank Biermann
Professor of Global Sustainability Governance, Copernicus Institute of Sustainable Development, Utrecht University

Sikina Jinnah
Professor of Environmental Studies; Affiliated Graduate, Faculty of Politics, University of California

Pascal Lamy
Former Head, World Trade Organization; Coordinator, Jacques Delors Think Tanks (Paris, Berlin, Brussels); President, Paris Peace Forum

Chukwumerije Okereke
Professor in Environment and Development, AEFUNAI, Nigeria

Janos Pasztor
Executive Director, Carnegie Climate Governance Initiative

Gernot Wagner
Climate Economist, Columbia Business School; Columnist, Bloomberg Green,

Takeaway messages

"Questions about whether to pursue new technologies that could deflect the sun's rays and prevent more climate-affected droughts or heatwaves have become politically charged."

"Among the chief concerns is that tinkering with the planet's air to cool the Earth's warming climate might weaken resolve to reduce heat-trapping CO2 emissions from fossil fuel burning."

"Opponents of Solar Radiation Modification (SRM) believe that, from a scientific perspective, it's too risky and could open a Pandora's box; and, from a political perspective, even discussing it could weaken our emissions-cutting resolve."

"Without necessarily being supporters, some believe all options, including SRM, should at least be examined with scientific eyes, particularly since emissions-cutting alone won't save the day."

"The only firm area of agreement is that more action is urgently needed to keep the planet from overheating, which is why GESDA, a neutral platform for dialogue, invited the panel."

"The Paris Peace Forum and its Climate Overshoot Commission believes the pursuit of these new technologies should be the last priority, after first cutting carbon pollution, adapting to climate change and using carbon removal technologies."

"The Global South is paying the price for a problem largely created by rich nations and the voices of the most vulnerable populations aren't heard enough in the global debate. The discussion is predominately framed by North American scholars."

"African nations, home to vast renewable energy potential, proposed $3 trillion in carbon-cutting investment opportunities in accord with the 2015 Paris Agreement but received little money, leaving their leaders is heartened and more willing to delay curbing pollution."

Conference proceedings:
Controlling vector transmitted Infectious Disease

As humans move into previously undisturbed ecosystems, and as climate change broadens areas where vector-transmitted diseases such as dengue fever, Zika, and Chikungunya are present, the nee to monitor, detect, contain and, above all, prevent new outbreaks is paramount.

3.7 Infectious Diseases

More information

https://www.youtube.com/watch?v=7k5lsjTPcF0
https://twitter.com/i/flow/login?redirect_after_login=%2Fi%2Fevents%2F1580238883345907714

Genetic modification of mosquitoes is already being tested to stop disease transmission, but are poorly accepted publicly. The opportunity to constrain disease transmitters with a non-genetic — hence possibly better accepted — method is being evaluated for endorsement by the World Health Organization. Meanwhile next generation advances in synthetic biology and genetic engineering are looking at even more innovative ways to constrain disease, such as modifying the human microbiome to resist such viruses.

- How should governments use and deploy methods of disease management in a responsible and socially acceptable way?
- What role should scientists and policymakers play in making sure innovative methods are understood and knowledgeably accepted or rejected by populations?

Participants

Moderated by:

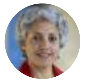
Olivier Dessibourg
Head of Science Scouting and Transfer; Curator of the Summit, GESDA

With:

Arnaldo Correia de Medeiros
Secretary-General, Health Emergencies, Ministry of Health, Brazil

Jeremy Farrar
Director, Wellcome Trust

Scott O'Neill
Chief Executive Officer, World Mosquito Program



Soumya Swaminathan
Chief Scientist, World Health Organization

Takeaway messages

“Aedes aegpyti mosquito-transmitted diseases, like dengue, Zika and chikungunya, have become global health emergencies in recent decades.”

“A small bacterium called Wolbachia that occurs naturally in almost 50% of all insect species but not in Aedes aegpyti can render these mosquitoes unable to transmit disease.”

“The technique of infecting Aedes aegpyti with Wolbachia to render them harmless does not involve the sort of genetic modifications that could alarm the public, like “gene drive” techniques.”

“An endorsement from the World Health Organisation (WHO) could facilitate its adoption across the planet if governments take it up and the financial support to do so is provided.”

“More than 10 million people in Australia have been protected as a result of testing that became a model for global projects.”

“Even with WHO’s recommendation, more government-approved use of mosquitoes with Wolbachia around the world may need philanthropic backing to scale it up.”

“WHO’s chief scientist says more evidence is needed before it will endorse this solution and support scaling it up in an equitable fashion to reduce the rising global burden of dengue, but some sort of recommendation – even a weak one – is likely.”

Conference proceedings:
What is the Future of Polar Research in the Current Geopolitical Landscape?

The poles are the most challenging and expensive frontiers on Earth for scientific research and resource acquisition. The current geopolitical situation has put efforts to pursue research in those regions at risk. It is, in fact, accelerating the race to exploit essential resources such as oil, gas, and rare earth minerals, causing increased concern over environmental preservation, ecosystem balance, and lack of clear authority or ownership.

3.5 Ocean Stewardship

More information

https://www.youtube.com/watch?v=qbe1JCe-2WU
https://twitter.com/i/flow/login?redirect_after_login=%2Fi%2Fevents%2F1580237593580638208

If we see the poles and their resources as an important contributor to meeting the demand of a more manageable energy transition,

- How can nations and multilateral coalitions move forward with global research programs and tenuous collaborations overshadowed by geopolitical realities?
- What is the right balance between exploitation of resources and exploration of scientific unknowns?

Participants

Moderated by:

Doaa Abdel Motaal
Author of "Antarctica, the Battle for the Seventh Continent"; Senior Counsellor, World Trade Organization

With:

Alexandra Baumann
Ambassador; Head, Prosperity and Sustainability Division (incl. Polar Affairs), Swiss Federal Department of Foreign Affairs

Rasmus Bertelsen
Professor of Northern Studies, Barents Chair in Politics, The Arctic University of Norway

Katarina Gårdfeldt
Director-General, Swedish Polar Secretariat

Larry Hinzman
Assistant Director, Polar Sciences, White House Office of Science and Technology Policy

Yeadong Kim
President, Scientific Committee on Antarctic Research (SCAR)

Takeaway messages

"As climate change drastically reshapes the polar regions, geopolitical conflicts are likewise fracturing the polar research landscape, particularly since Russia's invasion of Ukraine."

"A race is on for control of Arctic resources and access; the Arctic Council provides a loose governance forum in this regard."

"Scientists and diplomats should improve their engagement of Indigenous peoples living in the Arctic region."

"The situation is different in the Antarctic region – a barometer for the health of our planet – where a 1959 treaty provides for sustained international scientific cooperation."

"When the treaty comes up for review in 2048, nations could seek to reverse its strict ban against mining for mineral resources."

"Pollution spreading to the polar regions is already a problem. Mercury and microplastic emerges from industrial sources and shows up in polar ice cores, seawater and the atmosphere."

"Polar science has a strategic component. There is a need for more science diplomacy in the Arctic region – this has been key to mutual nuclear deterrence between the US and Russia."

"Switzerland, a leader in Alpine research, has a strong interest in polar research and believes its future depends on the sort of multilateralism and international cooperation that GESDA promotes."

Conference proceedings:
Collaborating on a Decarbonisation Accelerator

Global decarbonisation efforts are being stalled by objective gaps in science, technology, processes, and diplomacy. The nature of the gaps is often complex and systemic, and therefore impossible to solve with linear or single-party solutions. Solutions currently in the pipeline need to be accelerated to reach the right stage of maturity for their implementation.

3.1 Decarbonisation

After COP26, there is global agreement for governments, businesses, and citizens to embark in a decarbonisation global effort at every level. The global ambition is to achieve net-zero CO2 for 2050, which requires accelerating the energy transition to switch to renewable energy and deploying technologies that directly remove CO2 from the atmosphere.

- How can cooperation help boost R&D on decarbonisation processes, scale them up and accelerate the transition?
- How will collaboration create sector-specific sustainable business cases for decarbonisation technologies?
- How can we create a policy framework connecting science and diplomacy to enable the net-zero CO2 ambition?

Participants

Moderated by:

Carlo Giardinetti
Sustainability Lead for Consulting, Deloitte

With:

Belinda Cleeland
Head, Research & Innovation, International Organization for Standardization

Jim Hagemann Snabe
Chairman, Supervisory Board, Siemens AG

André Hoffmann
Businessman, Environmentalist and Philanthropist; Vice-Chairman, Roche Holding

Wendy Lee Queen
Associate Professor of Chemical Engineering, EPF Lausanne

Nikhil Seth
UN Assistant Secretary-General; Executive Director, United Nations Institute for Training and Research (UNITAR)

Massamba Thioye
Project Executive, Global Innovation Hub, United Nations Framework Convention on Climate Change

More information

https://gesda.global/solutions/
https://www.youtube.com/watch?v=sqiZjJ_GwZk
https://twitter.com/i/flow/login?redirect_after_login=%2Fi%2Fevents%2F1580616286144454656

Takeaway messages

"The challenge is to expedite the technology to decarbonise the world by 2050, then reach net zero, then get to net negative, in a way that is fair to everyone."

"The "sharpest knife" for accomplishing decarbonisation is setting a global price, or tax, on CO2. GESDA can play an active role in communicating the need for global CO2 pricing and how urgently the world needs to act – and in building trust among all communities."

"Research and technology assessment is needed. For many advanced materials, scaling up their use from the lab to industries has not yet been demonstrated."

"The 2° Paris target is gone in ten to 15 years; the 1.5° target is already gone."

"Clean energy provides a better business model than fossil fuels, and business leaders cannot afford to wait any longer to make the transition. Many of the technologies needed are already here."

Conference proceedings: Can we Bolster Democracy Through Technologies?

Many experts anticipated that greater connectivity and access to information would help build a broader foundation for democratic values, but political projections of the future no longer easily align with these expectations. As digital tools are increasingly used in democratic systems, the judiciary, and other governmental processes, the operating foundation for many nations and their citizens has never had more at stake.

4.4 Democracy-Affirming Technologies

Digital threats to democracy – misinformation, propaganda, political tribalism – are trending toward a future of destabilised political and community coherence.

- Can we employ digital technologies to bolster democracy and embody the values of an integrated and educated public?
- Will increasing digitalization breed divisiveness and threaten the foundations of democratic values?

Participants

Moderated by:

Chris Luebkeman
Chief of Foresight, ETH Zurich

With:

Agnès Callamard
Secretary-General, Amnesty International

Micheline Calmy-Rey
Former President, Swiss Confederation; Visiting Professor, University of Geneva

Niva Elkin-Koren
Professor of Law, Tel Aviv University

Aaron Maniam
Deputy Secretary of Industry and Information, Ministry of Communications and Information of Singapore

Nanjira Sambuli
Policy Analyst; Advocacy Strategist; Board member, Digital Impact Alliance, Development Gateway and The New Humanitarian

More information

https://www.youtube.com/watch?v=5v03mZkcTvA
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580233749593202688

“Decisions automatically made by algorithms are not transparent but are learning from data and therefore changing over time; this creates a huge challenge for auditing and oversight.”

“The element of digital taxation could spur change among big tech companies that bill themselves as forces for good.”

“New designs to boost democracy might look to the experience of populous nations like India and Kenya, rather than North America and Europe, to include those who live in the Global South.”“What people are motivated to do matters more than what technology is being used when we talk about its role and uses in society.”

“Managing both the upsides and inevitable downsides of technology must include coming to terms with the enormous amount of personal data that is collected.”

“The advent of digital technologies is a double-edged sword: they have the power to help fight injustice, and yet hold the potential to be misused as a tool of repression.”

“When designing digital technologies that might come to the aid of democracy, the traditional checks and balances of liberal democratic institutions don’t match with new technologies – like artificial intelligence – that assign traditional societal decisions to the realm of algorithms.”

“The goal of efforts like GESDA’s should be to build new institutions, norms, behaviours and international laws.”

“GESDA could build a platform to facilitate citizens’ greater digital participation in public affairs modelled after Switzerland’s decentralised governance and tradition of direct democracy.”

Conference proceedings: **Where are the Limits in the Digitalisation of Conflicts?**

Machine-learning, data policies, and social media platforms are already adding complexity to the conflict zone, and conventional technologies are being continuously enhanced by digital capabilities and computer systems. Ultimately, reliance on non-state actors, large global tech companies, and informal citizen groups to engage in direct political actions may be a standard part of conflict and intervention, but we cannot wait until tomorrow to assess the boundaries of this transformation.

The Future of Peace and War

In the future, nanotechnologies could upend international policies. Exposed health data could put individuals at risk from precision-engineered pathogens. Governments require a much deeper expertise to respond to unconventional threats.

- What are the best diplomatic approaches to such destabilising forces?
- How can governments and societies move forward and address this ideological change in the boundaries of conflict?

More information

https://www.youtube.com/watch?v=zIlgqJi9Rxo
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580632844984094721

Participants

Moderated by:

Anja Kaspersen
Senior Fellow, Carnegie Council for Ethics in International Affairsh

With:

Kobi Leins
Visiting Honorary Research Fellow, Centre for Science and Security Studies, Department of War Studies, King's College London

Charlotte Lindsey
Chief Public Policy Officer, CyberPeace Institute

Elina Noor
Director, Political-Security Affairs; Deputy Director, Washington, D.C. Office, Asia Society Policy Institute

Jean-Marc Rickli
Head of Global and Emerging Risks, Geneva Centre for Security Policy

Balthasar Staehelin
Special Envoy for Foresight and Techplomacy, International Committee of the Red Cross

"With growing cyber involvement in conflicts and the weaponization of data, the line between direct and indirect participation in conflicts is becoming blurred."

"The range of involvement includes tech platforms that are used to raise volunteers and money for fighting or a multibillionaire tech mogul whose donations can upend the geopolitical balance."

"A growing number of cyberinfluence operations are vying to control the information space, which is as much about sovereignty today as it is about influencing populations or the narrative."

"The weaponization of nanomaterials through neurological and biological applications is another complication. The combination of artificial intelligence, nanotechnology and biotechnology can be used to create unmanned intelligent robotic systems."

"Micro-targeting on popular platforms like Facebook also can track users throughout the internet."

"The rise, fall and continuing threat of the Islamic State militant group over the past decade show how digital technologies began proliferating in warfare at a rate that outpaced governments' ability to counter them."

"Technology and digitalization are most often viewed from an economic and trade standpoint in Southeast Asia but are also being exploited for intelligence gathering and geopolitical concerns."

"Cyber weaponization used against civilians and civilian infrastructure, and the unwilling involvement of tech companies, raises questions about enforcing the Geneva Conventions, the 20th-century treaties that govern the rules of war and military occupation."

"Disinformation and hate speech can erode the trust on which humanitarian organizations depend."

"Consensus-building and a focus on realistic possibilities are needed to counter the challenges of a fragmented and highly divided world."

Conference proceedings: Creating a Global Curriculum on Science & Diplomacy

A new mindset and professional pathway are needed to establish anticipatory science and diplomacy methodologies among experts and decision-makers. We must start with the way we train our current and future leaders across all sectors — in STEM fields, national governments, multilateral institutions and in the private sector.

4.2 Advances in Science Diplomacy

More information

https://gesda.global/solutions/
https://www.youtube.com/watch?v=ytfyz9QLHhY
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580614927852703766

If we are to empower the current and next generation with a "multilingual" mindset in science and diplomacy and foster boundary spanning professionals and institutions,

- What are the necessary ingredients (knowledge, skills/competences, and network) for an effective curriculum in Anticipatory Science & Diplomacy?
- What coalition of institutions must come together to design and deliver this curriculum?
- Where and how should it be deployed for future leaders to understand and jointly promote anticipatory Science & Diplomacy as a tool for a renewed multilateralism?
- How can we create effective opportunities and spaces for intensified interaction and understanding between scientific and foreign policy actors?

Participants

Moderated by:

Achim Wennmann
Director, Strategic Partnerships, Geneva Graduate Institute

With:

Francesca Bosco
Chief of Staff & Head of Foresight, CyberPeace Institute

Ismael Buchanan
Senior Lecturer, University of Rwanda

Martin Chungong
Secretary-General, Inter- Parliamentary Union

Tamara Gomez Marin
Consul General, Embassy of Costa Rica in Rome, Italy; Minister Counsellor, Ministry of Foreign Affairs and Worship of Costa Rica

Marga Gual Soler
Head of Capacity Building and Outreach, GESDA

Nicolas Levrat
Director, Global Studies Institute, University of Geneva

Sandeep Mishra
Expert, Digital Technologies and Innovation, India

Alysson Muotri
Professor, Department of Pediatrics and Cellular & Molecular Medicine, University of California

Christina Orisich
Deputy Director; Head of Executive Education, Geneva Centre for Security Policy

Rémi Quirion
President, International Network for Governmental

Nicolas Seidler
Executive Director, Geneva Science- Policy Interfacee

"GESDA is working to establish anticipatory science and diplomacy as an academic topic, a mindset and a new professional pathway; it emerged as a leading idea from the inaugural GESDA Science Breakthrough Radar and Summit in 2021."

"The aim is to widen the global circle of beneficiaries of advances in science and technology and close the gap between scientists and diplomats so they can effectively work together on policies and actions."

"The prototype of this global curriculum began in May 2022 as Science and Diplomacy Week, an immersion programme and open forum in Geneva for emerging science and diplomacy leaders."

"GESDA continues to build a global curriculum around the premise that no single individual or organization has a monopoly on how best to merge science anticipation with multilateralism."

"Diplomats are often crisis-oriented and don't take time to think about the future, but scientists also need time to understand how policy is made."

"To make better laws and policies, policymakers need to understand what is happening to people."

"The complexities behind merging education and training in science and diplomacy present a new kind of challenge to universities."

"Leadership skills and mindsets for driving change must be cultivated so people are prepared to listen, ask the right questions, empathise and understand others."

"Geneva is a great place for boundary-spanning professionals and mechanisms to thrive."

Conference proceedings:
Reviving the Human Right to Science

The notion that everyone has a right to benefit from scientific progress is enshrined in the United Nations' 1948 Universal Declaration of Human Rights. However, for most of its history, governments have largely allowed this right to remain dormant and neglected. As science and technology take an ever-greater role in our lives, is it time to bring this right back to life?

The Human Right to Science

More information

https://www.youtube.com/watch?v=FQ76xCeMJQM
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580623301021470722

Anticipated scientific and technological breakthroughs have the potential to change not only society but even human beings themselves. We believe that decisions concerning the development and use of these powerful technologies should be adopted within a human rights framework.

- How can this Human Right to Science be used to benefit humanity?
- What are the current challenges for this right?
- What are the duties derived from this Human right regarding emerging technologies?

Participants

Moderated by:


Gérard Escher
Senior Advisor, GESDA

With:


Samantha Besson
Professor, International Law of Institutions, Collège de France and University of Fribourg


Andrea Boggio
Professor of Legal Studies, Bryant University


Frederick Fenter
Chief Executive Editor, Frontiers


Gabriela Ramos
Assistant Director-General, Social and Human Sciences, UNESCO


Alexandra Xanthaki
UN Special Rapporteur in the field of Cultural Rights, United Nations


Thomas Zeltner
President, Swiss UNESCO Commission

"The link between scientific research and human rights was firmly established in the United Nations' 1948 Universal Declaration of Human Rights and the International Covenant on Economic, Social and Cultural Rights."

"Everyone is entitled to benefit from and contribute to science, be well-informed about new developments and enjoy an environment that promotes research about it."

"Trust in science is being eroded by disinformation and misinformation spreading through the digital world and fuelled by populism."

"UNESCO pushes to expand protections for scientific research and for nations to live up to their legal obligations. The Swiss Commission of UNESCO has made the human right to science a priority."

"The second GESDA Summit sent an important signal that it is imperative to ensure the existing rules apply to freedom of expression and the obligation for science to benefit all."

"GESDA's inaugural summit in 2021 began a debate over how to rectify the world's unequal access to scientific advancement and its benefits."

"The human right to science could be more precisely expressed as the human right to participate in science; UNESCO and GESDA could try to reinvigorate this human right in the name of participatory science for the public good that entails anticipation."

"The core issues are how to balance competing interests, provide access to scientific information and protect vulnerable people.

"Lack of consideration for Indigenous people's points of view has shown that more consideration should be shown to local populations' reflection that science contributes to structural discrimination."

"Open-access publishing is an integral part of the human right to participate in science."

Conference proceedings: **Enabling Digital Empowerment with Trust and Transparency**

In a complex, changing and interconnected world, digital twins and avatars are set to become a norm for decision-making in policy, ecology and the economy. Currently, several initiatives plan digital avatars and digital twins on the scale of individuals, local municipalities and the planet. Sensor webs enable real-time synchronization of such twins and avatars with the physical world.

5.1 Complex Systems Science

More information

https://www.youtube.com/watch?v=O1ZBrNfLMxs
https://twitter.com/i/flow/login?redirect_after_log-in=%2Fi%2Fevents%2F1580618490733596672

Building trust between the science and diplomacy communities in this area is urgently needed.

- What challenges will these pose to data privacy, transparency of algorithms, accountability, and ownership?
- Who decides what a digital models should and should not do, and to whom are developers accountable?
- How can we empower citizens and other stakeholders in their design and use?

Participants

Moderated by:

Sean Cleary
Executive Vice-Chair, FutureWorld Foundation

With:

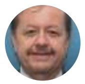
Jérôme Chenal
Senior Scientist, Urban and Regional Planning Community, EPFL; Academic Director, Excellence in Africa

Neil Davies
Executive Director, Richard B. Gump South Pacific Research Station; Research Affiliate, Berkeley Institute for Data Science

Soledad Garcia Ferrari
Professor, Global Urbanism and Resilience;
Dean, International College of Arts, Humanities and Social Sciences, University of Edinburgh

Dirk Helbing
Professor for Computational Social Science, ETH Zurich

Sami Kanaan
Administrative Councillor, City of Geneva; President of the Board, Geneva Cities Hub; Former Mayor of Geneva



Christian Kirchsteiger
Former Responsible, Strategy Development of EU Policies for Smart Infrastructures, EC Directorate-General for Communications Networks, Content and Technology (DG CNECT)

Mami Mizutori
Special Representative of the UN Secretary General for Disaster Risk Reduction, UNDRR

Huang Zhongwen
Director, Smart City Projects Office, Smart Nation and Digital Government Office, Prime Minister's Office, Singapore Government

Takeaway messages

"The use of "digital twins" and avatars raises questions about data privacy, algorithms, accountability and ownership, which is where GESDA might be able to help."

"Digital models collect huge quantities of data that call for government and corporate responsibility and greater transparency through good practices and international standards."

"The principle of building trust is important because the question in building the best solutions is: "Best for whom?" Since we don't know the systemic effects of these interventions, it's something that GESDA, the United Nations and other institutions need to work on."

"Digital models can improve the prediction and management of risk and thereby help vulnerable countries and communities build resilience. However, top-down solutions and decisions have failed to produce tangible results in vulnerable areas of the Global South."

"Before these digital tools for decision-making gain widespread use, experts say, new approaches will be needed for advancing and governing digital models, managing risks, developing ethics-based standards and avoiding dual use."

Conference proceedings: **Synthetic Biology, towards new geopolitical and economic frontiers**

Technological advances in genetic engineering and synthetic biology have created the potential for new biofuels, drugs, replacement organs, and biological threats. The democratisation of such technologies, coupled with the decreasing cost of DNA synthesis, will allow a broader set of actors to generate new organisms. This raises significant concerns about the governance of these technology innovations, capacity-building and benefit sharing.

5.5 Synthetic Biology

More information

https://www.youtube.com/watch?v=ZYnm75a3f1c
https://twitter.com/i/flow/login?redirect_after_login=%2Fi%2Fevents%2F1580426256637624322

It is essential that policymakers and regulators explore the social, environmental, economic and geopolitical implications of such technology advances.

- At the cusp of an explosion of uses and products, how can we harness the benefits of synthetic cells, biosensors, synthetic organisms and more?
- What effect will synthetic biology applications have on ethics, geopolitics, science policy and society?

Participants

Moderated by:

Jane Metcalfe
Co-founder, WIRED; Founder, NEO. Life

With:

Peter Gluckman
President, International Science Council

Arancha Gonzalez Laya
Dean, SciencePo Paris School of International Studies

Andrew Hessel
Chairman, Genome Write-Project; Founder, Humane Genomics

Timothy Swanson
Professor, International Economics; Academic Co-director, Centre for International Environmental Studies, Graduate Institute

Takeaway messages

“We’ve entered a new phase as a species, developing tools so powerful we could bring about our own extinction and, potentially, destroy the planet – but we’ve survived so far in the atomic era.”

“New and powerful synthetic biology tools are emerging that can rewire organisms, fight climate change, create new materials, cure human diseases or bring back lost species.”

“Synthetic biology is an information-based industry similar to how other information-based industries developed over the past half-century.”

“E. coli bacteria has been around for almost 4 billion years, but scientists recently made it from human-made DNA, opening a door to designer bacteria.”

“We need to create a space for conversations about science and diplomacy to occur, along the lines of what GESDA is doing, to avoid living in a world of conflicting regulations for new technologies largely based on different approaches taken in China, Europe and the United States.

“Fairness and diversity are needed to include the Global South and add legitimacy to the result.”

“Regulation of synthetic biology involves diplomacy and is a common theme of GESDA’s work: How do governments deal with the rapid pace of technological development?”

“Pragmatism, rather than optimism or pessimism, is an effective lens for considering humanity’s ceaseless arms race for new technologies, like synthetic biology.”

Appendices

The appendices provide access to the key resources that were cited in the different sections of the report, the full methodology used for the pulse of society analysis in the debates section — which led to the description of the 42 listed emerging topics as well at the collection of GESDA Best Read articles that appear throughout the Radar.

For more information visit:

radar.gesda.global/ap0

Methodology

The overarching goal for this report is to provide a constantly updated view on the societal debates related to fundamental questions about people, society and the planet. This section introduces the methodology for the Actions & Debates and Trends sections of the report.

For more information visit:

radar.gesda.global/apm

Cited Key Resources

Each of the 42 scientific emerging topics described in the GESDA Science Breakthrough Radar® presents a carefully vetted overview by lead scientists of the current state-of-the-art in a given field and what could be important science breakthroughs in 5, 10 or 25 years. The descriptions of the emerging topics and related sub-fields draw upon evidence from key resources and publications from the scientific literature. This section provides a list of cited resources, organised by emerging topic and related sub-fields.

For more information visit:

radar.gesda.global/apc

2023

Visit: radar.gesda.global

radar.gesda.global

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