The GESDA 2022 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

2022

Visit: radar.gesda.global

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A Letter from the Chairmen: Use the future to build the present

Anticipating scientific breakthroughs and accelerating their implementation – the aim of the Geneva Science and Diplomacy Anticipator Foundation – is more relevant than ever.

For the past year, everything around us has accelerated. We knew that science was advancing at a rapid pace, and that is precisely why the Swiss and Geneva governments created GESDA. Today, this acceleration is confirmed by the second Science Breakthrough Radar that you have in your hands. It validates our approach: to help science play a central role in solving the planet's grandest challenges.

Over the past year, these challenges have increased. We have been talking about climate change for a long time, but never before have these changes been so present as this summer. In terms of the geopolitical balance of the planet, the disruptions have been rapid and significant. Who still remembers the constructive speeches made by Presidents Joe Biden and Vladimir Putin during their meeting in Geneva? Yet this meeting took place little more than a year ago.

Since then, the war in Europe has had direct and tragic consequences for the populations concerned and repercussions for the entire planet. Energy and food crises are emerging that are putting populations and their governments in difficult situations. They must find answers to the problems posed in the short, medium and long term.

Leveraging International Geneva's ecosystem to anticipate, accelerate and implement advances that will result from emerging science in 5, 10 and 25 years to respond to Earth's biggest challenges is precisely GESDA's ambition. We are therefore grateful to our founders, notably the Swiss Confederation, the Canton and the City of Geneva for having decided this spring to extend our mandate for another 10 years.

We will continue our momentum by using the tools we have created:

1. **The GESDA Science Breakthrough Radar** - the result of a close partnership with the Fondation pour Genève - which scans and curates the cutting edge research conducted in the world.
2. **The Geneva Science and Diplomacy Anticipation Summit** - a space for dialogue between science, politics, diplomacy, business and citizens on the use and development of these promising scientific trends.
3. **The GESDA Solution Accelerator** - an instrument to develop concrete solutions that exploit the discoveries made by the Radar. Currently, there are eight solution ideas in our pipeline in various stages of development. They are designed in task forces composed of representatives from all GESDA communities (academic, diplomatic, impact and citizen).

The fourth step in GESDA's journey from think tank to 'do tank,' along the five scientific platforms presented in this document, is the creation of an **Impact Forum**, which will help fund the necessary multi-stakeholder actions.

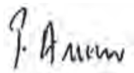
The annually released Radar, is essential reading for members and leaders of the different communities with which GESDA collaborates.

- For **scientists**, it offers the possibility to learn about the latest developments in fields that are not their own. This has become necessary as the convergence between sciences accelerates the pace of discovery and disrupts all areas of science.
- For members of the **diplomatic community**, the Radar provides a unique, carefully vetted and up-to-date overview of scientific and technological trends in a 25-year perspective. This transparent and understandable overview helps to anticipate and accelerate discussions about the implications of science and technology and their benefits.
- For the **private sector and philanthropy**, science and technology foresight as described in the Radar provides a longer-term perspective beyond traditional policy areas, and thus serves as the basis for a joint investment program using the future to build a better present.
- For **citizens**, the Radar is a tool for informed societal debate and action related to the opportunities and challenges presented by these advances. It offers open access to key scientific trends, and to what individuals and societies are thinking and doing about anticipated scientific and technological developments.

Nearly 800 scientists from 70 countries contributed to this second edition of the Radar. We would like to extend a warm thank you to them, to our Academic Forum, and to the entire team that worked on the production of this comprehensive report! We are convinced that reading it will contribute to enrich your reflection on the future of our world and its governance.

Peter Brabeck-Letmathe
Chairman of the Board of Directors
GESDA

Patrick Aebischer
Vice-Chairman of the Board of Directors
GESDA



Geneva, Switzerland, October 2022

Preface

For more than a century, International Geneva has contributed to the search for solutions to the major challenges facing our society and our planet. Geneva is today a major centre of global governance, acting through nearly 40 international organisations, 750 non-governmental organisations (NGOs), 178 representations of states, more than 1500 multinational companies and several world-class academic centres. This includes a variety of areas in which Geneva is already a recognised centre of expertise, from peace and security to economy, humanitarian action, health, environment and development. This unique Geneva-based ecosystem is working towards a global implementation of the 17 Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda

Our world is changing very rapidly, and the last 10 years have seen an acceleration of events with major implications for global governance and societies worldwide. Science and technology are taking an ever-growing role in these developments and are redefining multilateralism, just as they have already changed the world of work, politics and the functioning of our societies.

If we want to tackle the grand challenges of our time, there is no alternative to a renewed and efficient multilateralism that functions for the benefits of all. And anticipation is vital to this renewal. The Fondation pour Genève, which has supported the actions of the federal and Geneva authorities in favouring Geneva's international development since 1976, recognises the critical anticipatory role played by GESDA. Therefore, our foundation is proud to support its main project, the GESDA Science Breakthrough Radar, thanks to the commitment of local companies and entrepreneurs from the Geneva region.

Scientific breakthroughs and technological advances are now occurring at an unprecedented rate. They represent an exceptional opportunity to improve the well-being of populations around the world, but they also carry the risk of potential misuse. This is what the GESDA Foundation is all about: anticipating the technological developments of the next 5, 10 and 25 years, and coming up with new solutions to tackle emerging global challenges. This year's new additions, such as the geopolitical lens, provide additional tools for anticipating and rethinking the future international system.

The GESDA Science Breakthrough Radar has the potential to transform international Geneva and shape the future of modern multilateralism. It allows the different stakeholders to be aware of future scientific trends and, if necessary, to act sooner rather than later. By bringing together the different communities — scientists, diplomats, business leaders, civil society, public and private sectors — at an early stage, GESDA can significantly accelerate the development of solutions. GESDA's anticipation alongside the unique features of International Geneva's ecosystem is an ideal combination, making the GESDA Science Breakthrough Radar an exceptional tool for International Geneva.

Today's International Geneva is not the same as yesterday's, and the International Geneva of tomorrow — though it is yet to be conceived — will definitely be different. While the future remains very uncertain, it is crucial that we anticipate, and as GESDA puts it, "use the future to build the present". When it comes to implementing the United Nations 2030 Agenda and responding to today's mounting global challenges, the cost of non-anticipation for International Geneva is simply too high.

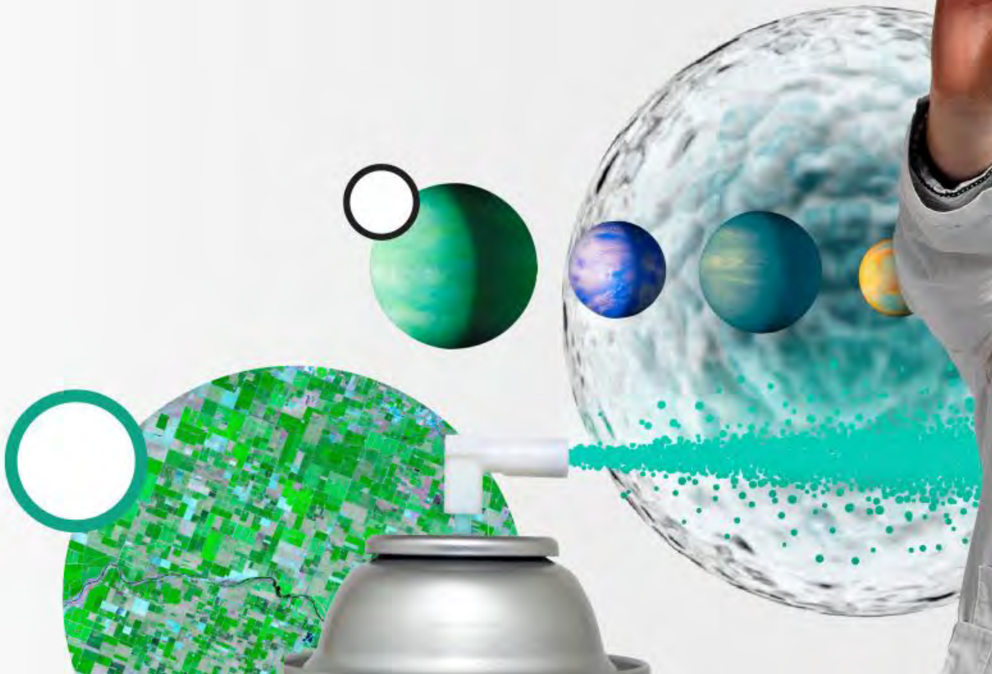
Marc Pictet
Président, Fondation pour Genève

Geneva, Switzerland, October 2022

GESDA in a nutshell: Anticipatory Situation Room pipeline of activities

	GESDA **Think** Tank	GESDA **Do** Tank		
Scientific Platforms	Science Anticipation Rolling Yearly Science Breakthrough Radar	Pipeline of Solution Ideas Academic-Diplomacy Task Forces	Exploratory Initiatives Demonstrators	Impact Fund
1 Quantum Revolution & Advanced AI	6 Emerging topics (+2) 2 Invited contributions	Open Quantum Institute Co-development, access & use of advanced AI	Gesda-Xprize Quantum Contest for SDGs	Core funding + prize purse for Quantum Contest
2 Human Augmentation	6 Emerging topics (+2) 1 Invited contributions	Neurotech Compass	Norms & Principles for neurotechnologies (tbd) Matrix on one use case (tbd)	Core Funding
3 Eco-Regeneration & Geoengineering	7 Emerging topics (+2) 3 Invited contributions	Decarbonization Accelerator	Power-to-X decarbonized energy for shipping (tbd) Decarbonization materials (tbd)	Core Funding
4 Science & Diplomacy	4 Emerging topics (+2) 1 Invited contributions	Global Science Diplomacy Curriculum Science Norms & Principles	Science Diplomacy Week Human Right to Science	Core Funding
5 Knowledge Foundations	5 Emerging topics (+2) 2 Lenses (+1) A / Philosophy B / Geopolitics C / Science (as of 2023)	Education, Public Agora & Youth Engagement (Radar based) Digital Twins for Citizens, Policymakers, City Mayors	Youth and Anticipation Initiative	Core Funding

“Use the future to build the present”



About the 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 Science Breakthrough Radar is:

- a new tool for multilateralism, informed discussions, and concerted action
- a single point of entry to catch up with the unprecedented pace of 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

Scientific Platform	Emerging topics in the 2021 edition that will be updated and enhanced	New emerging topics extended into full briefs	New invited contributions
1 Quantum Revolution & Advanced AI	1.1 Advanced AI 1.2 Quantum Technologies 1.3 Brain-inspired Computing 1.4 Biological Computing	1.5 Augmented Reality 1.6 Collective Intelligence	• The Technology Opportunity for Digital Humanities and Art • AI for Science
2 Human Augmentation	2.1 Cognitive Enhancement 2.2 Human Applications of Genetic Engineering 2.3 Radical Health Extension 2.4 Consciousness Augmentation	2.5 Organoids 2.6 Future Therapeutics	• Xenobots and Computer-Designed Organisms
3 Eco-Regeneration & Geoengineering	3.1 Decarbonisation 3.2 World Simulation 3.3 Future Food Systems 3.4 Space Resources 3.5 Ocean Stewardship	3.6 Solar Radiation Modification 3.7 Infectious Diseases	• Polar Resources • Coral and Ocean Renewal
4 Science & Diplomacy	4.1 Science-based Diplomacy 4.2 Advances in Science Diplomacy	4.3 Digital Technologies and Conflict 4.4 Democracy-Affirming Technologies	• The Challenges and Opportunities of Sustainable Finance
5 Knowledge Foundations	5.1 Complex Systems Science 5.2 Future of Education 5.3 Future Economics	5.4 The Science of the Origins of Life 5.5 Synthetic Biology	• The Philosophical Lens • The Geopolitical Lens • The Future of Peace and War • Futures Literacy • How Machine Learning is Transforming Regional Economic Development

Facts and Figures

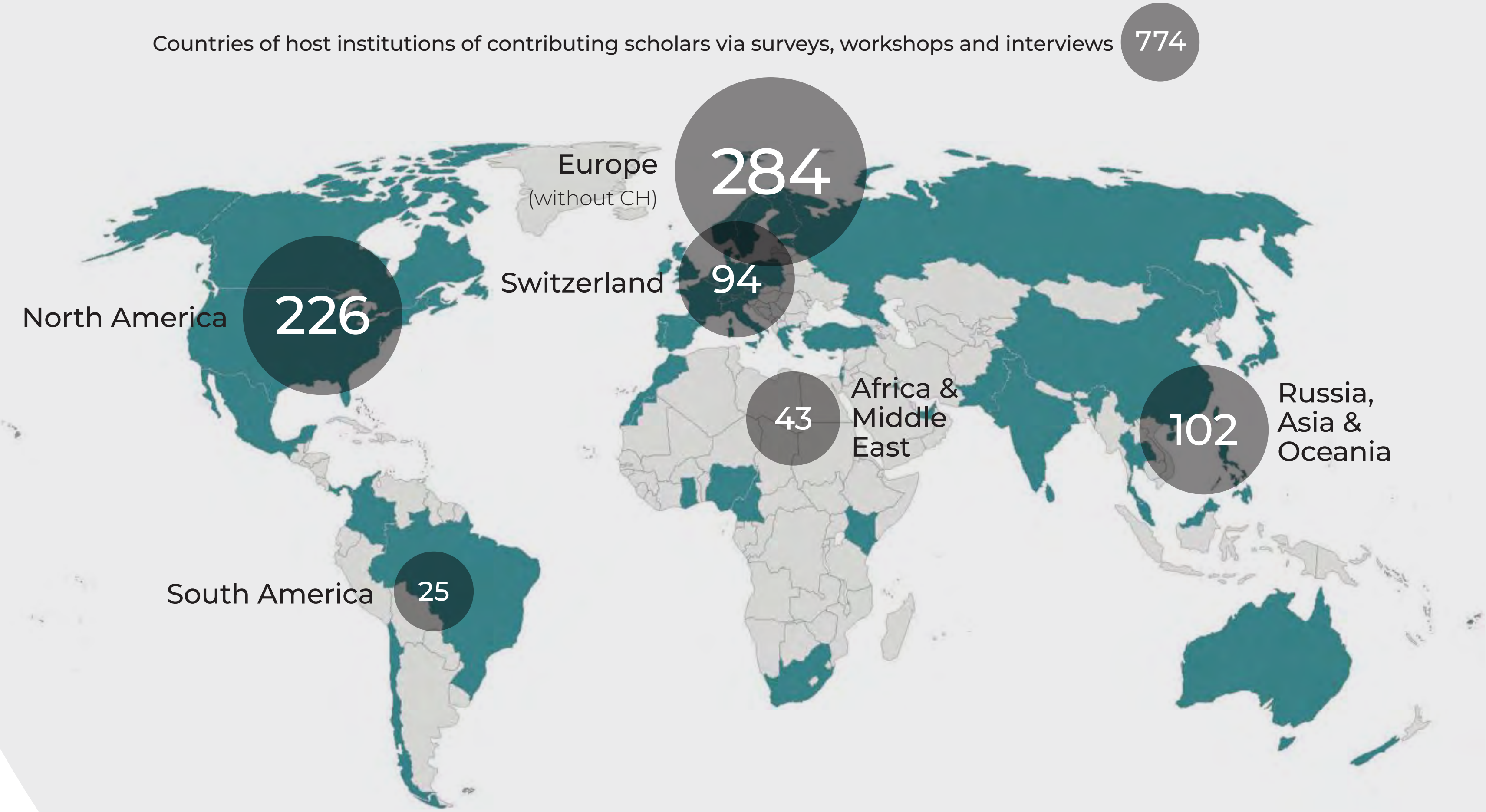
The Science Breakthrough Radar comprises **5** scientific platforms, **37** emerging topics and **336** breakthroughs at 5, 10 and 25 years of interest for science.

It contains **2** lenses on philosophy and geopolitics on **3** fundamental questions about the future of humanity, debated by **21** scholars from philosophy, social sciences, humanities and geopolitics. More than **1,100** scientists were involved in creating its first two editions:

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

It includes analysis of **11** million social media posts in order to take the pulse of society on what people do and say about the various scientific platforms.

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



Introductory Essay:
Engaging in science anticipation outside of ideological frameworks

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Sir Peter David Gluckman
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Prof. Michel Mayor
Prof. Emeritus at University of Geneva and 2019 Physics Nobel Prize Laureate. Representative of the Fondation pour Genève

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

The rapid advancement of science and technology is having profound consequences, fundamentally altering who we are, and the way we live and interact with each other and our environment.

It is a two-edged sword, however. While science and technology contribute to a better world, they are also linked to some of today's biggest global challenges — anthropogenic climate change, for example. It is therefore vital that we anticipate what is cooking in the laboratories right now if we want to ensure that as many people as possible on this planet will benefit from emerging technologies without having to also suffer further adverse societal and environmental consequences. 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.

The GESDA Science Breakthrough Radar is designed to do just that. It was conceived as a neutral, science-based, expert-informed platform for presenting possible advances and breakthroughs in selected areas of science and technology at 5, 10 and 25 years. In that sense, its purpose is neither to predict the future nor to present a hypothetical vision of a desired society towards which humanity should strive. Rather, it provides insights about what is being developed by researchers and innovators worldwide and provides the elements to initiate debates about opportunities over the next two decades or so.

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. This is a necessary pre-condition for grounded discussions about the implications of these advances on individuals, society and the planet. In the spirit of a renewed multilateralism, such discussions should involve all communities concerned, including scientists, citizens, diplomats and the private sector. Our science anticipation is a starting point. 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.

The importance of science anticipation in light of geopolitical tensions

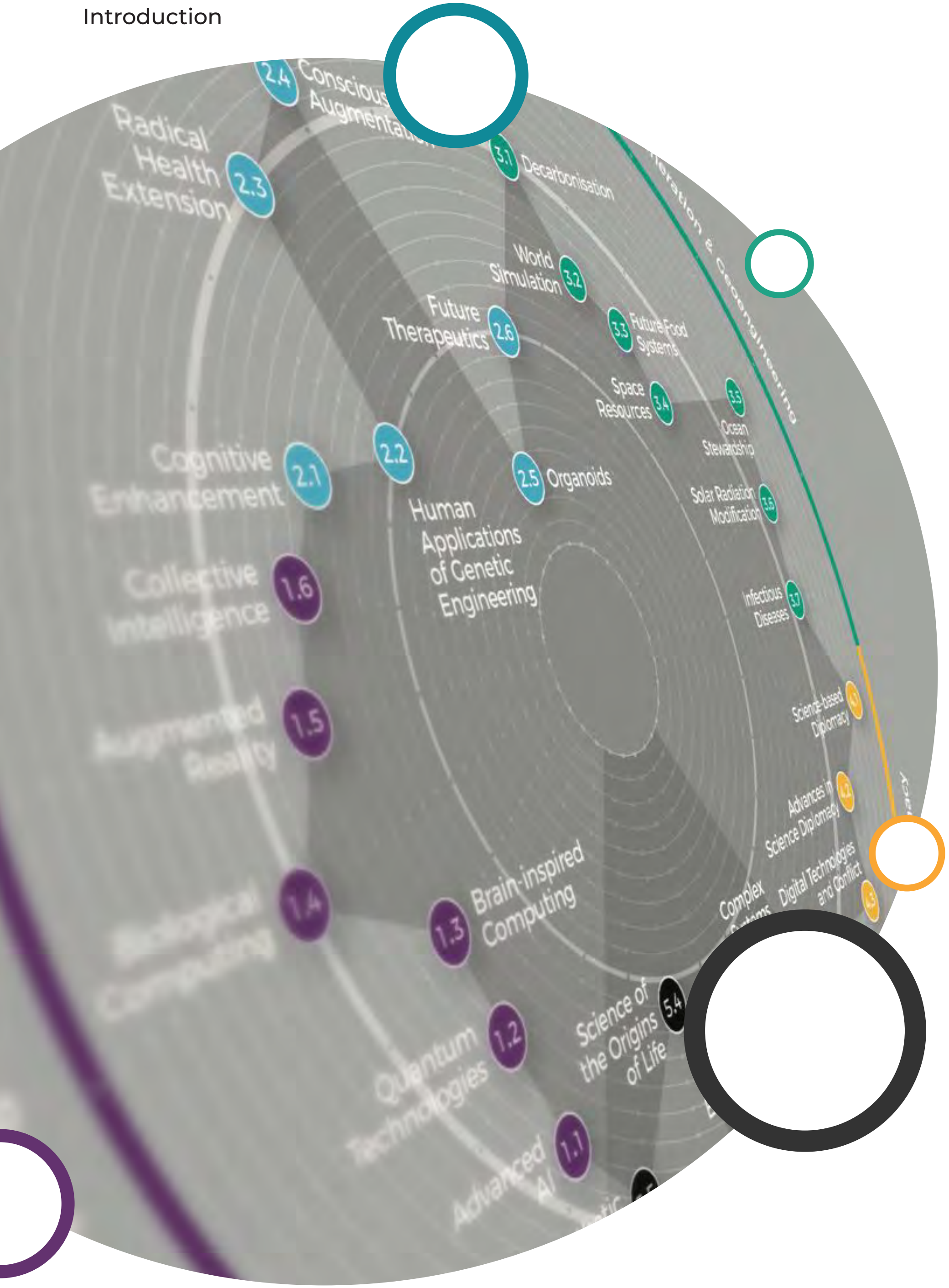
All this is taking place against the backdrop of rising geopolitical tensions and armed conflicts in Europe and worldwide. This could call into question whether one should engage in science anticipation, but we believe that it is now more important than ever that we envisage science anticipation as an open, non-partisan and fact-based instrument to bolster this dialogue at international level.

It is our conviction that humanity has the capacity to deal with today's challenges while keeping an eye on potential future issues. The radar, as an overview of what is underway in research worldwide in selected areas of natural sciences, engineering sciences, social sciences and the humanities, opens a space where informed and impactful conversations about science trends and their implications can start without endorsement or geopolitical influence.

Conclusion

We are certain that the world will continue its rapid change in the coming years — and science and technology will certainly be among the drivers of change. The GESDA Science Breakthrough Radar uses science anticipation as a means of preparing us for the changes to come. 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. This second edition of the radar already led to a significant increase in the number of contributing researchers and emerging topics covered.

The integration of knowledge foundations is a further step to include the natural sciences, social sciences, humanities and engineering sciences that are transversal and foundational to the broad areas covered. The radar will continuously be updated and expanded through interactions with scientists of all regions and of all backgrounds, from the public and the private sector, in a spirit of true open science.



Executive Summary

Welcome to the 2022 Science Breakthrough Radar from the Geneva Science and Diplomacy Anticipator (GESDA), presenting the most consequential developments in emerging science and technology. This second edition was commissioned during a global pandemic and compiled during a period of increased geopolitical tensions and armed conflicts in Europe and worldwide. It is being published amid rapidly mounting concern over the economic, social and environmental future of the planet, all of which are related to science and technology. It has surely never been 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.

These changes in the global environment have been reflected by changes in the Radar's scope and presentation. This 2022 release of the Science Breakthrough Radar is a significant expansion compared to the inaugural edition last year.

The main new conceptual elements compared to the 2021 edition are:

- The expansion of the community from 543 to 774 leading scientists
- An increase in the number of emerging topics from 24 to 37
- The addition of Knowledge Foundations as a fifth scientific Platform, anticipating advances in foundational topics across all fields of sciences and transversal to the four thematic platforms
- The monitoring of the actions people are taking in relation to our scientific Platforms, complementing the existing sentiment analysis (opinions) in the Actions & Debates section of the Radar
- The full integration of the GESDA summit proceedings in the Opportunities section of the Radar

Our core approach, however, 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 the respective topic areas 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 our **Science Breakthrough Radar** as carefully vetted anticipatory **Breakthrough Briefs**. The Briefs analyse the key developments in the selected emerging topics, and make predictions for their short, medium and long-term evolution, at 5, 10 and 25 years.

We see this process as an essential step towards achieving our aim of being an honest broker in fostering debate and appropriate action around future scientific breakthroughs. The way this works is showcased in what we call Zooms. Here we create a synthesis of the findings over all sections of the report. This provides an evidence-led, neutral and unbiased demonstration of where important new conversations and initiatives might be needed. Such an approach enables all parties to engage in fully-informed debate about possible future actions and initiatives without fear of encountering prejudice or hidden agendas. In this year's report we present five examples of Zooms — one from each of our scientific Platforms — as a first step towards creating what is, we feel, the distilled essence of GESDA's ambition.

Zoom on platform 1: Quantum Revolution & Advanced AI

1.2 Quantum technologies

Trends

Few emerging fields have received more attention in recent years than quantum technologies, with many countries, companies, and researchers producing roadmaps charting out the future of the field. Much of the focus has been on quantum computing so, despite its undeniably disruptive potential, much of the anticipatory work is already underway. With steady progress, universal quantum computers with millions of qubits are expected to run accurate and predictive simulations in chemistry and materials science in 25 years, accelerating discoveries such as, perhaps, materials that superconduct at room-temperature, catalysts for nitrogen fixation and new pharmaceutical products. Future quantum computers will also be able to crack most of the encryption techniques currently used to secure communications and data. This will have strong impacts on society (in terms of access to and use of the technology) and the environment (in terms of development of applications).

1.2.2 Quantum technologies

Actions & Debates

Many actors in civil society are aware that developments in quantum computing are underway and most see these developments positively. Understanding quantum science remains a challenge with much activity needed in educating and raising awareness about quantum technologies, especially with regards to privacy issues and potential applications. The recent opening up of national quantum computing platforms and programmes will speed up entrepreneurial activities and provide better access for developers.

What do people say?
What do people do?

Opportunities

Quantum computing is costly however, and only a few private and public entities have the resources for the most ambitious developments. It has become a strategic and key enabling technology, with a strong potential for the future. As highlighted at the GESDA 2021 High-Level Summit, building a quantum ecosystem is complex and there is a need to steer research towards beneficial applications that are not only focused on economic, geopolitical or military advantages. Out of the discussions at the summit, the idea of a hybrid organisation for quantum that could guarantee safe access to and use of critical quantum infrastructures for communication and computing was proposed.

Opening quantum for the benefit of humanity

Zoom on platform 2: **Human Augmentation**

2.1 Cognitive enhancement

Trends

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 is also becoming possible to manipulate those brain states in more targeted ways using a wide spectrum of methods, from electrical to chemical. As imminent brain monitoring technologies combine reading and writing brain states, aided by ever more capable AI, the ability to decode cognitive and emotional states and make them increasingly transparent will yield unexpected applications across society.

Closed-loop devices — devices that use machine learning algorithms to decode mental states and baseline brain activity and stimulate "on demand" without needing the intervention of a clinician — are expected within 10 years. Those algorithms will also identify brainwave patterns associated with useful stages of the sleep cycle and the devices could then amplify these oscillations to improve memory consolidation. In 25 years, they could be widely adopted, with onboard AI seamlessly translating brain function and transforming cognition into commands, augmenting memory and cognition for increasing numbers of healthy people.

2.1.3 Hybrid cognition

Actions & Debates

Cognitive enhancement and future brain monitoring technologies are widely debated in society, with a somewhat ambivalent sentiment. There is a concern about losing agency and mental autonomy through a widespread deployment of brain-computer interfaces, while at the same time the possibility to augment one's cognitive capacity is seen positively. This suggests that those technologies will be widely adopted to enhance cognitive function in healthy people once the technology gets to a particular inflection point, as our ability to both read and write brain data grows.

What do people say?
What do people do?

Opportunities

The creation of two-way conduits into people's minds and huge pools of sensitive brain data raise profound questions about privacy, personal agency, and the integrity of the individual. The session at GESDA's 2021 High-Level Summit considered these anticipatory perspectives from the viewpoint of "neuro-rights". It was clear that unanticipated societal outcomes must be considered in the deployment of future neurotechnologies and emerging governance frameworks need to be able to cope with a dynamically evolving field. Four levels of governance were suggested: self-regulation; ethical guidelines and so-called soft law; binding national regulations; and international human rights law. It is clear from the perspectives of the panellists that the involvement of scientists and policymakers is not enough; the voices of citizens also need to be heard because of the profound implications.

Establishing neuro rights

Zoom on platform 3: Eco-Regeneration & Geoengineering

3.1 Decarbonisation

Trends

The reports of the International Panel on Climate Change (IPCC) make clear that climate change is a direct result of anthropogenic activity, which is primarily related to the combustion of fossil fuels The consequences of this activity on our habitable environment are serious, and implementing a global strategy to curb CO_2 levels is an urgent task. Energy transitions are historically slow and hence the continued use of fossil fuels is expected for many years to come. Thus, the concurrent advancement of many other technologies is required. Such technologies are related to capturing CO_2 from large point sources such as power plants, improving energy efficiency, producing synthetic fuels from waste products such as CO_2 and biomass, and CO_2 storage, both underground and in the form of useful, value added products such as concrete. However, a major part of the IPCC solution is to directly remove CO_2 from the atmosphere using a range of “negative emissions technologies” (NETs), which can be incentivised through robust CO_2 pricing.

By combining solar energy and various CO_2 extraction methods, including newly developed approaches to NET such as Direct Air Capture, the production of synthetic fuels from carbon could become commercially viable in 10 years.

In 25 years, breakthroughs in DAC and conversion technologies may allow large industrial scale applications where CO_2 is captured from air and converted into synthetic fuels and other value-added chemicals, provided the right economic and policy incentives are in place.

3.1.1 Negative emission technologies

Actions & Debates

Public sentiment on decarbonisation is naturally ambivalent. While a large share of opinions expressed on social media views the development of technological solutions to decarbonisation as positive, a significant number fear the slow pace of progress and the high costs related to the transition to a decarbonised society. As a consequence of this, civil society actors are engaging in an increasing number of activities around decarbonisation technologies and the energy transition. Beyond awareness raising activities about the consequences of climate change and potential solutions, local challenges and crowdfunding campaigns for the development of carbon-neutral and carbon-negative applications mobilise actors from civil society.

What do people say?

What do people do?

Opportunities

While the potential of NETs to reduce our carbon footprint has been demonstrated, how can we get promising decarbonisation technologies out of the lab that are viable in the marketplace? The challenge is to accelerate and 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. For many advanced materials critical for DAC technology, scaling up their use from the lab to industries and the real world requires a global interdisciplinary effort.

Accelerating the active decarbonisation of our planet

Zoom on platform 4: **Science & Diplomacy**

4.2 Advances in science diplomacy

Trends

The products of science, such as vaccines and intelligent machines, are now becoming part of the currency of international negotiation and diplomacy, an effort that will be ever more vital in the 21st century. The discipline of Science Diplomacy seeks 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 whether they are from global companies, from grass roots organisations or from non-governmental organisations. Big science projects themselves are increasingly becoming part of this landscape. As global challenges multiply, these groups must find ways to manage the global commons fairly and effectively, and avoid the fragmentation in technology and world affairs predicted in future geopolitics. Science diplomacy could begin to shape future technology platforms in 10 years and multi-stakeholder science diplomacy could become the norm in 25 years.

- The geopolitical lens
- 4.2.1 Multistakeholder technology diplomacy

Actions & Debates

Citizens globally recognise the contribution of science diplomacy in solving global challenges and understand the importance of maintaining global scientific collaboration in an uncertain and fragmented world. These sentiments are strongly polarised in the context of the COVID-19 vaccines development and roll-out, with many opinions voiced on social media expressing distrust in science.

- What do people say?
- What do people do?

Opportunities

Making the most of science diplomacy requires a revitalisation of the concept: a major update on its underpinning frameworks is needed. The focus on anticipation should be a key feature, given the speed of development of new technologies. For this to work, this requires us to build trust in science, to raise science and technology knowledge and awareness, and to educate generations of potential future leaders.

- Revitalising multilateralism through anticipatory science and diplomacy

Zoom on platform 5: Knowledge Foundations

5.3 Future economics

Trends

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. 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.

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.

For example, as the power of artificial intelligence develops, there is significant displacement of jobs because of smarter and more efficient machines.

5.3.2 Automation and work

5.3.4 Sustainable global trade

Actions & Debates

Concerns are already mounting within civil society, strengthened by the aftermath of the COVID-19 pandemic and fear of inflation. This will push governments in the coming 10 years to implement policies that ensure human capital is not wasted and that education and retraining is common, preparing workers and rising generations for a changing workplace.

What do people say?

What do people do?

Opportunities

A wide range of economies have begun trialling universal basic income paid for by the taxation of capital and automation. These measures were discussed at the 2021 GESDA High-Level Summit with the conclusion that automation can be managed without losing potential gains through labour and education policies, such as investing in skills, and good jobs, and by redistributing the gains of automation.

As a consequence of economic decoupling and fragile global supply chains, the focus is shifting towards resilience and we could see the emergence in 10 years of supply chain stress tests and new technologies tracking the resilience and environmental impact of supply chains in 25 years.

Designing an economic compass for sustainable, inclusive and resilient societies


System HACKED
FAKE
SHAME
TROLL

Acknowledgements

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Prof. Joël Mesot
President ETH Zurich

Prof. Martin Vetterli
President EPFL

and GESDA's Diplomacy Forum chaired by:

Michael Møller
Former Under-Secretary-General of the United Nations

This enabled the development of a product of sufficient breadth and depth to become a useful tool for multilateralism.

We would like to thank here all those involved, with particular attention to:

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The Members of the Scientific Advisory Board:

Prof. Michael O. Hengartner
President of the ETH-Board, incoming Chair of the GESDA Academic Forum

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 Laureate. Representative of the Fondation pour Genève

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

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Martin Müller
Executive Director Academic Forum GESDA

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Trends

Taking the Pulse of Science: The Science Breakthrough Radar

The 2022 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 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.

But 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 28 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 770 scientists from 67 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 336 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 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 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

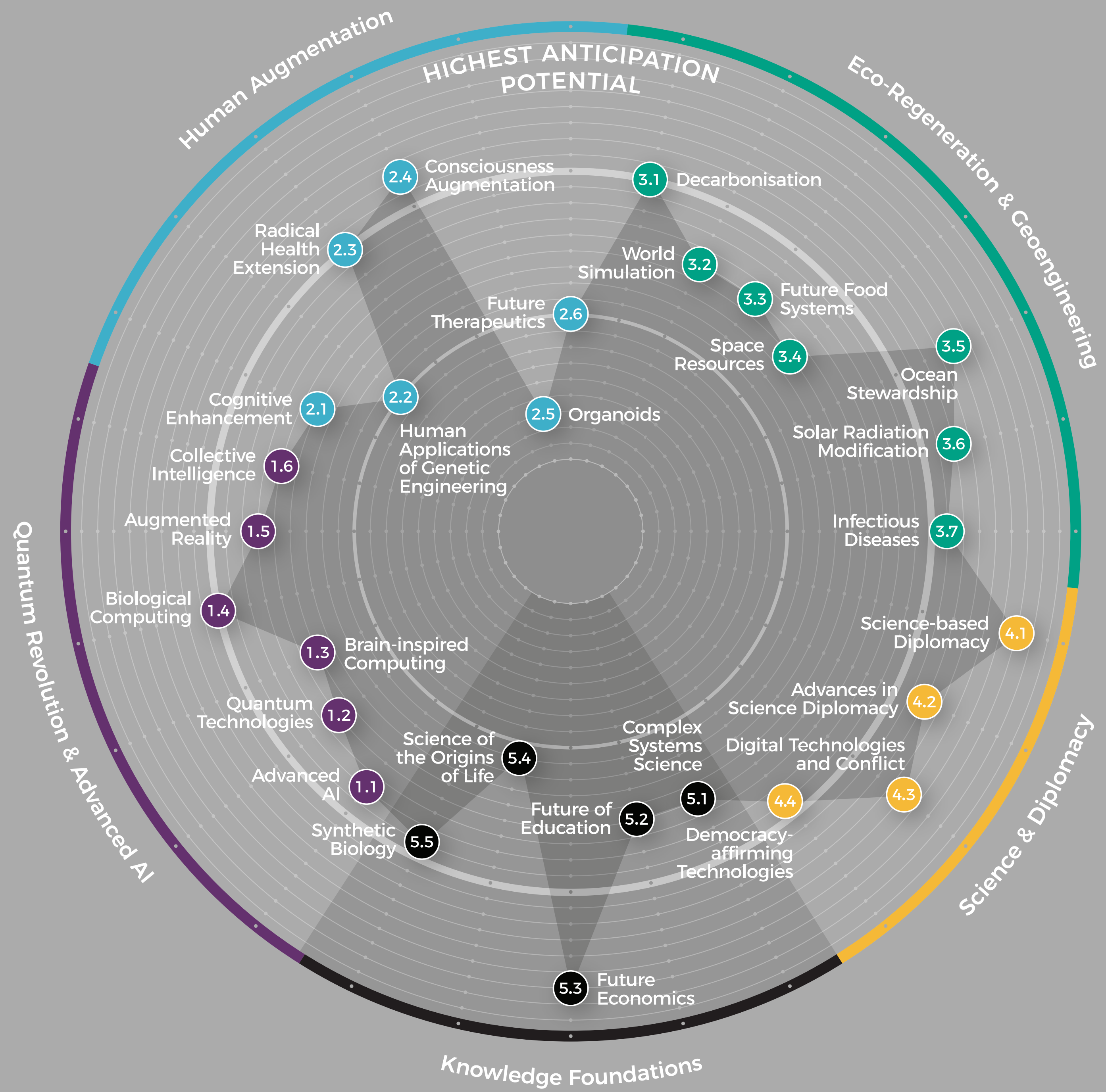
Our radar screen measures and illustrates the "anticipation potential" of each of the emerging scientific topics. Each frontier issue is represented by one quadrant of the Radar, and each scientific emerging topic by a dot. The farther the dot is from the centre of the radar screen, the higher the opportunity 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 human beings 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 Appendix 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
2.4 Consciousness Augmentation
2.3 Radical Health Extension
2.6 Future Therapeutics
2.2 Human Applications of Genetic Engineering
2.1 Cognitive Enhancement
2.5 Organoids
3.1 Decarbonisation
3.2 World Simulation
3.3 Future Food Systems
3.4 Space Resources
3.5 Ocean Stewardship
3.6 Solar Radiation Modification
3.7 Infectious Diseases
4.1 Science-based Diplomacy
4.2 Advances in Science Diplomacy
4.3 Digital Technologies and Conflict
4.4 Democracy-affirming Technologies
5.1 Complex Systems Science
5.2 Future of Education
5.3 Future Economics
5.4 Science of the Origins of Life
5.5 Synthetic Biology
1.6 Collective Intelligence
1.5 Augmented Reality
1.4 Biological Computing
1.3 Brain-inspired Computing
1.2 Quantum Technologies
1.1 Advanced AI

Johan Rochel
Co-Founder, Ethix –
Lab for Innovation Ethics

Invited Contribution:
The Ethics of Anticipation

Anticipation is a vital part of any decision one has to make. When we innovate, we create opportunities and risks. If our innovations are to bring long-term economic, social and ecological progress, it is important to anticipate the widest possible variety of outcomes and steer innovation in the direction that brings the most added value and the least harm.

But anticipation is not neutral. It involves making choices about how to view potential futures, and thus it requires its own ethical consideration. An ethics of anticipation faces two main challenges. The first challenge is linked to the nature of ethics itself. Ethics, understood as the scientific discipline that deals with moral principles, norms, and concepts, is a normative discipline. By contrast with other disciplines of the natural sciences, ethics aims at outlining how human beings/society ought to act and to be organised. When applied to science and technology, it is crucial to consider that technological developments can deeply challenge the way ethics as a discipline works and, consequently, might impact what is required of an ethical anticipation of scientific and technological development.

It is certainly clear that technological developments can improve one's capacity to anticipate. An increase in computational power, for instance, might generate more fine-grained information about potential futures. But in several scientific areas, the changes could go deeper. Consider neuroscience and genomics, for example. Here, some technological developments might affect basic assumptions about moral agency and human freedom, and the corresponding capacity to bear responsibility.

"who are we?"

“how will we be living together?”

For example, reports of genetic predisposition and disruption of certain neural circuits have both been used by defence lawyers to explain and excuse criminal behaviours. An ethics of anticipation must therefore anticipate how such developments affect the core parameters of ethical reasoning.

The second challenge is about the way anticipation is done. An ethics of anticipation should cultivate the ability to shed light on the opportunities that advances generate. It should avoid one-sided focus on risks and mere precaution, because precautionary reasoning can prevent anticipation from deploying its full potential. Developing and applying an ethics of anticipation does not mean slowing down innovation and human development but supporting it towards enhanced sustainability and a more just distribution of goods, capabilities, and opportunities.

To face this methodological challenge, an ethics of anticipation should also consider the fact that every act of anticipation is confronted with different ways of conceptualising uncertainty. As discussed in the literature, there are three approaches to this. First, predictive anticipation, which aims to forecast the future based on probability calculation informed by the past (or the present). Adaptive anticipation, on the other hand, accepts the non-predictability of the future and uses it to emphasise the potential of both individuals and societies to adapt. This keeps the future radically open by focusing on conditions that can be encouraged to arise in the present. Finally, projective anticipation separates the future from the influence of the past: it overcomes determination by anticipating futures as something radically new and fundamentally different, showing no continuity with previous times.

Once aware of these parameters, all anticipation methods should be able to respect the following ethical criteria. First, anticipation needs to be practiced free of a sense of inevitability and aware of its inevitable preconceptions. It should be an opportunity to imagine a better world, evaluate it and decide whether that future is desirable or not. Second, choices made in anticipating must be carefully justified, as a contribution to avoid biases and unfair omissions. Third, it is necessary that anticipators always be able to account for the unforeseen, including radical disruption.

Properly considered, all of this can have an impact on the three guiding questions that GESDA addresses. As a matter of “who are we?”, increased knowledge relevant for the conception of moral agency will play a key role. This is the dimension in which what we call ethics will evolve. A world in which interaction with advanced autonomous systems becomes routine may challenge the traditional limitation of attributing moral agency to humans only. Moral agency represents a core aspect of human self-understanding, and an ethics of anticipation calls for scrutiny with regard to potential effects of future developments on that very concept. For instance, it will be increasingly important to clarify which capacities that autonomous systems may acquire in the future will determine agency in a meaningful sense. Also, it will be necessary to keep an eye on applications that may shift norms allowing to distinguish human from non-human and that may question moral agency.

With regard to “how will we be living together?”, technological and scientific advancements can be expected to have implications on the issue of determining limits of, and obligations within, what we might term the “moral community”. At the same time, it seems plausible that an increased understanding of natural diversity will influence the way human “normality” is perceived. For instance, such knowledge may influence the level of tolerance — both positively and negatively — of the diversity of “normal” human conditions (as far as genetic preconditions are concerned) becomes increasingly visible.

On the issue of “how will we live on earth?”, finally, ethical reflections on anticipation underline the importance of developing and adapting narratives to apprehend our situation as humans in the context of a natural environment. Technological solutions will play a major role here, as they increasingly affect the key foundational narratives of what it means to be human — and what constitutes a “person” in the sense of a moral agent.

“how will we live on earth?”

1

Introduction to Quantum Revolution & Advanced Artificial Intelligence

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 set to grow in power and influence. It is clear that our current systems realise only a small part of AI's potential, and as it grows more powerful and flexible it will affect us ever more profoundly. Anticipating and directing how that growth will occur is a vital part of the research effort in this area: we must shape **advanced artificial intelligence** to be reliable, transparent and equitable, but that may require a deep reappraisal of how these technologies are developed and deployed.

The effort to process information in entirely novel ways using the unique properties of subatomic particles is making significant progress. **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, finance and online commerce, and to accelerate scientific discovery.

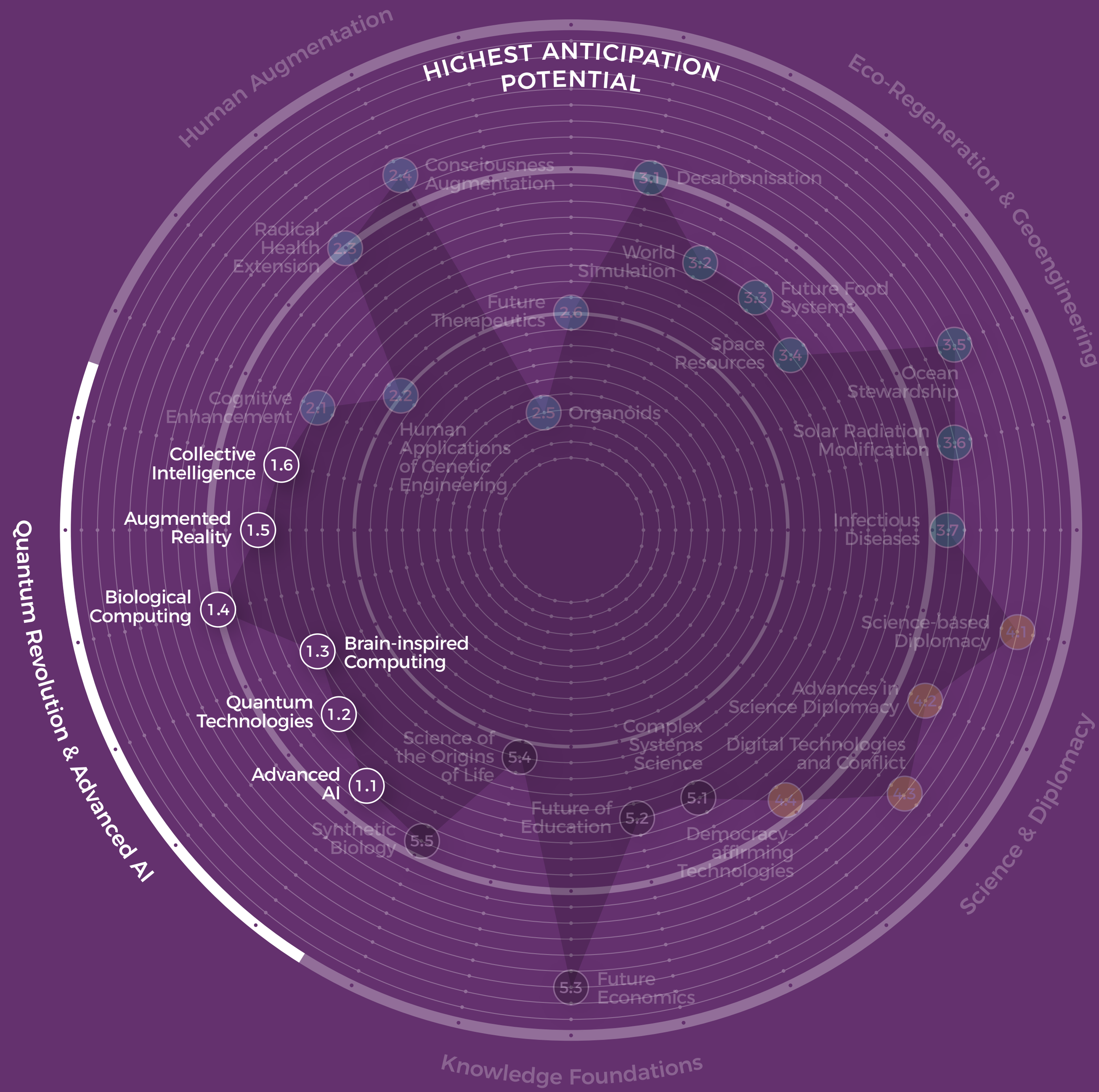
Computing researchers are looking to harness biological innovations honed through millions of years of evolution. If they can achieve even a fraction of the energy efficiency and processing power of the human brain, for example, we will have unleashed an extraordinary new era of computing. **Brain-inspired computing** seeks to take neuroscience's understanding of the brain's architectures and processes and use them to create autonomous, low-energy information processors that offer the potential for radical new computing applications.

Living matter uses more than just brains to process information. The biochemistry of cells, bacteria and other biological systems and organisms is a form of information processing that has vast potential for technological exploitation. **Biological computing** seeks to harness, and sometimes re-engineer, biological information processing to perform tasks such as environmental sensing, remediation of pollution and medical diagnosis. These new thinking devices may be very different to today's conventional computers, requiring us to rethink how we can use them to best effect.

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. 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 artificial intelligence, 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 the following pages we explain and explore the various ways in which, properly directed, novel information technologies can have a transformative, positive impact on our world.



1.1

Advanced Artificial Intelligence

Artificial Intelligence (AI) aims to build machines that are able to behave in ways we associate with human activity: perceiving and analysing our environment, taking decisions, communicating and learning. There are various approaches to achieving this. The most well-known, and arguably most advanced, is machine learning (ML), which itself has various broad approaches.

To mention just two approaches, in supervised learning algorithms make associations between a given input and the desired output by learning on training sets comprising many correct input/output pairs. In reinforcement learning, the ML algorithm repeatedly chooses from a given set of actions in order to maximise a reward function which should lead it to the desired result. A typical example is learning to play a game such as Go, chess or video games, where the reward function is increasing the score or winning the game. Reinforcement learning is considered to be a promising strategy to address complex real-world problems.

Machine learning algorithms have passed a number of impressive milestones in recent years. They identified objects by vision 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] Deep learning algorithms have become extraordinarily adept at mimicking traditionally human activities such as language processing, artistic creation and even scientific research.[4] This rapid progress is primarily due to the increasing amount of available data and computing power. However, many applications require even more sophisticated skills, such as the ability to make sensible decisions in highly uncertain environments; transparency and traceability; the ability to combine data from heterogenous sources, long-term memory and consideration of context.

Rüdiger Urbanke
Dean for Computer and Communication Sciences, EPFL

Anticipation Potential

EMERGING TOPIC:

Advanced Artificial Intelligence

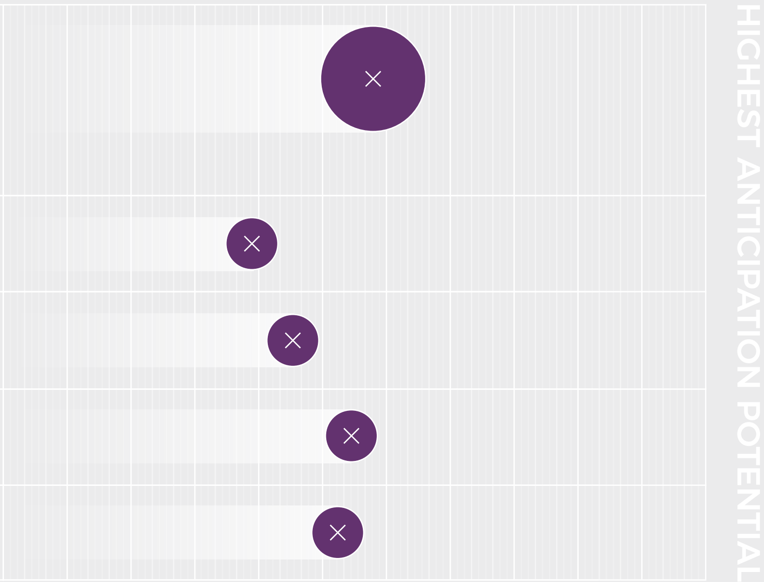
SUB-FIELDS:

Deeper machine learning

Human-centred AI

Next-level AI

Interdisciplinary AI



SURVEY OBSERVATIONS:

Rapid progress in the development and adoption of AI has already spurred many efforts to chart the trajectory of this transformative technology. While advances in deeper machine learning could have widespread consequences, it has already received considerable focus and has a relatively short path to maturity, so the need for anticipation here is lower. Next-level AI — and the path towards human-level intelligence — on the other hand, has received less attention so far and is further from maturity, suggesting more work is needed to understand its potential implications.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

There are several large-scale efforts to map the state of the art of artificial intelligence and to predict its evolution. Stanford's "One Hundred Year Study on Artificial Intelligence" produces a summary of the major technological trends and applications by domains as well as legal, ethical and policy issues every five years. [5]

The "20-Year Community Roadmap for Artificial Intelligence Research in the US" from the Association for the Advancement of AI (AAAI) proposes detailed research roadmaps and recommendations about research infrastructures and education. [6]

The yearly State of AI Report summarises the main developments of AI of the past year in the fields in research, industry and politics as well as education and expert systems. [7] Other roadmaps focus on the opportunities and expert systems of integrating AI in government, society and industry from European and Chinese perspectives. [8,9]

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

Artificial intelligence algorithms have become ubiquitous in modern life thanks to successes in machine learning research. However, they have very limited flexibility, operating within narrowly defined parameters and unable to transfer knowledge across domains. They also require vast amounts of training data and enormous computational resources. But there are reasons to believe that they can be made more flexible in the foreseeable future.[10]

The dramatic progress of recent years has resulted largely from increases in data availability and processing power, rather than advances in the fundamental theoretical foundations of artificial intelligence. If these foundations can be developed through targeted research, we will gain an understanding of what is missing from the current paradigm, and how it can be improved and its applications expanded — safely, and with human needs at the focus.

A stronger theoretical basis may also help us solve problems created by the current nature of AI. The field of explainable AI is aiming to create a better understanding of how ML algorithms work, with increased reliability and transparency.[11] This will have an important impact on applications, as it will then be possible to deploy AI techniques in sensitive domains where liability is paramount (for example, the health, financial, legal and engineering spheres).[12]

5-year horizon:

Machine learning expands its sphere of operations

Further exponential growth in computing power and access to data enables an increase in performance. The current trend of digitalisation, including the deployment of sensors and connected objects, provides increasing scope and scale of data sets to be used by machine learning algorithms. Research begins to establish ethical and regulatory frameworks.

10-year horizon:

Algorithms begin to generalise

The ability to incorporate basic knowledge and deductive reasoning helps algorithms to interpret their surroundings and make generalisations. This boosts the fields of unsupervised learning (using little or no training data) and reinforcement learning, expanding the scope and relevance of ML. Algorithms are increasingly able to learn from fewer examples.

25-year horizon:

Machine learning becomes a tool for specialised enquiry

Deep machine learning continues to inform and instantiate progress in complex and abstract scientific fields of inquiry, although issues of explainability change the nature of what it means to "understand" scientific issues.

1.1.2 Human-centred AI

The limitations of the machine learning approach to AI mean that powerful AI tends to be hidden in static systems that have to be connected to data centres. However, the goal of many AI developers is to have AI systems embedded in machines that operate dynamically within the human environment.[13] This does not require human-level intelligence, but it does require a degree of flexibility and adaptability, and an ability to sense and react to moving objects and changing conditions in the human environment, as well as dexterity and agility in manipulation of objects and human-safe operation.[14]

This is a significant challenge, but one that could create a new era in our interactions with machines, potentially bringing a sea-change to medical care (especially in an ageing population), industrial production and education, among other areas. It will require advances in sensors, the processing of sensor data, interface design and autonomous decision-making. Researchers anticipate that these kinds of advances will accelerate as the commercial potential for embodied AI begins to be realised.

5-year horizon:

AI established in dynamic machines

Trials of AI-enabled healthcare robots show potential to assist in dealing with ageing populations. Autonomous vehicles operate with reduced need for human intervention, moving in convoys through interaction with smart road environments. Industrial robots become increasingly safe for deployment in open environments alongside human workers.

10-year horizon:

AI becomes significantly more flexible and useful

The ability to learn from few data points and to deal with open-ended questions vastly increases the relevance and applicability of AI. This in turns induces an exponential growth of AI knowledge and increases the opportunities for human-machine collaborations, including the augmentation of human capabilities through AI.

25-year horizon:

AI augments human capabilities

Brain implants coupled to robust, verifiable AI systems accelerate the development of brain-machine interfaces. These are useful in therapeutic settings (e.g., for neuroprosthetics) but also open avenues towards augmenting human abilities. They enable discoveries in neuroscience which bring new insights into human consciousness.

1.1.3 Next-level AI

Moving beyond the machine learning paradigm towards more flexible AI is likely to involve coupling the strengths of ML with the strengths of other approaches to AI. The aim here is to move towards the kind of intelligence displayed by human beings, where learning happens without vast data resources, without intensive training, at low computational cost.[15] In addition, humans gain knowledge in a way that allows them to use "common sense", and to transfer knowledge and experience between domains by representing data in compact hierarchical structures based on concepts and their relationships.[16]

As our survey results made clear, replicating human level intelligence (often referred to as strong AI, or Artificial General Intelligence (AGI)) remains a distant goal, but even small steps in this direction will open up a host of transformative applications. One approach with potential is Symbolic AI, which has the advantages of being adaptable to context, and having a degree of transparency, allowing us to understand, validate and live comfortably with AI-sourced decisions, whether in healthcare, the judicial system, workplace recruitment or other domains.

5-year horizon:

AI systems display potential for "common sense"

Symbolic AI algorithms demonstrate basic knowledge transference across domains and begin to perform basic functions without extensive training.

10-year horizon:

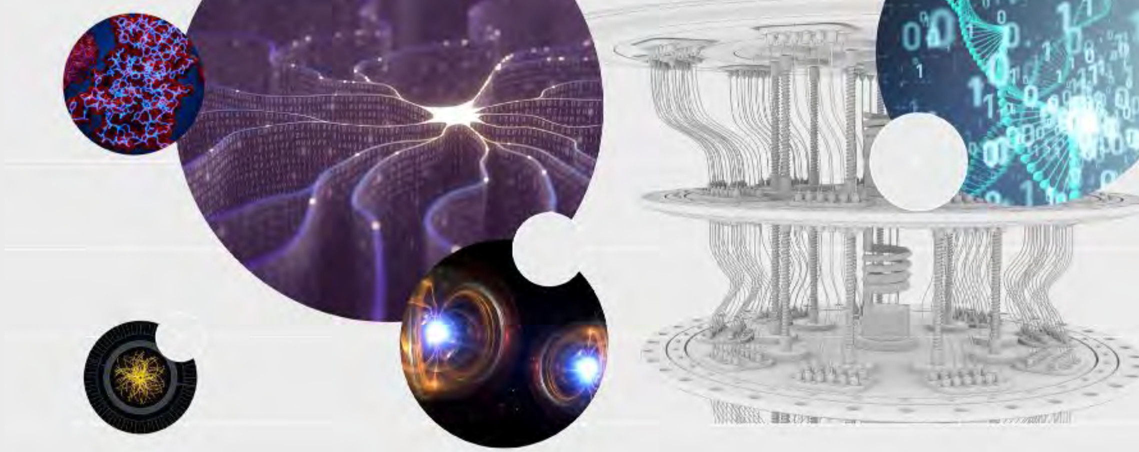
AI begins to display more human-like learning

Artificial curiosity expands the scope for learning in situations where tasks are not yet well defined. Algorithms can look up and integrate knowledge found in encyclopaedias. Continuous learning includes memory effects, working with dynamic data (e.g. cumulative rainfall) that can introduce changes to the algorithm's operation. Research helps uncover algorithms' vulnerabilities, understand their limits and devise possible strategies to protect them from malicious data.

25-year horizon:

AI becomes more like human intelligence

AI may reach a number of milestones towards human abilities within this time frame. These include tasks such as understanding people's motivations (testable by answering open-ended questions about the hypothetical scenarios shown in a video sequence), transferring knowledge between different tasks, emulating analogies, or guessing how an appliance works and using it in a real-world situation.[17]



1.1.4 Interdisciplinary AI

As AI shifts away from huge datasets and brute-force computing approaches, this will create incentives and opportunities for combining with alternative approaches such as neuromorphic computing (chips mimicking neural networks directly into the hardware; see 1.3) and biocomputing (information processing based on biochemical components such as nerve cells, DNA or metabolic processes in the cell and which takes advantage of naturally occurring stochasticity and evolutionary processes to manipulate information; see 1.4).

Hybrid architecture combining these approaches with traditional machine learning might yield unexpected advantages. Additionally, running machine learning algorithms on quantum computers (see 1.2) might prove useful for problems with small data sets and dealing with quantum objects, such as simulating chemical reactions or new materials.[18,19] Quantum computing researchers are already working in collaboration with machine learning experts to assess the potential of leveraging a partnership between these fields, and the first demonstrations of a quantum speedup for machine learning algorithms have increased the hope that the field could have synergies with AI.[20]

5-year horizon:

The era of quantum machine learning begins

Research identifies clear quantum advantage in machine learning applications, proving that quantum computers can assist classical machine learning algorithms to perform tasks more efficiently than either would achieve alone.

10-year horizon:

Neuroscience accelerates AI development

Explorations of small-scale circuits in the human brain provide new interconnection models that inspire interesting new AI implementations in the lab. AI researchers and neuroscientists spin-out new startups aimed at exploiting these ideas.

25-year horizon:

Quantum-based AI makes scientific breakthroughs

Quantum machine learning running on quantum computers proves useful for problems with small data sets and dealing with quantum objects, such as simulating chemical reactions or new materials.

1.2

Quantum Technologies

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 affect 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

EMERGING TOPIC:

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:

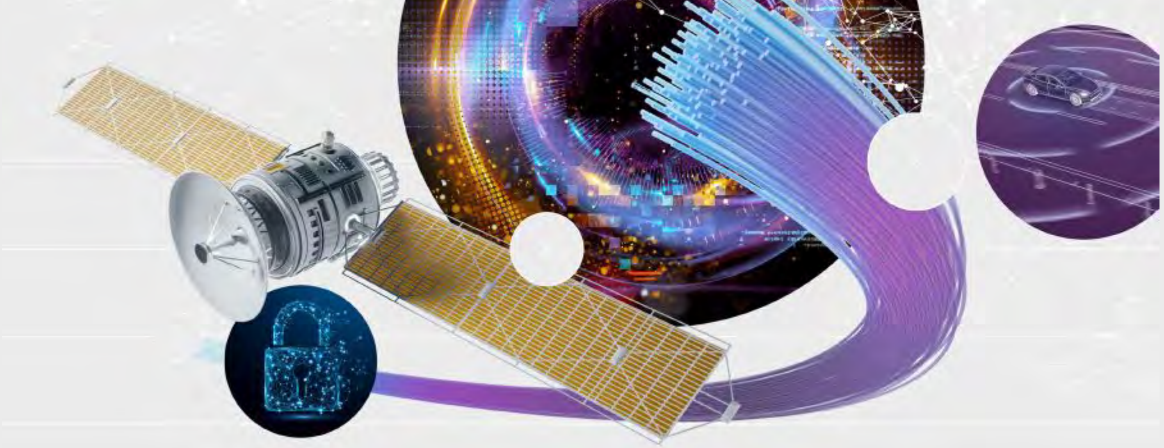
Many countries, companies, and research collaborations have produced roadmaps outlining the technological milestones on the way to mature quantum technologies. For example, the European Quantum Flagship's Strategic Research Agenda offers a good overview of the field including milestones.[1]

The UK's roadmap lists concrete applications.[2] The US National Strategic Overview for Quantum Information Science addresses policy issues related to education, workforce and the collaborations between academia, the government and the quantum industry.[3]

The Oida Quantum Photonics Roadmap provides a table of possible applications.[4]

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/r1-2



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 >500km 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 127 "quantum bit" (qubit) Eagle 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 commercialize 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 miniaturized 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:

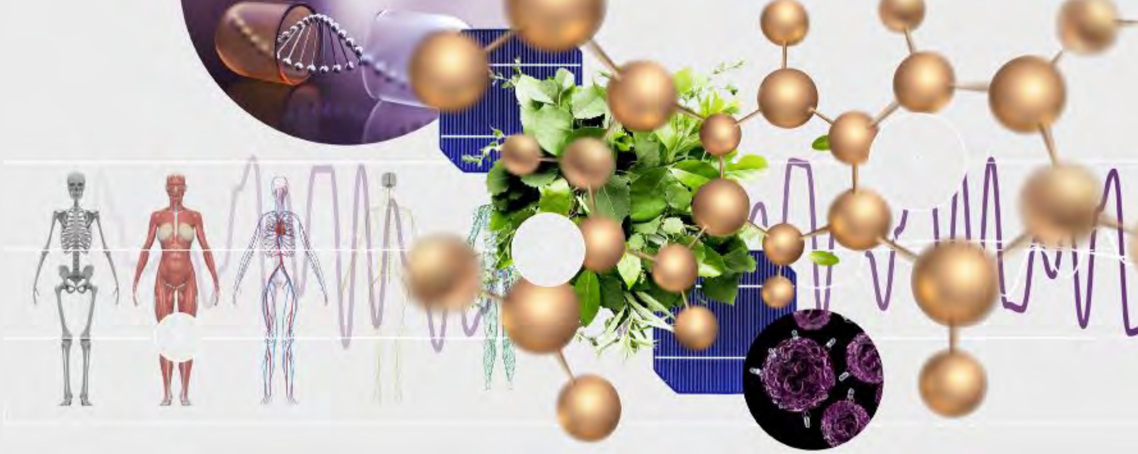
Quantum detectors monitor earthquakes and nuclear tests

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]

Finally, 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

Brain-inspired Computing

The most powerful, flexible and efficient "computer" that we know of is the one we all carry in our heads: the human brain. Research in the field of brain-inspired, or neuromorphic, computing seeks to develop machines that will ultimately display the same capabilities, often by emulating the brain's elements, structures and processes.

Brains perform low-energy, high-speed operations using rules, memory and transfer of knowledge across domains, in order to enable organisms to function, survive and thrive. Neural systems have to process interactions with the environment and with other living organisms, either in real-time or in imagined encounters that anticipate gains and losses. To do so, they process a potentially confusing array of information from multiple sources — sound, touch, vision, memory and so on — and apply remarkably flexible algorithms to plan, make decisions, and act on them through movements or communications.

The fundamental principles of information processing and storage in the brain are far from understood. It is clear that the brain operates in a very different way from the stored-program computer, which makes mimicking the brain conceptually difficult. However, various biologically plausible networks of artificial neurons are being built, and their properties explored. If any of these can inspire a route to brain-like information processing, the technological applications will range from robotics and intelligent systems in mobile phones to breakthrough treatments for diseases of the brain and new accelerators of scientific discovery.

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Senior Researcher, Intel

Steve Furber
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Anticipation Potential

EMERGING TOPIC:

Brain-inspired Computing

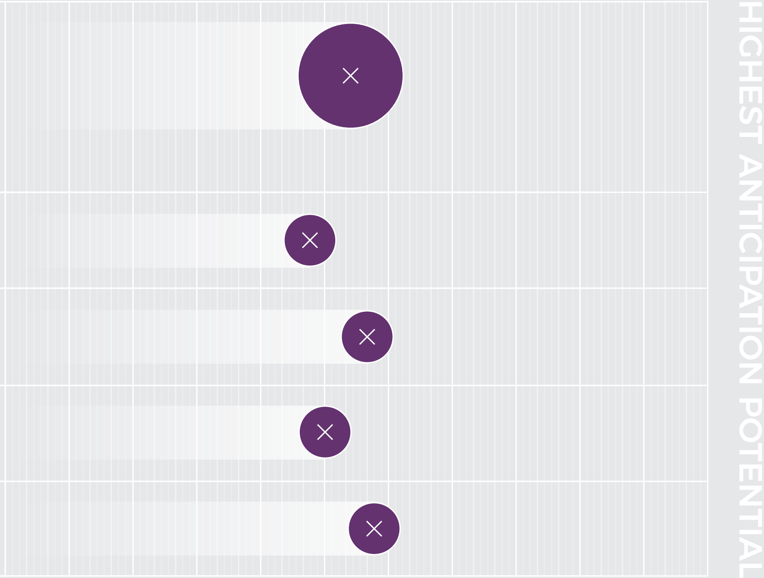
SUB-FIELDS:

Neural network architectures

Neuromorphic systems

Neural network algorithms

Neuromorphic benchmarking



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. Breakthroughs are also likely to have highly pervasive effects, with neural networks in particular having potential uses in a wide range of areas. Tempering this is the fact that respondents predict this field is less than a decade away from maturity. That means many of these technologies are already upon us, reducing the need for anticipation.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Perhaps the most recent roadmap for the field is the multi-institution “2022 Roadmap on Neuromorphic Computing and Engineering”[1].“Large scale neuromorphic computing systems” offers a brief history of neuromorphic engineering and an analysis of the principal current large-scale projects.[2]

“A Survey of Neuromorphic Computing and Neural Networks in Hardware” is a 2017 review by IEEE members that digests research in progress and highlights the important gaps in achievement that will need to be addressed.[3]

“The building blocks of a brain-inspired computer” focusses on the central primitives of a brain-inspired computer.[4]

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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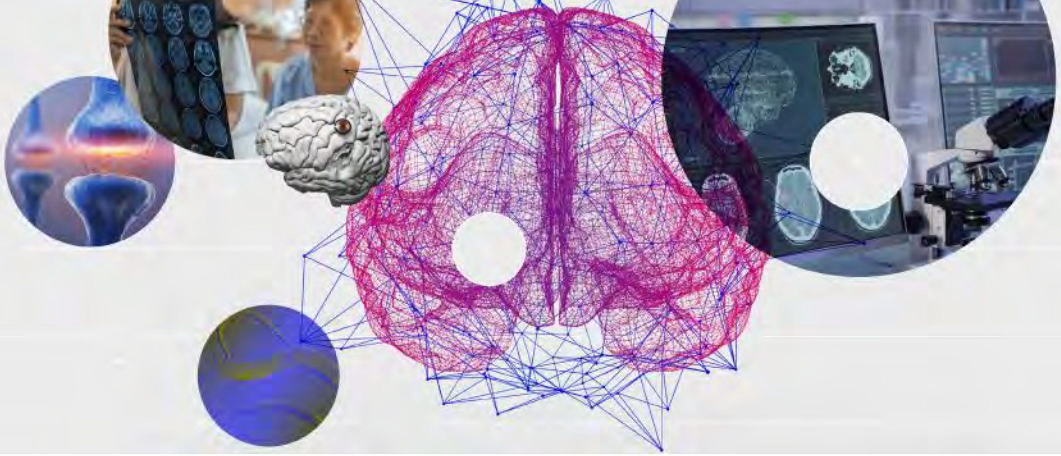

1.3.1 Neural network architectures

Efforts to build brain-like processors take a number of different forms. All of them, however, take inspiration from what neuroscientists have discovered about the structure and operation of the brain. That means building networks of nodes that mimic the action of the brain's neurons, and having the nodes emit signals in the same way that the neuron soma's spike to allow neurons to communicate.[5] The topology, size and exact nature of the experimental networks vary immensely, because it is not yet clear how large a network has to be, and how interconnected it must be, for it to demonstrate neural-type properties.[6] Continued progress is likely to require better theoretical underpinnings, conceptual refinements in computational neuroscience and better models of the brain's mechanisms.

Understanding the sub-mechanisms of the brain's component parts will also be important. The cortical structures, the thalamus, the cerebellum, the hippocampus and the basal ganglia all play roles within the brain that could have technological significance if we can learn to replicate their operation. Additionally, it is not enough to map the connections and topology of our networks of neurons. We need to understand the dynamics, synaptic and structural plasticity of the brain, and genetically-defined developmental programs that are responsible for a large portion of the brain's wiring.

Alternative approaches to brain-inspired computing include those that consider proposals and hypotheses about how things happen at a cognitive level, elucidating rules and descriptions of behaviour and planning rather than seeking to generate these by emulating neuronal activity. There is still debate over whether analogue or digital processing offers the best route to mimicking the brain, and it is possible that a hybrid system, combining the energy efficiency of analog and the precision of digital, might provide competitive performance.

5-year horizon:

Brain structures and sub-structures are mapped and simulated

We have practically useful neuronal architectures for navigation and map formation based on rodents (rat, bat - hippocampus and entorhinal cortex) and insects (bee - navigation complex) brains. These circuits help us understand, model, and program practically usable building blocks, or algorithms. They are deployed in small autonomous domestic robots. Emerging neuromorphic technologies include olfaction-inspired chemical sensors; retina- and eye-inspired vision sensors (with fovea, targeted microsaccades, adaptive thresholds and active sensing); active spinal cord-inspired controllers and central pattern generators for flexible snake- or salamander-like robots.

10-year horizon:

Neuromorphic computing provides useful technology

Based on understanding of human and animal reaching and grasping, a robot arm can grasp and manipulate things, helping with maintenance work at home, on factory floors and construction sites, and supporting the elderly and sick. Simultaneous localisation and mapping (SLAM) provides robots with sophisticated indoor and outdoor mobility, allowing them to work in complex and hard-to-reach environments. 3D vision enables artificial systems to perform movement around, and seamless interaction with, physical objects including humans. Brain-machine interfaces process biological information for medical purposes such as control of prosthetic devices, monitoring of heart and brain activity and seizure prediction.

25-year horizon:

Brain maps begin to show useful, granular detail

We finally understand the processes and causal relationships between different levels of the brain, going from molecular to cellular to circuit to population to cortical micro-area to larger cortical areas and subcortical structures. We know the connectivity and structure as well as the genetic programs and rules of plasticity by which the structure is formed. We know how to cure different malfunctions, and develop mathematical models of brain processes on different levels that can be used to implement similar functions to solve technical problems.

1.3.2 Neuromorphic systems

Biologically plausible artificial networks of neurons take a number of different forms in current research. A researcher's choice of approach relates to which of the biological factors they wish to mimic most strongly. Convolutional neural networks (CNN), for example, are based on the visual cortex. Spiking neural networks (SNN), based on the brain's asynchronous processing, allow each neuron to fire independently of the others and offer a greater efficiency than synchronous networks. SNN is the architecture used by the SpiNNAker project at the University of Manchester,[7] as well as by IBM (the TrueNorth chip) and Intel (the Loihi chip). There is also some interest in using photonics, rather than electronics, in neuromorphic networks.[8,9] Different hardware configurations seem to provide different capabilities. Intel's Loihi is highly configurable for specialised applications,[10] for example, and IBM's TrueNorth is particularly suited to high-speed and low-energy image processing and classification tasks.[11]

In addition to these mainstream efforts, there are several alternative technological approaches. Some emerging architectures involve memristors, for example, which are simple transistor-like components that have variable resistance and the ability to store multiple memory states. Several dozen AI start-ups are also developing different architectures. It is not yet clear how soon — or indeed whether — we will begin to see convergence between these efforts. To mimic the brain, all will need to find ways to efficiently integrate learning and memory in hardware elements.

5-year horizon:

Engineers finesse elements that host learning and memory

We understand how to use biologically-inspired local learning rules to learn useful tasks or form short-term memories

10-year horizon:

Animal-like learning becomes possible

We create networks of artificial neurons and synapses that permit autonomous learning via a combination of reinforcement and self-supervised learning based on predictive models. This is supported by neuronal networks on chip, and displays adaptation, fine-tuning, and calibration, all of which co-occur through closed-loop behaviour. Autonomous systems form their own representations, make decisions and plan actions or movements based on these representations.

25-year horizon:

Artificial mammal-like brains begin to emerge

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. Research replicates different capabilities of animals in technical systems, ranging from all kinds of sensors to situation awareness systems, simultaneous location and mapping, environment-independent navigation, decision-making under uncertainty, continual learning, and safe and reliable movement control.

1.3.3 Neural network algorithms

The architecture of the brain is inextricably intertwined with the algorithms that it performs; in many ways, the architecture is the algorithm. Furthermore, the brain is autonomous and uses distributed computing: it contains many densely interconnected local hubs that build a modular, hierarchical, but interconnected system. It also exhibits extraordinary plasticity: memory and experience (in performing tasks, for example) actually change its physical structure. This makes it even more difficult to separate its architecture from its function: the connections and topology of its neural network create its functionality, and these properties are fluid and flexible.

This has two consequences for brain-inspired computing. First, truly neuromorphic computing will be fundamentally different from the familiar Turing machines, where a range of programs can run on a single machine. With the algorithm physically implemented in the network structure of a neuromorphic computer, sequential programming ideas simply do not apply. Although this means we will have to compute in a new and different paradigm, there are clear upsides: brain-inspired computing may well open up avenues of information processing that are impossible with traditional machines.[12]

Second, architecture (hardware) choices affect the range of algorithms that can be run on each implementation. At the most basic level, the closer to normal silicon computing, the more flexible and reprogrammable the machine will be; the more analogue and physical, the more the algorithms are fixed by the architecture choice. The hardware-specificity of neuromorphic computing has limiting effects on both innovation and progress, and there is a need for standardisation in the way algorithms can be implemented. There is progress here: in October 2020, for instance, researchers laid out a conceptual foundation for designing algorithms and hardware separately.[13]

5-year horizon:

Multi-sense processing is consolidated

Engineers develop stretchable, smart, large-scale electronic skin; low-power and low-latency 3D vision, motion detectors; olfactory sensors and chemical sensors; sensors for electric fields and air currents. These are augmented with smart signal processing that enables efficient extraction of task-relevant information and its integration in multimodal concepts.

10-year horizon:

Neuromorphic computing takes the AI crown in niche applications

Neuromorphic computing becomes the dominant computing framework for embodied AI — AI that works with sensory signals and motion control — as well as for human-machine interaction and computing on the interface to the physical world, including large-scale simulations. Conventional computers will only be used for storing and processing "vintage" digital data, with computing distributed between ultra-edge (the smart device), edge (computer in the room) and cloud (server), supported by ultra-fast and high-throughput wireless connectivity.

25-year horizon:

The rules of thinking emerge

We have neuro-physics on the level of today's physics, with models and explanations across different levels — from molecules to societies.

1.3.4 Neuromorphic benchmarking

Neuromorphic chips should be well-suited to situations where information and demands are fluid, energy consumption has to be low and adaptation to novel situations is required. But as yet there is no "killer app" for early brain-like computing that might demonstrate its potential, and no agreed universal standard for benchmarking how well the field, or an individual device, is progressing. This is going to be a crucial part of the research effort, since it will provide conceptual understanding, incentive for progress and rewards for investment and innovation.[14]

It is important for the field to begin demonstrations of its potential for fast, low power processing.[15] However, it is also important not to try to compete with deep learning algorithms of artificial intelligence research programmes, which have received significant input on extremely specific capabilities, such as machine vision. There are many other sensory modalities, such as hearing and touch, that will be technologically important, and just as important is the ability to do fast, real-time, self-contained sensory processing, rather than rely on connections with a cloud-based data centre.

5-year horizon:

Standardised benchmarking tools emerge

Researchers agree a set of simulators or standard robotic platforms for benchmarking progress and accelerating promising candidate architectures. Aware of the pitfalls encountered in machine vision and deep learning, they resist the pressure to optimise their systems for achieving benchmarks over useful real-world tasks.

10-year horizon:

Real-world testing accelerates progress

Hand-held devices that embody insect-level intelligence and learning become ubiquitous, and real-world benchmarking brings commercial pressures that accelerate progress. Energy-efficient, low-latency neuromorphic systems can be tested against, and begin to outperform, data centre-connected deep learning algorithms for tasks such as speech recognition.

25-year horizon:

Human-machine interfaces allow subjective testing and user review

Bio-compatible neuromorphic machine interfaces, integrated with the nervous system, become widely available. This creates a product marketplace based on user experience, further accelerating progress.

1.4

Biological Computing

The component parts of biology often take a molecular input, carry out some process using molecular or cellular "machinery", and output a related molecule or set of molecules. This has clear parallels with the way silicon-based computing works: take some input, transform it using some arrangement of Boolean logic gates, and produce some output. This observation has seeded the field of biological computing, or biocomputing, in which researchers attempt to modify or build biological systems to perform computing-like routines.

Biological computers need not necessarily be like conventional computers, and that is both their potential and their challenge. The biological cell is more than a "little engine" and can process chemical information in ways that do not fit with what we usually identify as information processing. This may allow us to go beyond what is possible with traditional computing. But in order to fully tap into this potential we will need to break out of the mindset imposed on us by our usual paradigms of engineering and digital computing. There are technological barriers too: our tools and techniques for modifying and re-assembling the components of molecular biology — largely shared with synthetic biology research covered in later sections of this report — still lack the precision necessary for many of the breakthroughs we would like to achieve.

However, there are many good reasons to pursue this research effort. It is becoming increasingly clear that biocomputing may be uniquely applicable to such challenges as environmental remediation, drug discovery, the production of novel materials and medical diagnosis, among others. As we discover more about the range of biological computing processes, optimised by evolution over billions of years, we are likely to find additional unanticipated benefits.

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Head of the Biocomputation Lab,
Technical University of Madrid (UPM)

Anticipation Potential

EMERGING TOPIC:

Biological Computing

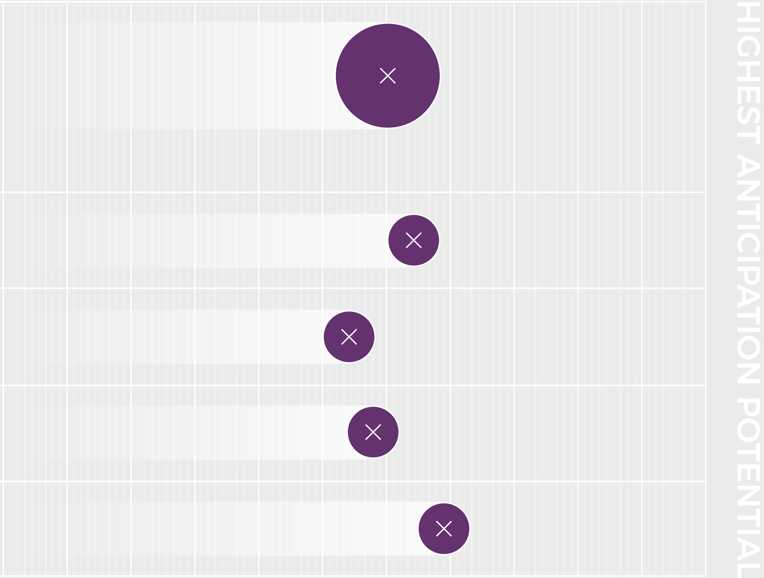
SUB-FIELDS:

Bio-architectures

Bio-computational logic and strategies

Programmable bio-synthesis

Novel bio-computing paradigms



SURVEY OBSERVATIONS:

Attempts to understand biological systems in computational terms have been underway for some years now. Significant work on new bio-architectures and implementing logic operations in cells is already ongoing, though awareness of the field is generally low. Respondents judged that biological computing is likely to have its biggest impact on the environment, pointing towards the potential for bioremediation and the development of new catalysts that boost the sustainability of industrial processes. Of particular note are novel paradigms that could unleash a stream of new applications within the next 15 years. Low awareness of their potential suggests this is an area that requires particular attention.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Researchers from various academic institutions and Microsoft Research's biological computing effort, Station B, produced an insightful report in 2018.

"Computing with biological switches and clocks"[1] gives a historical view of the subject, plus the authors' vision for its future.

"Pathways to cellular supremacy in biocomputing",[2] published in 2019, gives an overview of the potential of the field. Two 2014 papers also provide valuable foundational overviews:

"Synthetic analog and digital circuits for cellular computation and memory"[3] and "Principles of genetic circuit design".[4]

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 Bio-architectures

Most biocomputing research to date has sought to replicate silicon-type computation involving logic gate-based architectures, with significant success. For example, researchers from ETH Zurich have used the CRISPR-Cas9 gene editing tool to create processors inside human cells.[5] The Cas9 enzyme reads inputs in the form of guide RNA, and responds by expressing particular genes that then create certain proteins as the output. The result is that the cells effectively compare (or add) two inputs and deliver the result as two outputs.

Impressive as such proofs of concept are, a plethora of different functionalities occurs naturally in the operations of biological cells such as bacteria, and if we look, we may find a multiplicity of architectures for biological data processing. Research to date has tended to focus on programming DNA-based systems, for instance, creating "genetic circuits". This is an issue of familiarity: we know how to perform genetic engineering operations well enough to make progress. However, alternative biological hardware, such as nerve cells or the cytoskeletons of cells may provide an even richer set of possibilities for biological information processing. There is also scope for performing "whole-cell biocomputations" that tap into the cell's metabolism.[6]

5-year horizon:

Commercial potential begins to emerge

Standardisation of biological parts and processes is established, opening the door to commercialisation. 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:

Metabolic biocomputing comes of age

Researchers establish ways to harness a cell's metabolism to perform computations.

25-year horizon:

Biocomputing hardware has moved beyond genetic circuits

Biocomputers based on nerve cells begin to show promise, and processing based on cell metabolism performs complex and useful routines.

14.2 Bio-computational logic and strategies

The limitations of conventional computing are taken for granted and seldom contemplated. Cellular computing is so qualitatively different, however, that it may well escape or bypass those limitations and open up a wide range of unanticipated applications and abilities. This is because cellular components have a set of distinct traits that can be harnessed to perform logic operations that differ from those we have employed in traditional silicon-based information processing.[7]

First, a cell's components can be re-configured in response to external stimuli, allowing a variety of outputs. They function in the presence of noise, and thus do not require inputs that are clean representations of data – indeed, in some cases they even exploit the natural messiness found in biological systems. There are multiple signal pathways within the cell, enabling the components to engage in concurrent, massively-parallel information processing.[8] The communication pathways that exist between biological cells allow for new forms of distributed computation.[9] There is no requirement to use only digital signals in inputs and outputs of cellular processes; the cell mechanisms are able to function as analogue computers.

Finally, at a population level, they use their naturally inherent variety to evolve solutions to problems over time. All of these properties suggest that there will be a rich array of computing strategies available to us as the field of biocomputing matures.

5-year horizon:

Distributed biocomputing comes of age

Small-scale biocomputing networks of biological cells work together in the lab to provide potential solutions for real-world problems.

10-year horizon:

Engineers build circuits inspired by lab-based evolution

Monitoring the mechanisms of bacterial evolution provides inspiration for the design of new biocomputing pathways.

25-year horizon:

New computing toolkits emerge

Research has catalogued an array of natural biocomputing pathways and created a new, post-Boolean set of logic operations and design tools for information processing.

1.4.3 Programmable bio-synthesis

Generally, the study of how environmental signals affect and direct intracellular processes has been confined to a fairly narrow range of examples. But it is fair to assume that natural evolution will have found solutions to myriad problems that we have not examined, and thus that we have not identified biological organisms whose properties and metabolisms are uniquely suited to performing functions in a swathe of interesting niche scenarios.

Engineered living systems are likely to be useful in situations where their natural autonomy and ability to thrive in uncertain environments gives them an edge over traditionally designed, silicon-based engineering solutions. We are already beginning to see the fruits of exploring this. Biosynthesis is being deployed in aviation security, for example, with genetically engineered odorant receptors designed to literally sniff out biological hazards.[10] It is likely that significant medical applications will eventually be found,[11] and that suitably engineered bacterial networks will be able to achieve large-scale bioremediation of, for example, environmental pollution, through operation on whole ecosystems.

5-year horizon:

Engineered cells assist medical diagnosis

Human cells are programmed, synthesised and engineered to detect and respond to illness such as tumours.

10-year horizon:

Biocomputers begin to solve human issues

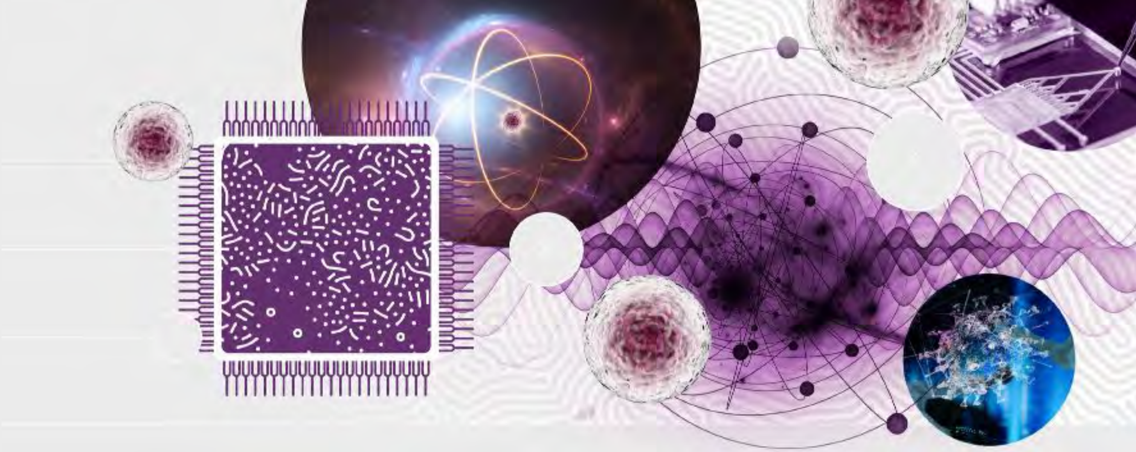
Bacterial metabolic computing is routinely used to find remediation solutions to pollution, diagnosis pathways for disease and provide atmospheric sensing tools.

25-year horizon:

New bioremediation and hybrid hardware solutions emerge

Networks of bacteria are employed to clean up environmental pollution. High density arrays of cells (bacteria, for example) on chips, with clear, translatable signal input and output mechanisms, will be performing "intelligent" inference functions such as diagnosing disease from breath.

1.4.4 Novel bio-computing paradigms



Impressive as today's supercomputers are, they remain "Turing machines": processors that perform the kinds of mathematical operations that humans can do, albeit exponentially faster and on a massive scale. Turing machines have particular limitations: there are computations that they cannot perform. However, biocomputing may not suffer these constraints. It is highly likely that bacterial networks can be encouraged to self-organise into arrangements that compute in ways that go beyond traditional Boolean logic implementations, and beyond what Turing machines can achieve.

These computations will inspire new, supra-Turing models of computation and information processing and may lead to an era of "cellular supremacy", where biological networks solve problems that are intractable to traditional computation models.[12] It may also be possible to create "hybrid" architectures that interface cellular systems with traditional silicon-based computers, creating a different form of computational advantage.[13] The ability to compute in the presence of noise, and with analogue signals, may also give biology an edge over digital Turing machines.

5-year horizon:

Metabolic computation begins to show promise

Research unpicks mechanisms behind whole-cell interactions that create pathways towards useful analogue metabolic computing.

10-year horizon:

Biological computations reflect neural processing

Investigations of programmable analog cellular processing in noisy environments give insights into mind-like states.

25-year horizon:

The era of biological quantum computation begins

Biological computation combines with quantum biology research to create interesting and potentially fruitful new approaches to information processing.

1.5 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.

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Anticipation Potential

EMERGING TOPIC:

Augmented Reality

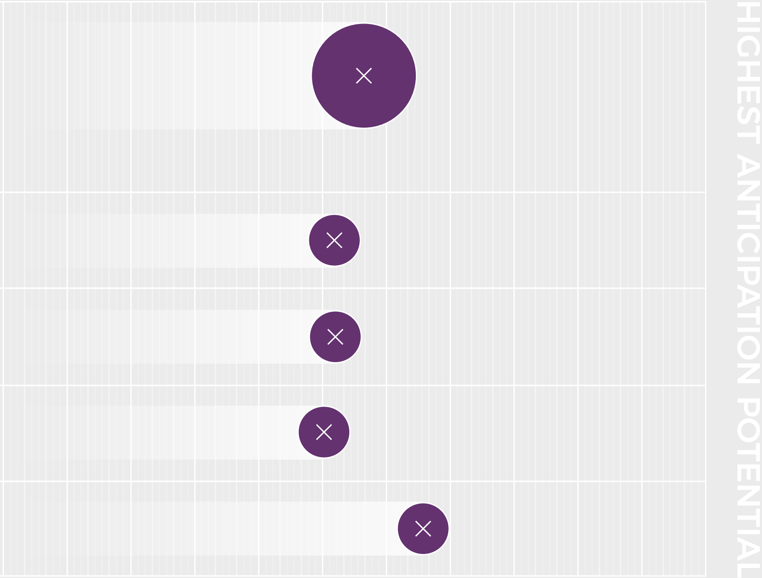
SUB-FIELDS:

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:

PwC's "Seeing is Believing" report[7] predicts that the combined XR ecosystem could be worth $1.5 trillion by 2030 and highlights key areas of growth. An overview of the XR landscape in Applied Sciences provides a summary of the latest research and potential future directions for the field,[8] while another paper in the Journal of Physics provides the Chinese perspective on the state of AR research.[9] Meta's "AR/VR: New dimensions of connection" report gives crucial insights into the strategy of a leading XR technology company.[10] And the Future of Privacy Forum has provided a useful guide to the potential risks to privacy and autonomy presented by XR.[11]

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/r1-5

1.5.1 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 of expensive eyeglasses and insert 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.

1.5.2 Augmented experiences

Early incarnations of AR will be concerned with two fundamental activities: learning about the world and interacting with other people. This will include tasks like overlaying instructions or translations on the real world, or participating in 3D video calls.[17] Near real-time interaction is 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.

1.5.3 AR platforms

Connecting the virtual and the physical worlds will require a new global computing infrastructure. Responsive 3D content tied to spatial information requires far more data and processing than the text, images and videos that make up today's Internet. AR hardware will not be capable of providing this alone and so a massive expansion in cloud services will be necessary to render high-fidelity graphics at scale. 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 delivery of high-fidelity AR experiences to headset via wireless, significantly boosting realism and immersion. Companies dramatically expand their cloud infrastructure to support the huge amounts of data required to support millions of AR users. Moderating AR content becomes a major concern for AR platforms.

25-year horizon:

Era of the open metaverse begins

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

1.5.4 Human factors of AR

AR will lead to a blurring of the boundaries between the physical and digital worlds, which could have profound impacts on human psychology and social relations. The reality-distorting effects of social media are a harbinger of what could come, and phenomena like disinformation, echo chambers[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..

1.6

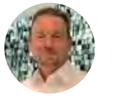
Collective Intelligence

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]

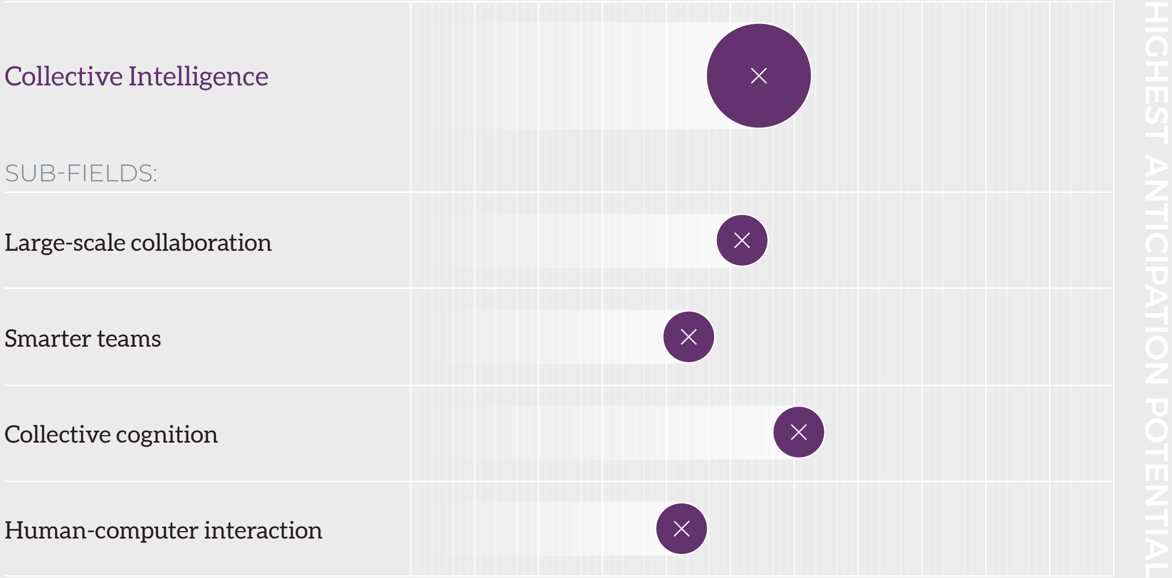
In the last decade, there has been significant growth in the use of technology to enhance the CI of groups both large and small. This ranges from web platforms designed to coordinate large-scale collaboration to the use of artificial intelligence to facilitate group discussions. However, although efforts 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:



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:

The "Handbook of Collective Intelligence" provides a comprehensive introduction to the multidisciplinary field of modern CI research,[4] while Nesta's "The Collective Intelligence Design Playbook" shows how these ideas can be put into practice.[5] An overview in the journal ACM Computing Surveys of the diversity and potential synthesis of CI frameworks gives a solid grounding in the state of the underlying theory.[6] And a pair of books from Gianni Giacomelli outline the potential of combining AI and human networks to created "augmented" CI.[7]

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/r1-6

1.6.1 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.

1.6.2 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.

1.6.3 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.

1.6.4 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
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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 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.

2

Introduction to Human Augmentation

Over the past century, public health interventions have nearly doubled the average lifespan. This welcome development has been compromised by commensurate rises in the incidence of cancer, Alzheimer's and many other diseases of age. However, advances in genetic engineering, neuro-technology and drug development now look set to increase our "healthspan" too.

Neurotechnologies and drugs can modulate and improve the human condition. Recent advances in neuroscience and machine learning have ushered in innovations for **cognitive enhancement**, 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 therapy exists. Human memory augmentation will become increasingly available for enhancement purposes as well, 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. Small-molecule drugs and other interventions now in clinical trials promise to significantly reduce the burden of disease on society, radically altering what it means to age.

Beyond dealing with existing problems, scientific and technological tools may change the fundamentals of what it means to be human, and what it means to be old. Research 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 could even reversed.

Efforts towards **radical health extension** could also have a useful side effect: adapting human physiology to life elsewhere in the solar system.

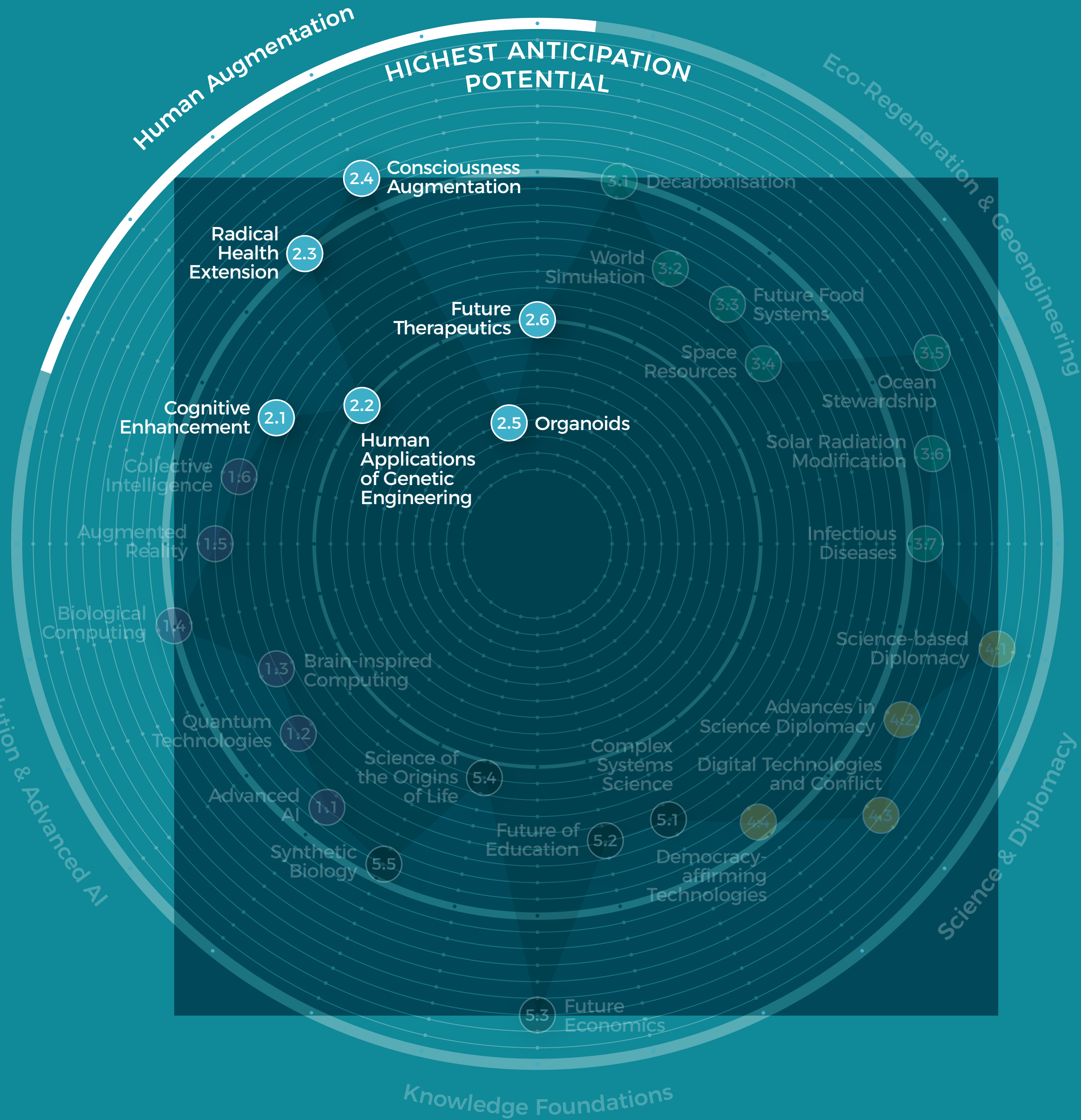
Lab research suggests that it is possible to expand consciousness beyond the limits imposed by human senses, standard cognitive capacity and injury or disease. Such **consciousness augmentation** could help us better coexist with the species with which we share the planet, improve our understanding of how humans can educate themselves 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 disease and the efficacy of drug candidates requires investigation in 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 kidneys, tumours and brains.

They are being grown and put to work to investigate the fundamental processes of human biology, the pathology of diseases such as Zika, and the potential for novel treatment pathways. When grown from a patient's own cells, organoids can provide a strong indication of suitable interventions. Eventually, they may allow the growth 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, diagnostics of disease and the results of medical interventions.

Bringing 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. In the following pages, we examine the research on human augmentation now underway, and explore how, if carefully regulated and deployed, it could be truly transformational.



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 is also becoming possible to manipulate those brain states in more targeted ways using a wide spectrum of methods, from electrical to chemical.

Many of these interventions have been developed to aid people with incapacitating disorders of memory such as Alzheimer's disease, the incidence of which is predicted to increase dramatically in the developed world by 2035. Alzheimer's is typical of the diseases that have driven academic research into memory enhancement. But other disorders can also be characterised as disorders of memory — for example post-traumatic stress disorder (PTSD) — which suggests that not only boosting memory but also its suppression and manipulation could fall under the rubric of enhancement. Furthermore, manipulating memory could boost other types of cognition: enhancing procedural memory, for example, may upgrade task competency in a way that makes memory enhancement attractive to healthy people, and usher in an age of cosmetic cognitive augmentation.

As imminent brain monitoring technologies combine reading and writing brain states, aided by ever more capable AI, the ability to decode cognitive and emotional states and make them increasingly transparent will yield unexpected applications across society. New privacy schemes must be developed and ethical guidance formalised to ensure that this kind of data is protected. Even more urgent is governance around emerging ways to alter and improve cognition. Being able to 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. Unanticipated societal outcomes must be considered.

Olaf Blanke
Bertarelli Foundation Chair of Cognitive Neuroprosthetics, EPFL

Anticipation Potential

EMERGING TOPIC:

Cognitive Enhancement

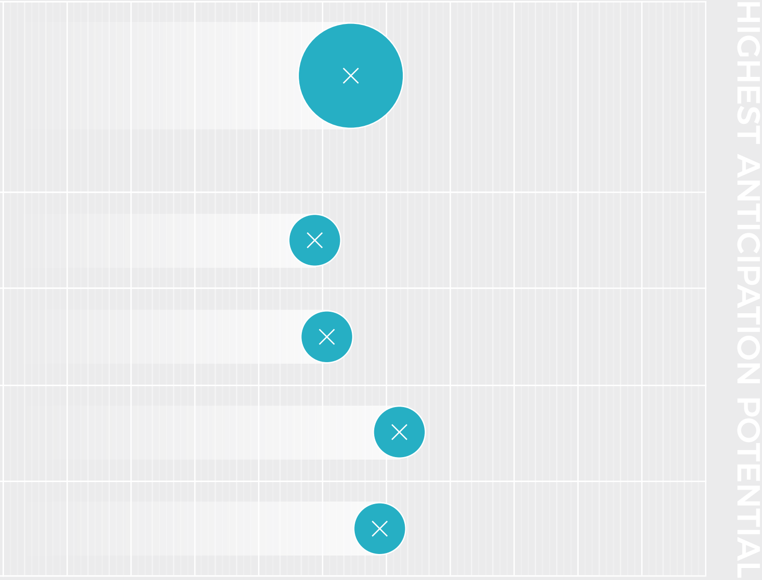
SUB-FIELDS:

Brain monitoring

Neuromodulation delivery systems

Hybrid cognition

Memory modification



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. Memory modification should be a particular focus, as the least mature technology.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

The 2019 "Neurotechnologies for Human Cognitive Augmentation: Current State of the Art and Future Prospects" provides a useful overview of the field.[1]

A US clinical trial of deep brain stimulation for mild Alzheimer dementia gives an interesting perspective on the efficacy of this intervention.[2]

Significant progress in reading and interpreting brain signals was described in Nature in 2021.[3] In 2019, the UK's Royal Society published a perspective on neural interfaces.[4]

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 Brain monitoring

To successfully manipulate cognitive processes, the first step is to read and interpret the brain's signals. Only when we understand how the brain processes and represents information can we hope to alter that language when it goes wrong or to improve upon its baseline functioning. A wide range of technologies, from deeply invasive brain implants to non-invasive wearables, are now in various stages of sophistication.[5] Some are beginning to emerge into the clinic and — as with many medical interventions that start as therapy — into the general population. Major invasive techniques are deep brain stimulation (DBS), cortical stimulation and opto- and chemogenetics, which are used mostly in animal research. Non-invasive techniques to record brain activity are electroencephalography (EEG), magnetoencephalography (MEG), and functional magnetic resonance imaging (fMRI).[6] Each class of technology has benefits and trade-offs; invasive technology yields higher resolution data yet non-invasive is more convenient and will get us more generalisable data in the general population.[7]

5-year horizon:

First commercial non-invasive neuromodulation devices validated

Non-invasive brain recording devices improves enough to be wearable and provide a signal-to-noise ratio comparable to MEG and fMRI, which currently require large and costly infrastructure. Consequently, the availability and use of such devices for non-medical purposes will likely increase.

10-year horizon:

Open brain data stimulates research

Increased data sharing and storage accelerates basic research, allowing for faster selection from the cognitive enhancement methods that are being evaluated.

25-year horizon:

Miniaturisation makes invasive devices less invasive but more intrusive

Optogenetics and gene therapy advance to the point where advanced electrical recording and stimulation devices, and optogenetic technologies, can be implanted into the brain and operated wirelessly from outside the skull to monitor brain activity at high resolution. Cheap, portable non-invasive imaging technologies are used in a greater variety of real-world situations, allowing for example the legal system to distinguish between real memories, false memories, and lies in the courtroom in real-time.

2.1.2 Neuromodulation delivery systems

Experimental research is already using neurotechnologies and other delivery systems to modulate memory and other cognitive functions. As with brain monitoring, these fall into broad categories of invasive and non-invasive. Non-invasive technologies to modulate brain signals are transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).[8] tDCS has been shown to enhance certain cognitive functions, such as episodic memory in older adults.[9] Non-invasive technologies and focused ultrasound (FUS) could make it possible to remove unwanted memories. Invasive techniques for neuromodulation include optogenetics[10] and deep brain stimulation[11], which has been successful for Parkinson's and is now in trials to rescue memory in Alzheimer's disease. A third category blurs the line between invasive and non-invasive, and includes drugs and nanobot drug delivery systems to carry chemicals across the blood brain barrier.

Progress in this area rests on the development of closed-loop devices, which can read and decode brain signals, and respond by making decisions — often aided by AI — and then also engage stimulation in specific brain regions in order to override, dampen or amplify a faulty signal. The first commercial applications will likely be invasive devices that treat epilepsy and Parkinson's, but closed-loop neuromodulation will eventually encompass invasive and non-invasive technologies.

5-year horizon:

Brain stimulation devices become more widely available for medical use

Within 2-3 years, 1000-channel electrode arrays like NeuroPixel are available for humans, allowing for simultaneous recording and stimulation in multiple regions across the brain. Used in large clinical trials, these gather better data and accelerate the pace of discovery. High profile influencers — like gamers — start wearing noninvasive stimulating brain-machine interfaces to boost cognitive skills like reaction speed.

10-year horizon:

Miniaturisation drives wider adoption of cognitive modulation

Closed loop devices stimulate and treat an increasing variety of diseases including depression and will also include, besides brain signals, a variety of other physiological, motor, perceptual, and cognitive signals acquired by wearables. The devices become wireless, driving early adoption by healthy people.

25-year horizon:

The era of high-precision optogenetics arrives

Optogenetic manipulation and related new technologies target specific networks and types of human memory with high resolution and precision. This will create new, more granular molecular control mechanisms to manipulate neural activity at the level of single neurons, circuits, and larger networks, enabling more specific tailoring than today's comparatively crude methods. The results could be implantation and control of patterns of memory and emotions.

2.1.3 Hybrid cognition

Among the most important drivers of cognitive enhancement will be advances in artificial intelligence. This will happen in two separate but related ways. First, machine learning algorithms will help academic researchers to sift quickly through large amounts of brain data. This will enable them to find relevant signals to help better understand principles of cognition and memory, and thus to develop better closed-loop devices.[12] This approach has been used to decode primary visual cortical activity and reconstruct movie scenes as they are being viewed in real-time,[13] and to decode the content of dreams based on pre-recorded visual cortical activity patterns.[14] It has yet to be applied to memory research, but potential applications include decoding memory encoding, retention, and retrieval. A separate line of research suggests that functional magnetic resonance imaging (fMRI) can be used to distinguish between true memories, false memories, and lies,[15,16] and machine learning algorithms could potentially be applied to the analysis of such brain activity patterns.

The second advance will come through AI embedded in devices worn by consumers to extend their cognitive abilities. People already offload partial cognitive capacity to Google; this tendency will multiply as people wear more internet-connected and AI-enabled devices in their daily life. The scope of future applications is wide and includes downregulating undesirable brain states and tuning the brain for optimal task-specific performance.

5-year horizon:

AI stimulates discovery

Machine learning helps to find memory patterns in brain data coming out of clinical trials. This will stimulate discovery around early disease progression, or more controversially, decode in ever finer detail the content of our thoughts. It may even offer new insights around neuroscience and consciousness.

10-year horizon:

Machine learning closes the loop

Closed-loop devices use machine learning algorithms to decode mental states and baseline brain activity and stimulate "on demand" without needing the intervention of a clinician. Machine learning also identifies brainwave patterns associated with useful stages of the sleep cycle. Closed-loop devices then amplify these oscillations to improve memory consolidation. Such devices are used to combat age-related cognitive decline, reducing the risk of developing Alzheimer's Disease and other forms of dementia.

25-year horizon:

AI integrated into memory and cognition

Closed-loop AI implants are widely adopted, and onboard AI seamlessly translates brain function and transforms cognition into commands, augmenting memory and cognition for increasing numbers of healthy people.

2.1.4 Memory modification

Boosting memory has already been accomplished in experimental laboratory work by stimulation of the medial temporal lobe, performed with depth electrodes during pre-surgical evaluation of epileptic patients. This was shown to enhance performance on certain types of memory tasks.[17,18] Suppression of memory has also been achieved in the past 10 years. Researchers have been able to identify and label ensembles of hippocampal neurons that encode specific memories in the mouse brain, enabling them to then reactivate those ensembles to trigger memory recall, or inhibit them to prevent memory recall.[19,20] Implantation of false memories is also under development. More targeted interventions seem likely to arise: closed-loop, miniaturised and AI-assisted technologies may make it possible to identify areas of the brain whose electrical stimulation augurs a boost in memory performance.[21] Or we may find areas to target for memory suppression, or even implantation.

5-year horizon:

The basic science of memory becomes better understood

Deep brain stimulation, currently in Phase 3 clinical trials for Alzheimer's, yields results and advances understanding of Alzheimer's disease and memory. Specific brain functions are elucidated. It becomes possible to target specifics of memory to enhance cognition. Invasive and non-invasive brain stimulation are used to target and suppress the brain network activated in response to traumatic memories.

10-year horizon:

Memory modulation becomes a reality

Drug-induced modification of memory engrams and specific, long-lasting learning enhancement begin to be applied in education. The ability to modify the expression of memory-associated genes is combined with exposure therapies to efficiently extinguish traumas and phobias.

25-year horizon:

Implants aid memory in healthy people

Memory aids are used pervasively to facilitate learning, transforming the learning process and the way we use our "native" cognitive functions. Optogenetic manipulation suppresses fear memories experienced in phobias, or the intrusive memories of PTSD. Induced false memories help to change self-harming behaviour, for example by transposing memories of calm and happy situations onto dangerous states of mind.

2.2 Human Applications of Genetic Engineering

Human genome editing is a fast-growing field, 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 ex vivo as is practiced, for example, in cancer immunotherapy. But much of the work 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.

This is not without problems, as illustrated by the cautionary tale of Chinese geneticist He Jiankui. In 2018, He announced that he had used the CRISPR gene editor to alter the DNA of human embryos to make them less susceptible to HIV. The birth of these first edited children caused a global outcry. He was sentenced to prison and the incident thrust the capabilities of CRISPR, only discovered 6 years earlier, onto the world stage. He has since been released.

He's work was met with international repudiation because it affected the germline (and thus those children's future children) before full safety had been demonstrated. However, powerful techniques are now emerging that could soon make direct edits to hard tissue without being passed to future generations, or even that make germline edits safer. The same pathway He edited in the twins is involved in resistance to several diseases such as dengue, yellow fever, and West Nile virus. The promise is clear. But it is also clear that this work must be done under international oversight.

To bring in vivo genome editing into the mainstream, gene editors need to become more precise, less toxic and create fewer side effects, unintentional alterations, and immune reactions. This requires not only a better understanding of the links between gene networks and disorders, but more targeted ways to deliver the editor into tissues that are hard to reach, including novel viral and chemical methods and techniques from synthetic biology.

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Associate Professor University of Pittsburgh School of Medicine

Anticipation Potential

EMERGING TOPIC:

Human Applications of Genetic Engineering

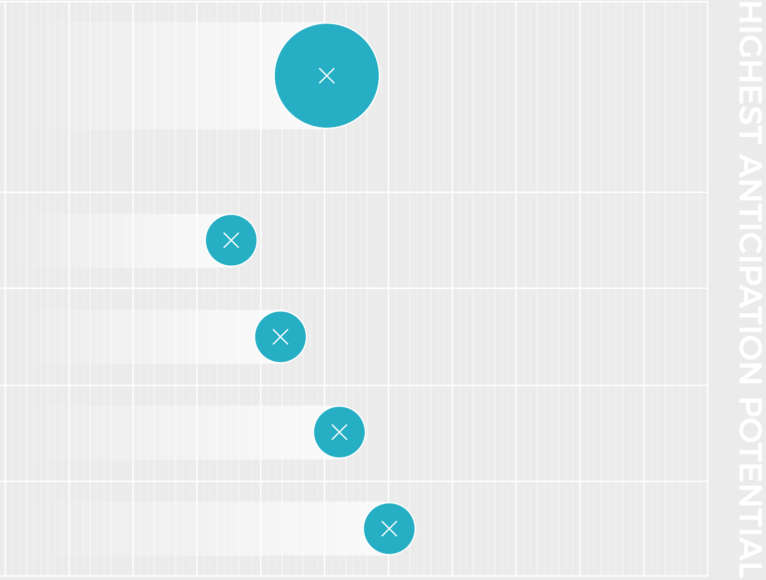
SUB-FIELDS:

Genetic diagnostics & prevention

Gene therapies & enhancement

Novel bioengineering approaches

Synthetic organisms



SURVEY OBSERVATIONS:

Breakthroughs in our ability to manipulate the human genome are likely to come in two waves that will require different responses. Gene therapies and genetic diagnostics have already received significant attention and are expected to have broad applications within the next eight years. Synthetic organisms and the use of genetic enhancement on the other hand are not expected to go mainstream for at least a decade. Synthetic organisms have received less attention so far, suggesting it should be an area of particular focus in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In 2017, Weisberg et al surveyed a large and diverse cohort of Americans about their attitudes to genetically modifying human germlines; the results make fascinating reading.[1] An international commission of the U.S. National Academy of Medicine, U.S. National Academy of Sciences, and the U.K.'s Royal Society, "Heritable Human Genome Editing" considers potential benefits, harms, and uncertainties associated with genome editing technologies.[2]

In 2019, the WHO Expert Advisory Committee on Developing Global Standards for Governance and Oversight of Human Genome Editing issued a useful background paper: "The Ethics of Human Genome Editing"[3]

A useful overview of non-germline research can be found in the NIH publication "The NIH Somatic Cell Genome Editing program".[4] In July 2021, WHO published "Human Genome Editing: Recommendations".[5]

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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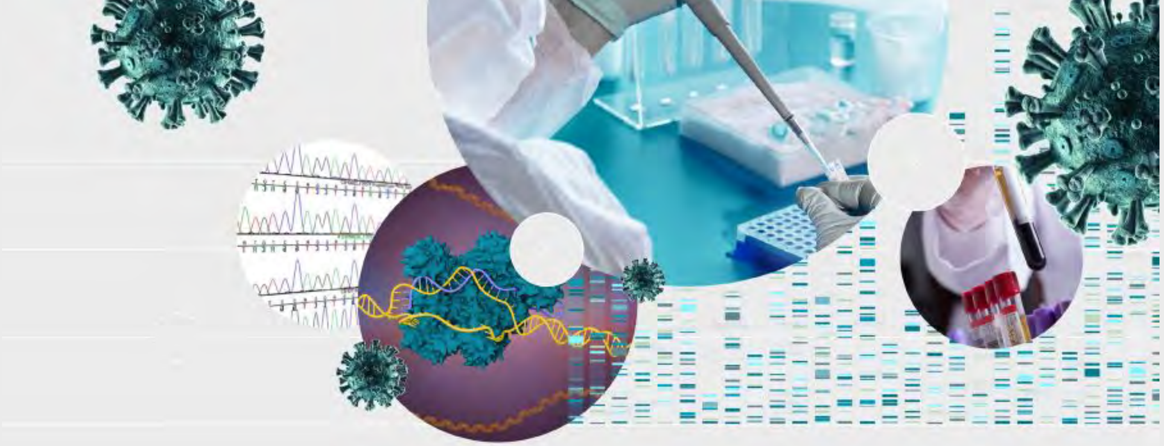


2.2.1 Gene-based diagnostics & prevention

Reading and interpreting the genome – whole genome sequencing – has helped to diagnose disease and genetic predispositions to disease. For example, a recent genome-wide meta-analysis linked certain regions of the genome to blood glucose and insulin levels, both of which contribute to the risk of Type 2 diabetes.[6] These kinds of advances will help us identify and respond to potential threats to health.

Further advances in diagnostics will also be necessary in order to bring genome editing into the mainstream. Whole genome sequencing is expensive, slow, and often challenging to interpret. New generations of genome editors require faster, better, and cheaper diagnostics to ensure precision, and to detect and prevent editing errors on the DNA.[7] Many of the newer reading/detection methods remain laborious, however. To enable mainstream in vivo editing, these technologies need to be further refined to ensure every laboratory can easily adopt them.

5-year horizon:

Faster, cheaper, better diagnostics become available

Enhanced DNA sequencing and reading technologies are lower cost, enable wider access, and monitor and increase the safety of genome editors. New generation of diagnostics including CRISPR-based methods are used to detect a variety of targets (tumors, inherited genetic conditions, viruses and other pathogens).

10-year horizon:

Reading finds biosecurity applications

Faster sequencing, and better interpretation, are helped by algorithms help trace pieces of DNA to their lab of origin.

25-year horizon:

Gene reading goes mainstream

Rapid diagnostics enable to-go or home-based devices for detection of complex diseases. Genome sequencing begins to dictate the choices of partners based on genetic compatibility.

2.2.2 Gene therapies & enhancement

CRISPR-Cas9 is now the most widely used gene editing technology in the world. It is not only powerful, allowing multiple edits with a single manipulation, it is also widely accessible.[8] What's more, the technology is constantly advancing. In 2020, scientists reported on a successful clinical trial of an ex vivo CRISPR-based cancer immunotherapy on four patients with advanced melanoma and metastatic sarcoma, for example.[9] In 2022, a CRISPR-based trial for treating acute myeloid leukaemia began. CRISPR has also shown promise in treating sickle cell anaemia and beta-thalassemia, and retinitis pigmentosa.

Nevertheless, CRISPR-Cas9 has some important limitations as a human genome editor that may make other alternatives more attractive in the long term. The compound's large size makes it more difficult to deliver into the cell than alternatives like zinc finger nucleases (ZNFs) and TALENs. CRISPR-Cas9 also seems to be more likely to trigger immune reactions.[10]

Gene-based therapy and enhancement is therefore awaiting technological developments. While TALENS has been used to treat an otherwise incurable childhood leukemia and ZNF has been used to treat Hunter's syndrome in vivo, for the moment, these alternatives to CRISPR-Cas9 are less popular, since they are harder to use. Next-generation genome editors, such as mobile genetic elements, are already being used in the lab, and the future will probably see a combination of these technologies used, depending on the application. The boundary between what is considered therapy and enhancement is already somewhat blurred. Once in vivo genome edits become easy, cheap and mainstream, the line will become even more blurred, as will lines that demarcate prevention from treatment.

5-year horizon:

Ex vivo and in vivo therapies advance

Several large-scale stage III clinical trials for ex vivo therapies take place. Some ex vivo therapies are commercially available for some cancers and blood diseases. Early-stage clinical trials use in vivo editing techniques, targeting easily accessible tissues such as the cervix, the eye, or the liver. CRISPR corrects for mitochondrial genetic disease with in vitro fertilisation. Next-generation, novel genome editors appear on the stage.

10-year horizon:

Safer genetic editing further blurs boundaries between therapy and prevention

Somatic cell engineering (i.e. no germline) allows in-human treatment of conditions caused by the malfunction of several genes, such as cancer, diabetes, and cardiovascular diseases, and other conditions related to ageing. Human germline editing is also used to prevent monogenic diseases, i.e. genetic diseases caused by a mutation on a single gene, such as cystic fibrosis, Duchenne type muscular dystrophy, and Huntington's disease. We begin to see scattered preventative applications for preventive purposes.

25-year horizon:

The boundaries between therapy and enhancement are eroded

Human germline editing is mainstream, and we learn to engineer new sensory capacities for humans. Genome-editing conveys a higher resistance to radiation and becomes key for space travel. We use gene technologies to correct, slow down or even reverse processes linked to ageing.

2.2.3 Novel bioengineering approaches

Advances in nanotechnology will be necessary to help deliver editing cargo beyond easy-to-access tissue (such as blood cells) and to devise methods for tracking and controlling edited cells in vivo. Lipid, gold and polymer-based nanoparticles are now in development. Nonviral delivery is being tested in vivo in animals. Synthetic circuits are being engineered to turn off editors inside the cell if they are going off-track. This strategy could drastically limit immune reaction. Nascent efforts are underway to exert direct electrical control over the bioelectric signalling methods upstream of gene expression; pre-clinical studies show this method can control glycemic levels in diabetic mice.[11]

There is also a need for automated analysis of human tissue. Limitations in current understanding of the complex interactions between genetic and epigenetic factors that drive many disease pathologies could be overcome by artificial intelligence – specifically machine learning algorithms – that can identify the relationships among genes, gene networks and other factors involved in disease, and the potential consequences of edits to these.[12] 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. Searching 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.

5-year horizon:

Better predictions

AI augments our ability to predict the outcomes of our edits. Genome writing allows us to build large genetic circuits composed of many repeated guide RNA sequences that enable us to simultaneously target multiple genes.

10-year horizon:

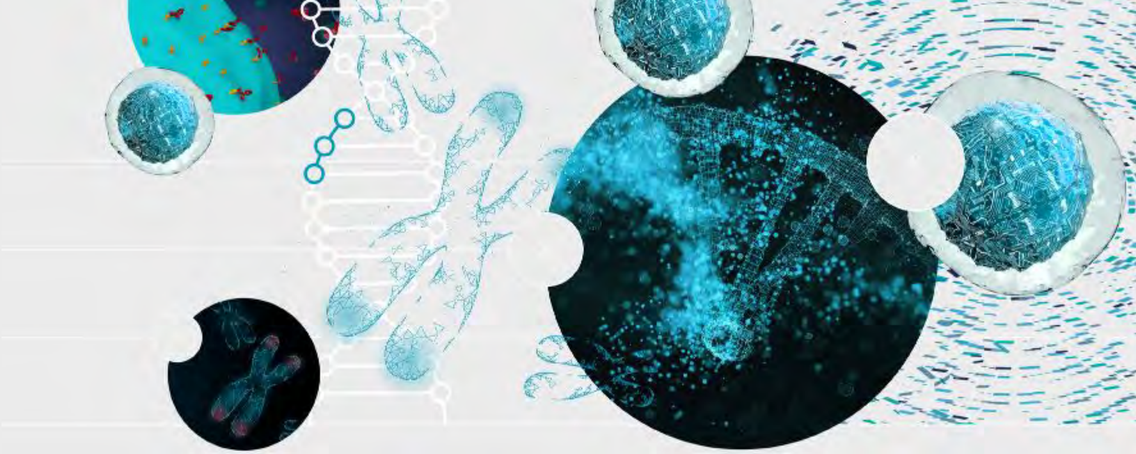
Machine-gene interfaces in clinical trials

Machine-gene interfaces tackle neurodegenerative diseases. These are much smaller electrical stimulation devices than today's existing ones, capable of interfacing with single cells and directly modulating gene expression there. As a result, receptors in our cells are engineered to sense electrical signals and translate them into genetic changes modulating memory or emotions. The first clinical trials are for diseases with no other treatment, possibly Alzheimer's disease.

25-year horizon:

Gene editing changes humans

Machine-gene interfaces enable new senses. Brain-machine interfaces translate electronic signals to "at will" genetic changes, and the first cyborgs, half-machine half biological entities, are created.



2.2.4 Synthetic organisms

Synthetic organisms will help advance genome editing for human applications in two crucial ways: by creating novel vehicles to deliver the editing tools to the body, and by creating experimental organisms that provide a better proxy for human testing.

Delivery is vital: before CRISPR genome editing materials can execute a therapeutic change, they must reach their destination. Today, viral delivery is the delivery of choice in vivo. Viruses have evolved many strategies to inject their material into a host cell, and these can be harnessed to deliver the editing cargo. Two problems with viruses are that they may be too small for the cargo, and that they may trigger the body's immune system. Synthetic organisms like viruses engineered to be bigger and/or evade immune response will help. More speculatively, engineered somatic cells could be delivery vehicles. Allogeneic cell therapy can create "universal cells" to carry synthetic biology circuits; they are less prone to rejection, and can be used to make any tissue in any part of the body.

Experimental organisms will be accelerated by the recent rapid advances in stem cell engineering, synthetic embryos, organoids (artificial and simplified versions of an organ), and tissue engineering. These techniques can provide human physiological models to study and predict the functionalities of genome editors outside the human body and before clinical applications. This is the approach prioritised by the NIH Common Fund's Somatic Cell Genome Editing and other funding agencies.

5-year horizon:

Synthetic biology circuits go in vivo

Synthetic biology circuits, now in mammalian cell cultures, find applications in vivo and for enhanced control of genome editors for gene therapies.

10-year horizon:

Chimeras, synthetic viruses and other models become mainstream

Chimeras generated by injecting human stem-cells into animal embryos grow organs for xenotransplantation or grow human-like brain structures to study gene edits. Scientists learn to make better synthetic viruses and develop genome editors that knock out genes in animal organs to supply the increasing need for organ donation without the risk of rejection.

25-year horizon:

Boundaries between synthetic and natural tissues blur

Engineered cells and tissues serve as novel delivery systems. Genetically modified viruses, synthetic viruses, and large genetic circuits are widely deployed for "gene surgery" on otherwise healthy people, directly linking genetic circuits to genome editors. We see the first demonstration in humans of universal cells carrying gene circuitry.

2.3

Radical Health Extension

In the past few decades, research has begun to suggest that there is an underlying biology of ageing that drives the diseases of ageing. One consequence of this is that, rather than accept the ageing process as a natural consequence of life, an increasing body of research is beginning to treat it specifically as a risk factor for disease, and target it for treatment. Experiments have identified ways to delay, stop and even in some cases reverse the process. A range of interventions, from small-molecule drugs to stem cell injections, is now under investigation. The goal is to use these insights to develop an entirely new kind of public health programme based on radical health extension.

Benefits won't accrue only to old people. 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. Finding ways to mitigate these processes is important across age cohorts.

The goal of these programmes is not to create billionaires that live to 500, but a society-wide eradication of frailty, high health expenditures in old age, and low quality of life. The goal is not years added to lifespan, but to "healthspan", where health, wellbeing and quality of life remains high until death.

Brian Kennedy

Distinguished Professor in Biochemistry and Physiology at the Yong Loo Lin School of Medicine at National University Singapore

Anticipation Potential

EMERGING TOPIC:

Radical Health Extension

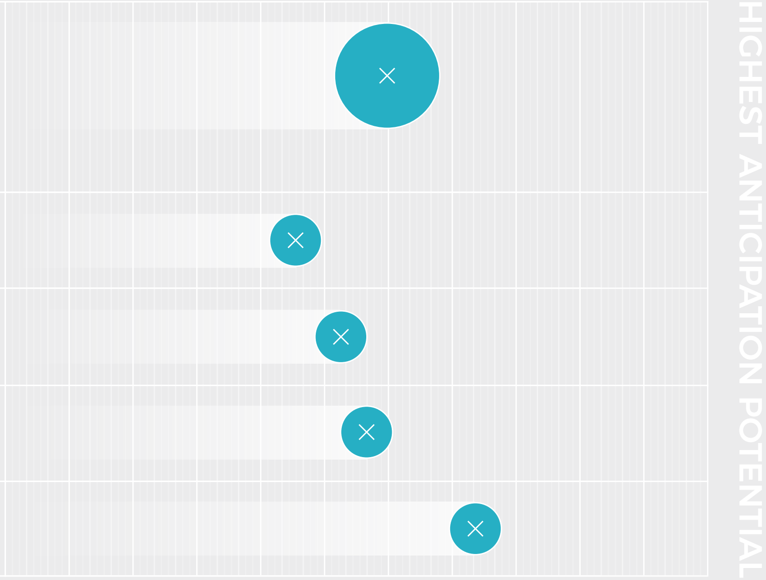
SUB-FIELDS:

Diagnostics and markers of age

Fundamental geroscience

Slowing biological ageing

Reversing ageing



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. This means progress here is likely to have a broad impact across society. Diagnostics and research to understand age are likely to reach maturity in the near future. Efforts to slow and even reverse ageing are considerably further off —11 and 21 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:

In 2013, López-Otín et al published "The Hallmarks of Aging", which detailed better ways to identify the progression of the ageing process at the molecular level, including cell senescence.[1]

In 2014, Kennedy et al published "Geroscience: linking ageing to chronic disease," which argued that these fundamental processes of mammalian ageing can be delayed with genetic, dietary, and pharmacologic approaches.[2] This became the basis of the approach now pursued by the US National Institute of Aging.

Kirkland reviewed the work targeting senescent cells with senolytics.[3] Barzilai's investigations of the diabetes drug metformin as a potential tool to target the metabolic processes associated with ageing and thereby reduce mortality, has led to the creation of what will be the first major clinical trial to test drugs to slow the fundamental processes of ageing.[4]

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 Diagnostics and markers of age

Traditionally a person's age has been measured by the number of years alive. However, this measure has recently come into question; we have discovered genes that slow ageing in centenarians, leading to healthier old age in some people.[5] Different tissues in the same body can age at vastly different rates as well, which may depend on genetic or environmental factors[6]. To create better measures of age, new strategies are investigating age-related variations in blood markers, DNA methylation states, or patterns of locomotor activity[7,8] and these may explain differences in longevity. AI technologies are being developed to combine many such factors.[9,10] These more precise measurement of age-related health can then more precisely evaluate the anti-ageing merits of competing preventive drugs, diets, supplements, and exercise regimes. It may also validate targeted ways of living to "minimise" your personal age, such as food clocking, ketogenic diets and fasting.

5-year horizon:

Age-measurement validation and standardisation begins

Companies' methods converge on standardised, validated diagnostics of real age. Multidisciplinary approaches use AI to generalise to yield new insights about relationships between the different factors in ageing. Proper validation begins of molecular theories of ageing and the prospects for altering them: telomere shortening, epigenome dysregulation, senescence-associated secreted proteins.

10-year horizon:

Epigenetic approaches find some success

Regulated public health measures advocate particular supplements, diets (e.g. ketogenic) and exercise, pushing natural human healthspan towards around 90 years and compressing the period of morbidity (reducing the gap between healthspan and lifespan).

25-year horizon:

Personalised "ageotype" and prevention

Age profiling diagnostics - both for individuals and for their different specific bodily tissues - and epidemiology combine to help people understand where they are on the spectrum of healthspan and how they can move along it. Strategies to further extend healthspan and to extend maximum lifespan become realistic.

2.3.2 Fundamental geroscience

The emerging research consensus is that ageing is driven by several different interacting processes.[11,12] These interlinked pathways influence the diseases of ageing in such a way that finding the right lever could likely defeat multiple causes of morbidity. In the longer term, researchers aim to re-appraise the fundamental process and its mechanics. Recent evidence suggests that the fundamental upper limit for human age is around 120,[13] but the questions of what determines this; why it differs from other species, and whether drugs modify it remain open. Trials are currently illuminating some ageing mechanisms. Among those mechanisms are age-related buildup of defective proteins, age-related disruption of adult stem cell function and an age-related increase in the number of senescent cells, which among other events drives an increase in chronic inflammation. Multi-morbidity studies are now planned to test whether alteration of a single pathway, such as metabolism or cell senescence, can ameliorate or prevent multiple diseases of age. This vision for geroscience goes far beyond treating old people: recent research suggests that the same pathways are involved in a variety of conditions, for example pre-eclampsia, accelerated ageing after childhood cancer treatment and radiation effects in space.

5-year horizon:

Better models of ageing emerge

Research begins to elucidate the dynamics of the interplay between the processes of ageing, and the knowledge gained is used to develop multiscale network models that incorporate the relevant physiological changes.

10-year horizon:

Ageing is integrated into healthcare as a treatable disease process

Insights into the epigenetic changes that happen after taking certain drugs, such as metformin, enable us to hone our therapeutic approaches. Health plans begin to prescribe them. Trials to identify certain hallmarks of age — frailty, for example — yield useful results.

25-year horizon:

Genetic insights begin to shed light on ageing

Machine learning algorithms help to identify the genes involved in healthy or less healthy ageing.

2.3.3 Slowing biological ageing

The new vision for geroscience goes far beyond treating old people. Recent research suggests that many of what are traditionally considered ageing pathways are also involved in a variety of conditions, including not just chronic diseases of ageing, but the acute response to infection and a variety of other conditions not obviously linked to ageing. Several interventions may slow down these processes, preventing or delaying the progression of multimorbidity and disability.

In the past few years, for example, data has begun to emerge that metformin, a drug prescribed for Type 2 diabetes and other metabolic diseases, 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. In observational studies across 78,000 people, metformin was found to decrease all-cause mortality by 17 percent in the active group, which was more diabetic, more obese and less healthy overall than the control group. Now small off-label trials of metformin and rapamycin, another drug that targets the mTOR pathway, seem to indicate that these small molecule drugs can change the biology of ageing in tissues to a younger profile. Big, multicentre trials are underway or will soon start.[14] Another approach is senolytics, a class of drugs that selectively clear senescent cells.[15] At the moment, most of the work is on small molecules, and lifestyle interventions. The first set of drugs that have been identified as interventions have been shown to affect all hallmarks of ageing, rather than one specific pathway: for example, rapamycin affects cell senescence but it also revitalises adult stem cells, affects protein synthesis and mitochondrial function and reduces inflammation. The same is true of metformin and sirtuins. The therapeutic interventions now going into clinical trials seem to affect the systemic process itself, and may elucidate the unitary hypothesis of fundamental ageing processes.

5-year horizon:

Age-slowing drugs filter into the mainstream

Off-label prescriptions of drugs like metformin yield data, and we begin to implement findings gathered from inadvertent studies, where drugs for diseases have increased the active group's healthspan. While new drugs are waiting to be approved, supplements that show some efficacy are validated. An early example, given that inflammation seems to be a pathway to ageing, is anti-inflammatory medicines.

10-year horizon:

Drugs to prevent ageing become available

Carefully-gathered understanding of which combinations of lifestyle interventions and drugs have synergistic effects on hallmarks of ageing and specific diseases enables us to use them on prescription. Drugs are found to alleviate early-stage indicators of ageing such as frailty and Alzheimer's disease. More trials are launched to investigate the efficacy of drugs such as metformin and rapamycin on a wider range of age-related disorders.

25-year horizon:

A unitary hypothesis of fundamental ageing processes

Instead of a single "silver bullet" that slows the ageing process, we know how to combine different anti-ageing strategies for personalised "ageomes" for additive and synergistic effects. It becomes possible to figure out the perfect age to start different drugs or interventions. Gene therapy is carried out in the womb to prevent other processes of ageing.

2.34 Reversing ageing

Age reversal is a radical and controversial idea, but there are reasons to believe that some progress is possible here. It has proven possible to reverse certain ageing biomarkers using restrictive diets[16], and certain phenotypes of ageing can be reversed in specific tissues, for example osteoarthritis by eliminating senescent cells. In transplantation medicine, researchers are conducting trials that aim to remove the age-associated chemicals found in the kidneys of older donors so that they can be successfully transplanted into young recipients.

There are suggestions that mesenchymal stem cells, epigenetic reprogramming, gene therapy for telomere lengthening, organ replacement and drugs may all have the ability to, in some specific tissues, trigger reversion to an earlier state. Stem cells can even be reset to age zero — this process has been used to regenerate a crushed optic nerve.[17] A gene therapy has been mooted to reverse the processes of multiple age-related diseases.[18] Gene editing has corrected a progeria mutation in mice allowing them to double their lifespan[19].

This remains a difficult research programme with many barriers to overcome. Most of the treatment approaches are currently very expensive, and there is no animal model organism or trial that could tell us how far these increase the human lifespan — waiting for results would take a prohibitive amount of time. However, it should not take long to discover whether these therapies have real effects on healthspan and as ageing biomarkers become more validated, it may be possible to estimate their effects on lifespan.

5-year horizon:

Organ rejuvenation is proved possible

Research succeeds in removing the age-associated chemicals in animal organs. The first trials of cell and gene therapy for ageing in humans begin.

10-year horizon:

Age therapies become affordable

Improvements in the tools and techniques of cell and gene therapy reduce the cost and widen the availability of treatments that slow ageing.

25-year horizon:

Limited age reset becomes possible

Stem cell delivery methods mature, allowing the targeting and rejuvenation of a range of tissue types. Organ derivation and replacement becomes a possibility.

2.4 Consciousness Augmentation

Even though there is no standard definition of consciousness, in the medical context, methods have had to be devised to verify its presence or absence, to define whether a patient is in a vegetative state, and whether they can be expected to return to normal conscious state. In this arena, the lack of agreement on what consciousness is does not prevent us adopting technologies and conceptual advances that help make decisions. As with many medical applications, these technologies will start in a clinical setting, but the insights they yield will eventually benefit the broader population.

This is because the same technologies that restore consciousness when there is a deficit or disorder can be pressed into service to enhance or augment healthy, functioning consciousness. Using tools devised from an array of disciplines, including robotics, optogenetics and virtual reality, it has been possible to augment missing or damaged sensory inputs to consciousness — or add entirely new ones. Similarly, research can pinpoint specific aspects of healthy consciousness that we might wish to enhance beyond current limits, for example attention, empathy and memory. Such insights will fundamentally change current approaches to education but also will have consequences in the workplace and in military contexts. Eventually, they may also yield a way to define the presence and quality of consciousness across different species, and this could have radical consequences for how we understand the other animals with which we share the planet. It would also make it much easier to set boundaries on how we allow ourselves to treat either the creatures we create the creatures we use in labs, or the creatures that simply suffer because of the way we treat the world.

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Professor and Director of the Wisconsin Institute for Sleep and Consciousness

Anticipation Potential

EMERGING TOPIC:

Consciousness Augmentation

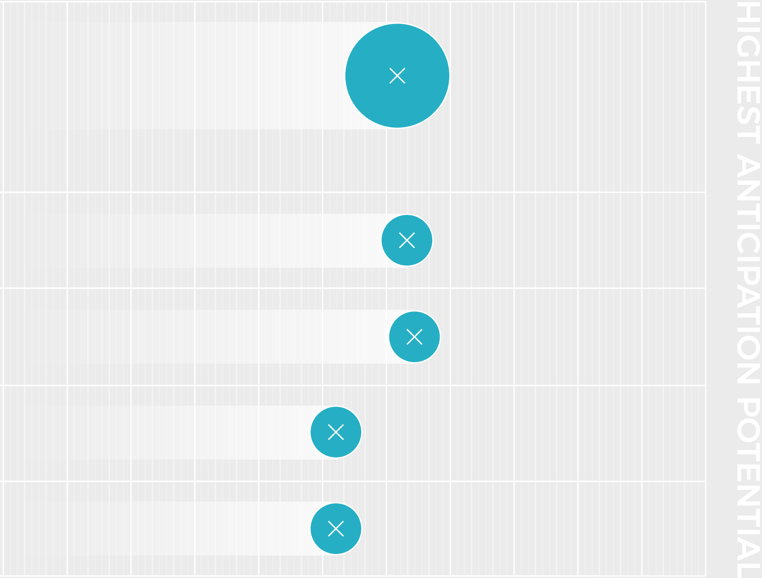
SUB-FIELDS:

Cognitive capacity enhancement

Consciousness assessment

Brain-machine interfaces

Sense-expanding technologies



SURVEY OBSERVATIONS:

Efforts to augment human consciousness are likely to reach maturity in the next 10-15 years. The field's reliance on interdisciplinary research drives some of the anticipation score. Assessing consciousness and enhancing cognitive capacity were deemed to be the most in need of anticipation, with further to go before these technologies reach maturity.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

In 2019, Michel et al published "Opportunities and Challenges for a Maturing Science of Consciousness", which closely examined the field's potential.[1]

Tononi and Koch's "Consciousness: Here, There and Everywhere?" provides an overview of the issues involved in developing a theory of consciousness, as well as the authors' take on what such a theory might look like.[2]

Dresler et al's "Hacking the Brain: Dimensions of Cognitive Enhancement" explores the various approaches to augmenting our natural cognitive abilities.[3]

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

Cognitive capacity enhancement

The 20th century saw a measurable and significant increase in the average human intellect as measured by IQ.[4] 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.[5] Further enhancement of cognition is a major project for the 21st century, to be realised by more of the same, plus drugs and machine interfaces. 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 human cognitive capacity is shaped by culture, including exposure to tools like mathematics and language, which underpin the ability to grasp abstract concepts and create complex models of the world. Boosting cognitive capacity further will require further enrichment of the cultural environment. Virtual environments have already been shown to boost empathy[6] and memory retention[7] in the classroom. Neuroscience can deliver better insights into how human brains learn. Next-generation artificial intelligence algorithms, designed to mimic the more probabilistic and error-tolerant computations done by human brain networks, will be hybridised with human intelligence to boost the human capacity for learning further.

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.

10-year horizon:

The re-engineering of education begins

We share our cognitive load with systems that enhance general consciousness, attention and recall. Neuromodulation technologies, for instance, 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.

25-year horizon:

Hybrid consciousness enhances cognition

Bio-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.

2.4.2 Consciousness assessment

It is broadly agreed that consciousness is an emergent property of complex nervous systems. But there is no granular understanding of which circuits are implicated. There is progress here, however. Researchers have developed diagnostic indices based on EEG activity, such as multivariate classifiers[8] and EEG reactivity, such as the Perturbational Complexity Index (PCI), [9,10] to reliably tell whether someone is in a vegetative state or a (more reversible) minimally conscious state. Therapeutic neuromodulation (precisely targeted noninvasive technology like Transcranial Direct Current Stimulation - tDCS) has successfully brought minimally conscious patients back.[11] There appears to be good agreement between these methods. Closed-loop neuromodulation is already able to act on, and sense, brain state based on feedback, though this is limited for now to epilepsy.

If deployed in line with a set of internationally validated guidelines to diagnose the presence or absence of consciousness, in future a combination of these technologies can be standardised to wake people from comas. Such guidelines could also identify areas of interest for probing the neural correlates of consciousness. Chinese Academy of Sciences researchers are looking at neural circuits associated with specific aspects of consciousness — notably self-awareness — in macaque brains.[12] Manipulating these parts of the brain may help people with Alzheimer's, or other disorders of consciousness. An understanding of the circuit basis of consciousness could also help quantify specific aspects lacking, and thereby point to the best intervention, e.g. thalamic stimulation. Such investigations and analysis may help us back into a working definition of consciousness.

Whether machines and animals have consciousness,[13,14] and most recently to understand whether organoids and other synthetic biological organisms are capable of developing a kind of consciousness remains a big scientific question.[15]

5-year horizon:

We become more adept at diagnosing consciousness

Improved brain state diagnostics emerge, using bedside electrophysiological tools to distinguish minimally conscious from vegetative. Some people with specific disorders of consciousness receive brain stimulation to enhance their conscious state. The neural circuit implicated in the mirror test — a key aspect of how we define consciousness — is found in macaques.

10-year horizon:

The tools to restore consciousness are developed

We have an agreed set of international guidelines (perhaps a standard scale) to diagnose the presence or absence of consciousness. We use non-invasive closed loop neurostimulation like tDCS or focused ultrasound to alter people's conscious state. Invasive stimulations detect consciousness in locked-in patients and give them ways to communicate using brain machine interfaces. Work to find best practices leads to recovery.

25-year horizon:

Theories and therapeutics of consciousness become established

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 communications with apparently unconscious people, even restoring natural consciousness in some cases.

2.4.3 Brain-machine interfaces

Brain-machine interfaces can help to augment human consciousness in three different ways.[16] First, augmenting the sensory inputs that define existing consciousness could redefine the resulting consciousness. Restoring and augmenting sensory inputs to consciousness is already done by gene therapy, cochlear and retinal implants. Secondly, interfacing with a different type of body could augment consciousness by expanding the human body map. Robotic appendages with different, non-human degrees of freedom are already at work in factories and in surgical suites. These make their operators navigate the world with a different body plan thereby altering their mental model of the world. While all brain machine interfaces start out in the therapeutic space, these will not make a big societal impact until they are in mainstream use. As more occupations and leisure activities incorporate such devices, future brain machine interfaces could couple humans to exoskeletons with different numbers of limbs or entirely different body plans, or to virtual environments. Third, altering the environment we experience in virtual reality could change our perception of and relationship to the spatial world by, for example, putting us into several places at the same time.

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.

10-year horizon:

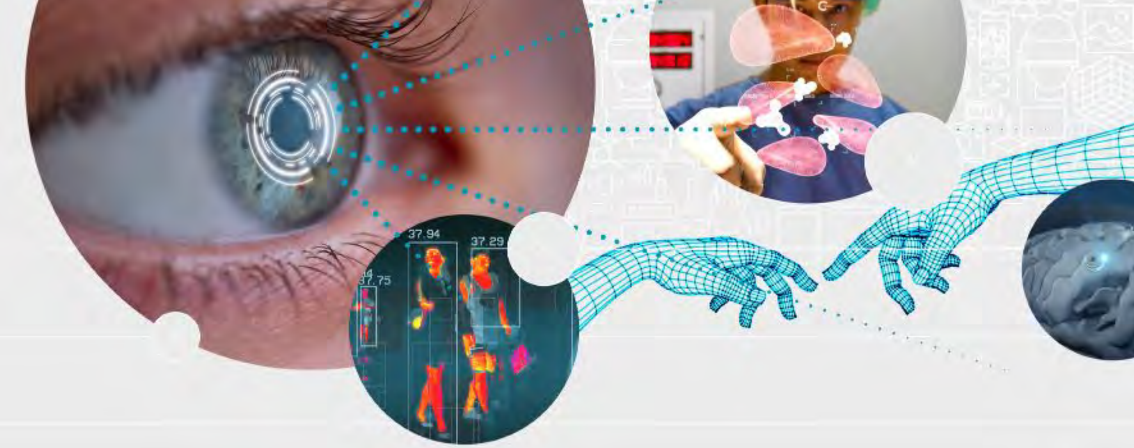
The first human-machine interfaces begin to see roll-out

The wider availability of more general-purpose daily use robotic devices means that some models begin to explore the advantages of invasive interfaces.

25-year horizon:

Neural interface for consciousness sharing

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



2.4.4 Sense-expanding technologies

In principle, neuroengineering and virtual reality can combine to give an experience of consciousness that is no longer bound by the five standard human senses. Expanding consciousness is about more than increasing cognitive capacity. The goal is to create better models of the world with more complete information, and to experience the world in a way that is not limited by the normal complement of human sensory input.

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 restore the full input portfolio to conscious experience. We can use the same principles to add extra senses to the human sensory portfolio, possibly from animals. 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[17]. Some researchers have used wearables or implants to give themselves magnetic senses[18] or the ability to feel sound.[19]

However, expansion of consciousness doesn't have to stop at senses. It is possible to deliver artificial sensory input with psychotropic drugs like psilocybin, virtual reality, and robotic embodiment. VR could make it possible to expand our definition of consciousness by changing our environment or body. Full immersion may even change our linear experience of time by allowing us to pre-live possible future experiences, or re-live past memories.

5-year horizon:

Humans begin to adopt augmentations

Targeted gene therapy allows augmentation of sensory scope — "seeing" in the infrared part of the spectrum, for example. 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.

10-year horizon:

Engineered body enhancements become commercially available

Some people choose to augment their natural senses with new engineered senses, or to adopt robotic limbs. 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 realities and between natural and artificial body parts — some of which display non-human characteristics. It becomes possible to better incorporate within our experiences the perspectives of other people and other species.

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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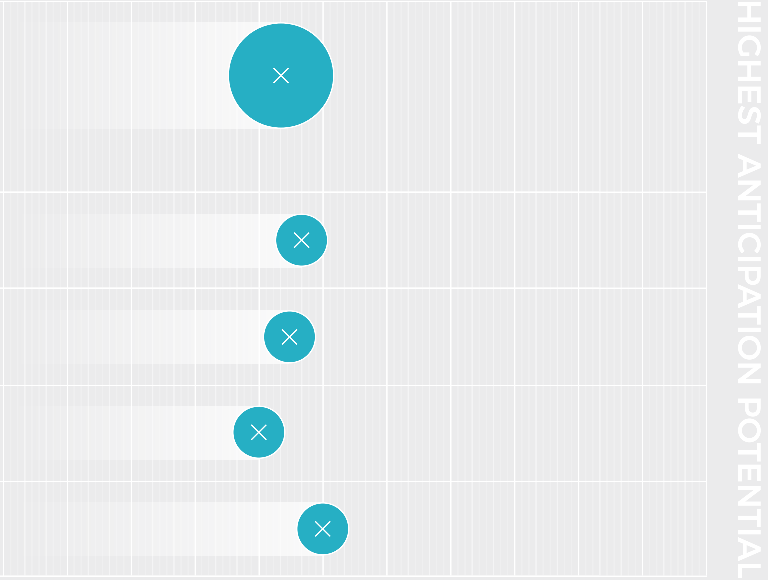
Anticipation Potential

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 2018, Rossi et al published “Progress and potential in organoid research” in Nature Reviews Genetics, which closely examined the field’s potential.[8] Hans Clevers in “Modeling Development and Disease with Organoids”[9] and Hofer & Lutolf in “Engineering Organoids” summarised the major technological trends and applications for organoids.[10] In “3D Brain Organoids: Studying Brain Development and Disease Outside the Embryo”, Arlotta et al. compared the biology of brains and brain organoids, and highlighted experimental strategies for using organoids to attain new insights into human brain pathology.[11] In “Cancer modeling meets human organoid technology” (2019), David Tuveson and Hans Clevers focused on cancer in a review of the current state and future prospects of the rapidly evolving tumor organoid field. In 2021, the National Academies of Sciences, Engineering, and Medicine published “The Emerging Field of Human Neural Organoids, Transplants, and Chimeras: Science, Ethics, and Governance.”[12]

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:

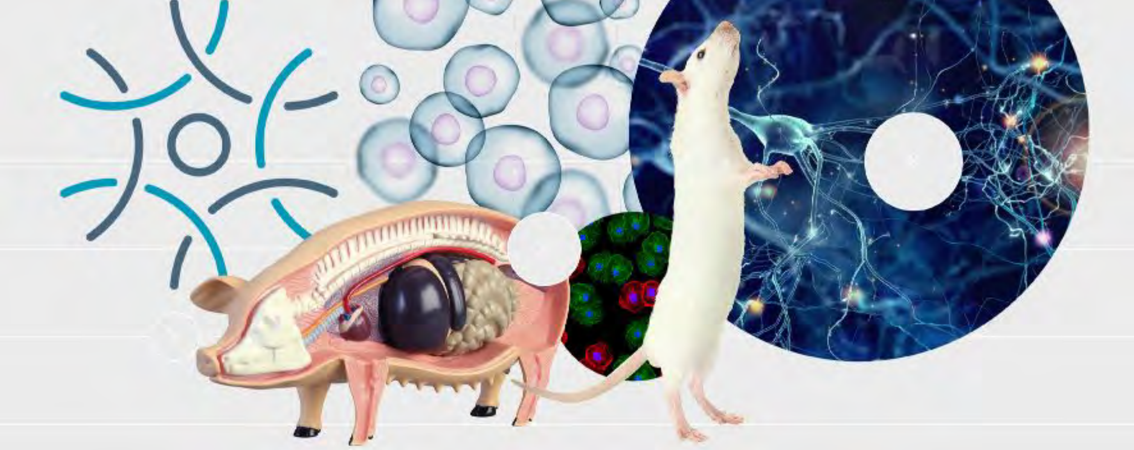
Predictive models have proven efficacy

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

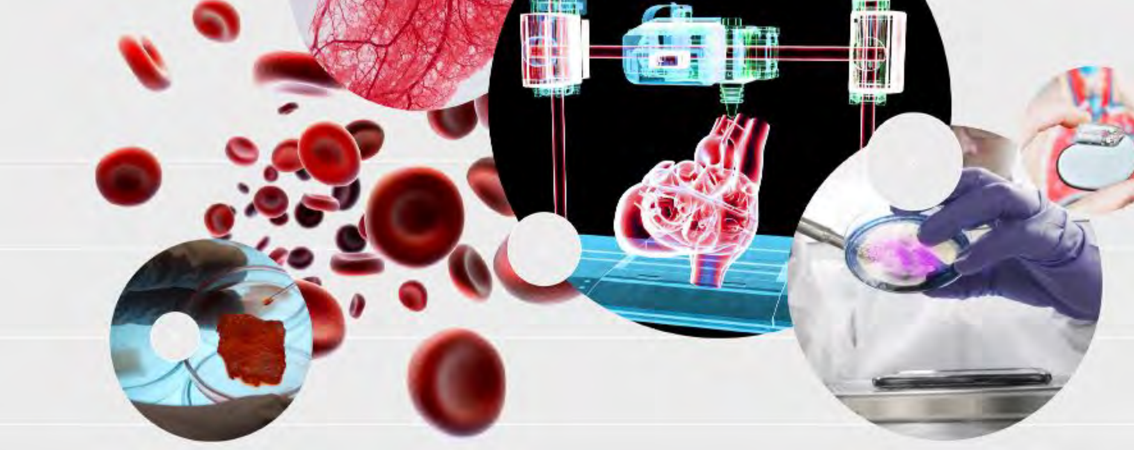
AI-assisted predictions can be made about individual response to some drugs. Tumoroids are grown from patients to develop treatments on a very fast, highly efficient turnaround. Organoid-derived cells are used for stem cell therapies in humans.

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.

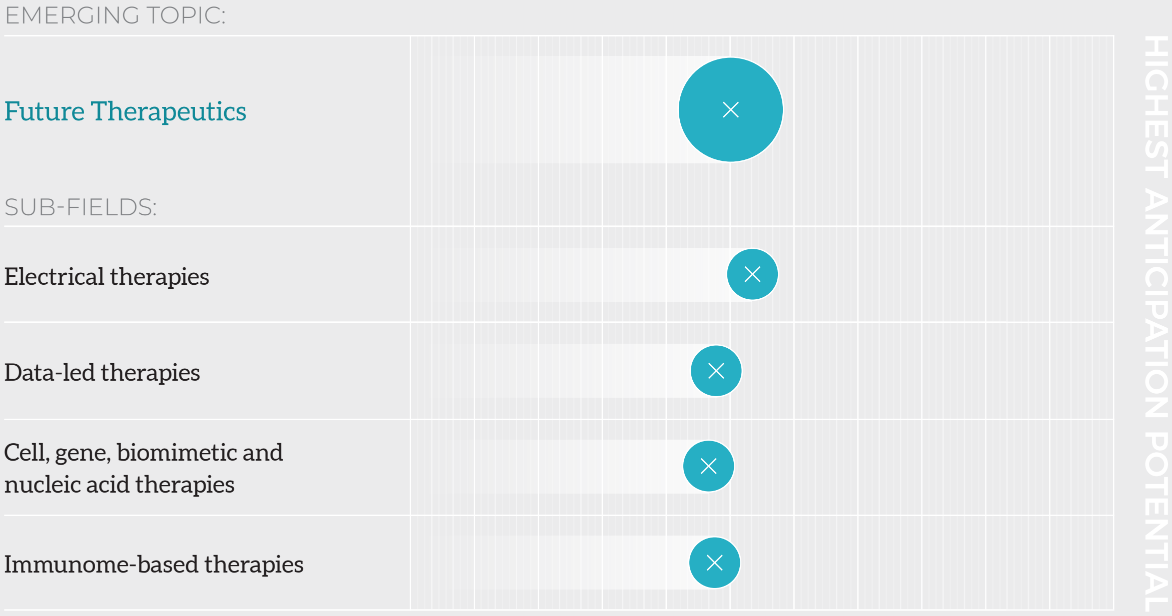
These future therapeutics collectively represent the next wave of innovation in healthcare; some are already entering the market. Their growing success is down to a number of changes in the philosophy and practice of medicine. First, there has been a gradual move towards seeing medicine's goal as actively 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



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:

Electrical therapies are still a fast-moving field, but their efficacy and acceptance is growing, as highlighted by a recent review in STAT News.[1] In 2002, Kevin Tracey published "the inflammatory reflex" to clarify the link between vagus nerve stimulation (VNS) and its effects on the immune system.[2] It remains a useful overview of the mechanisms of VNS's effects on the body downstream of the nervous system. Sixteen years later, Johnson and Wilson updated the field with "A review of vagus nerve stimulation as a therapeutic intervention", an overview of FDA-approved vagus nerve modulation and its increasingly clear role beyond approved uses.[3] Davenport & Kalakota highlighted the future of AI and medical data analysis in 2019.[4]

In 2021, Arnout et al summarised the promise of the immunome,[5] Kulkarni et al highlighted the current landscape of nucleic acid therapeutics,[6] Damase, Tulsi et al examined the future of RNA therapeutics,[7] and El Kadiry et al reviewed the field of cell therapy.[8]

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-based 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.

2.64 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:

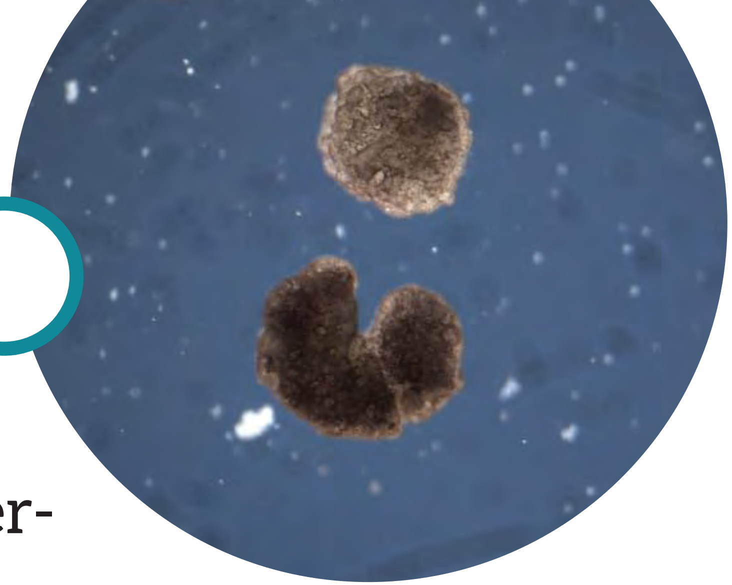
Manipulating the immune system becomes possible

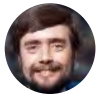
Researchers begin to unpick the intricacies of how wound healing and regeneration work. Most kinds of cancer become a chronic disease. Preliminary models emerge of the human immune system as the network of genes, proteins and cells that are its components. The first in-silico vaccine and immunotherapy 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.





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Invited Contribution: Xenobots and computer-designed organisms

Despite breakthroughs in our understanding of the intricate internal dynamics of cells, the question of how they form complex multicellular life that exhibits a robust, problem-solving, adaptive plasticity remains a mystery. Cracking that "morphogenetic code" could revolutionise medicine and let us design sophisticated living machines unlike anything found in nature.

Doing so requires a paradigm shift, however. We will have to switch focus away from the genetic and molecular mechanisms that underpin how individual cells operate, and look at how collective decision-making among groups of cells can lead to larger biological constructs that are greater than the sum of their parts. Fascinatingly, they solve new problems that the parts did not solve, and induce them to behave in ways they would not, by themselves.

In an effort to gain insights into these processes, our group has investigated whether cells could be coaxed into developing into forms entirely alien to those specified by their genes. One of our members, Douglas Blackiston, harvested skin cells from frog embryos, and used them to create passive structures, while heart cells acted as tiny motors thanks to their regular contractions. These initial designs helped us to understand how the configuration of cells impacted their behaviour, which in turn allowed Josh Bongard and his then PhD student Sam Kriegman to create computer simulations of these synthetic organisms. By combining these simulations with evolutionary algorithms that replicate the processes of natural selection, we were able to generate thousands of new designs. The resulting xenobots were able to walk, swim, carry loads and even work together as a swarm to tidy up piles of microscopic debris.

By poking and prodding them into place according to the AI-generated xenobot blueprint, and relying on cells' natural inclination to adhere to each other, we pieced together a variety of simple structures. In 2020, we unveiled our results: a menagerie of synthetic organisms that we dubbed "xenobots", after the African clawed frog (Xenopus laevis) whose cells we used to build them, and the future potential of this system as a bio-robotics platform. Last December, we even showed that our creations could self-replicate by pushing loose cells together to create new Xenobots – a new kind of large-scale replication not known in the natural world.

Today, these tiny machines are still unable to carry out arbitrary practical tasks, and are restricted to simple lab demonstrations that teach us about plasticity, evolution, and engineering with cells that have an unaltered genome. But they represent an entirely new approach to engineering at the smallest scales. Evolution has spent billions of years perfecting tiny machines, far more intricate than anything humans could build today, that boast a vast repertoire of capabilities. Rather than trying to reinvent the wheel, we're learning how to take advantage of their innate strengths and use them as building blocks to create adaptive biological robots.

This requires an entirely different design philosophy. It is less about piecing together carefully engineered parts to micromanage outcomes directly, and more about trying to coordinate what we call "agential materials" that have capabilities and agendas of their own. Crucially, this does not require an exhaustive understanding of the internal mechanisms of the cells themselves — no synthetic biology or genetic engineering was required to create our Xenobots, as we use a kind of behaviour shaping strategy to collaborate with the cells' inherent capacities.

In much the same way as you don't need to understand the neurology of a dog to train it, we are discovering that we can guide the behaviour of cell groups by manipulating their environment and the signals they receive; our on-going efforts will exploit chemical and electrical cues to shift the native collective behaviours of the cells toward desired morphogenetic and behavioural goals.

This project could not have happened without the use of AI to automate our design process. We calculated that actually building all of the designs our evolutionary algorithm explored would have taken 12 million years. Now we are working on automating manufacturing too, which will allow us to carry out the high-throughput experiments that are needed to hone our techniques.

That will also lay the groundwork for commercialisation. While it is still early days, xenobots are just the beginning of a massive field of computer-designed organisms. The technology is so fundamental that it is difficult to imagine all the possible applications. Living cells have a huge amount of in-built machinery for sensing, communicating and even navigating, all of which could be repurposed for a wide variety of use cases. And, as seen in the brain, cells of all kinds can form networks that perform computation and morphogenesis in ways that would be very difficult to implement bottom-up.

An early application is likely to be biosensors that are designed to detect dangers such as pathogens or gas leaks. These would take advantage of a biological system's ability to pick up signals in real-time and rapidly amplify them. Tiny biological robots also have clear future applications in aqueous environments, where they could autonomously navigate into hard-to-reach places to make measurements or clean up toxins.

Ultimately, these biological robots may be able to carry out these kinds of roles inside the human body: chasing down bacteria, killing cancer cells, helping heal wounds, or cleaning up arthritic knee joints. Stringent clinical testing requirements mean that this is likely many years away, but these devices' innate capabilities and biocompatibility could see them quickly overtake the man-made nanobots many are investigating for medical applications.

At a more foundational level, the approaches we have pioneered will be a powerful tool for deciphering the morphogenetic code. Learning how to design, program and control these xenobots is likely to teach us profound lessons about the way the human body organises itself. This could lead to major breakthroughs in regenerative medicine, potentially allowing us to coax our own cells into repairing birth defects, healing organs or re-growing lost limbs.

Democratising this technology will be key to realising that potential. That is why we have made our research freely available, and open-sourced the software used to design our xenobots. But it is crucial that we start anticipating future developments in this field: the technology's relative simplicity and wide applicability means that it is not likely to remain in the lab for long.

The technology should raise profound philosophical questions too. It seems inevitable that xenobots are likely to blur the lines between machines and organisms, and will start to chip away at notions of human, and even biological, exceptionalism that underpin much of Western philosophy. They will provoke us to ask what it means to be human — is a xenobot made from your own cells part of you?

Designing synthetic organisms not found in nature is also likely to provoke pushback from those concerned about upsetting the natural order of things. But it is important to remember that natural evolution does not optimise for happiness, intelligence or any of the things we value. The modern world is beset with human suffering, animal suffering, and environmental destruction and we are now on the cusp of a technology that could help fix many of these issues. In our view, we have a moral and ethical responsibility to do better than the meandering search process that has governed the development of life on this earth so far, using rational understanding of emergent agency to improve quality of life for all.

3

Introduction to Eco-Regeneration & Geoengineering

Our planet is hosting the ultimate tragedy of the commons. The planet is warming at an alarming rate as CO2 floods the atmosphere. The oceans are being emptied of fish, and flooded with plastic. Meanwhile, the human population is set to rise to about 10 billion by 2050, a change that will put unprecedented pressure on our food systems. If nothing is done to halt these trends, everyone and everything will suffer the consequences.

Our **decarbonisation** programmes give cause for optimism. From the development of negative emission technologies that extract CO2 from the atmosphere, to the rapid development and scaling up of renewable energy sources — including the development of advanced materials and energy storage capacity — the decarbonisation of the planet has a ready roadmap.

The burgeoning field of **world simulation** is experiencing rapid developments. The increasing convergence of big data, advanced computer modelling and artificial intelligence will allow us to model complex systems, from societies to whole ecosystems, with ever greater predictive power. This will prove an invaluable guide in policymaking.

Along with resilient societies, we will require our **future food systems** to be resilient, with an 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.

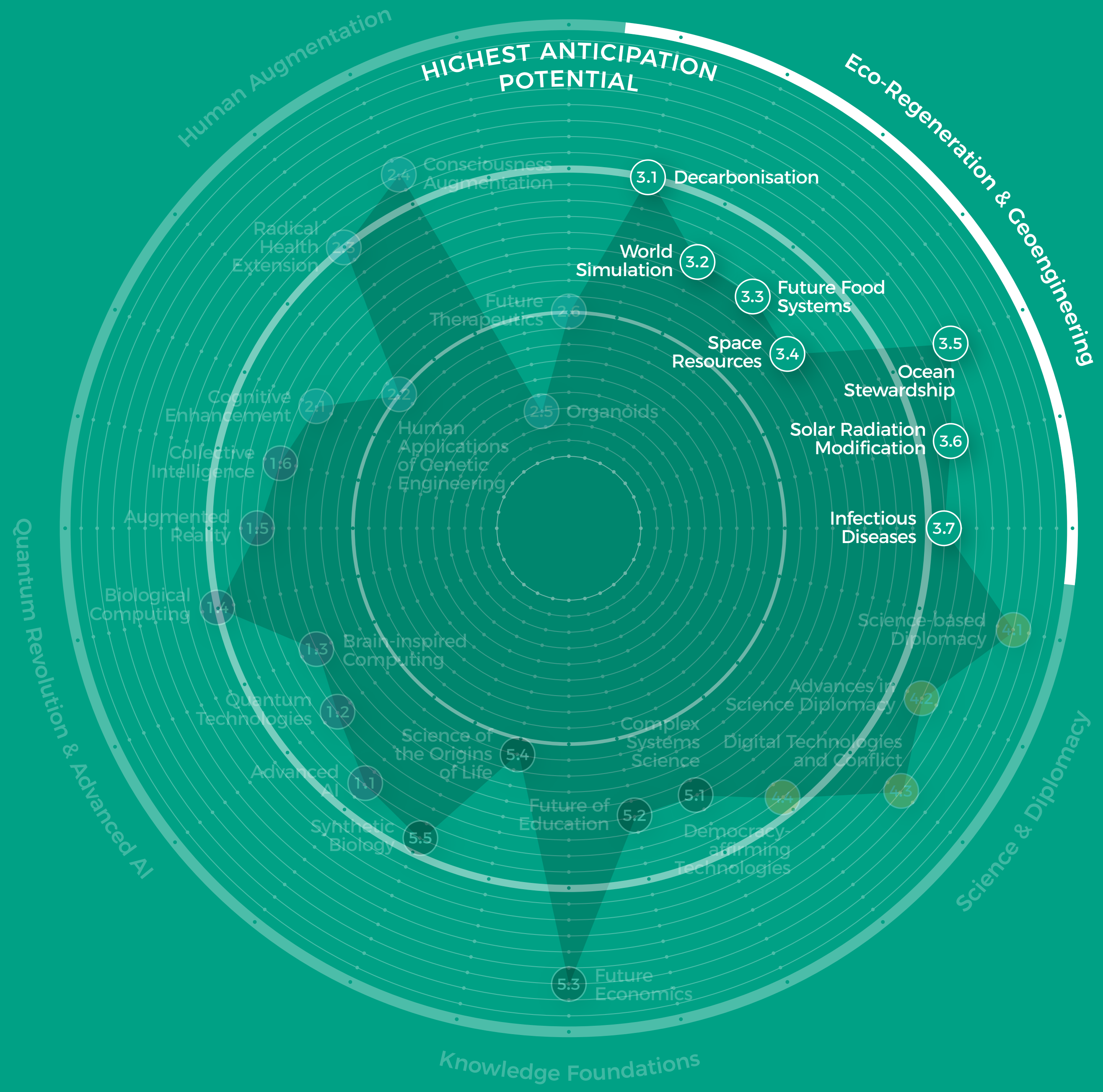
Our relationships to the oceans must change. We urgently need to understand them better, and to help repair their ecosystems where possible, but there are pathways opening up that will make this happen. We can deploy the emerging technology of autonomous sensors to gather relevant data, for example, and continue to explore the vast biodiversity of the ocean and the myriad cold-adapted organisms rapidly disappearing from the planet's retreating glaciers. As our understanding of their complex, interdependent networks grows, so will our ability to perform proper **ocean stewardship** and find solutions to the problems they are facing.

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.

Climate change is perhaps the most pressing issue of our time, and yet countering its effects has proved particularly 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 and Zika 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, as the following pages make clear.



3.1 Decarbonisation

The reports of the International Panel on Climate Change (IPCC) make clear that climate change is a direct result of anthropogenic activity, which is primarily related to the combustion of fossil fuels for energy production. The consequences of this activity on our habitable environment are serious, and implementing a global strategy to curb CO_2 levels is an urgent task.

Energy transitions are historically slow and hence the continued use of fossil fuels is expected for many years to come. Thus, the concurrent advancement of many other technologies is required. Such technologies are related to capturing CO_2 from large point sources such as power plants, improving energy efficiency (for instance within industry and the building sectors), producing synthetic fuels from waste products such as CO_2 and biomass, and CO_2 storage, both underground and in the form of useful, value added products such as concrete. However, a major part of the IPCC solution is to directly remove CO_2 from the atmosphere using a range of “negative emissions technologies” (NETs), which can be incentivised through robust CO_2 pricing.

The Paris Agreement established a global framework meant to limit global warming to “well below 2 degrees Celsius”, with the ultimate goal of not exceeding a 1.5 °C increase. Despite this, studies indicate that if humanity continues emitting carbon at the current rate, there will likely be enough CO_2 in the atmosphere to rapidly break through the lower 1.5°C target within the next decade.[1]
Thus, it is clear that urgent decarbonisation will require co-ordinated action at every scale as well as a concerted, unified effort across many disciplines, including policy, economics, industry, science, engineering, and technology. Understanding the challenges and uncertainties involved and proposing a path forward that ensures global access to renewable energy and participation in NETs through the right policies and economic incentives, is critical.[2]
Possible pathways to decarbonisation solutions are presented further down in the report.

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Anticipation Potential

EMERGING TOPIC:

Decarbonisation

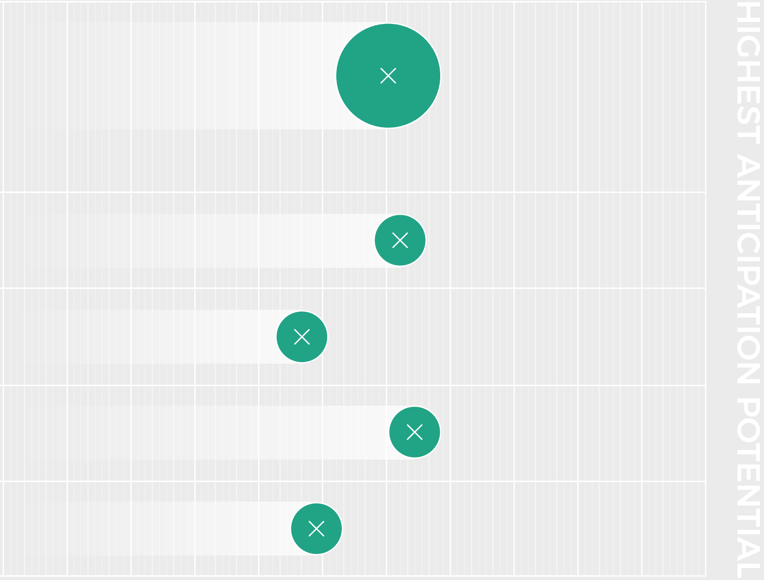
SUB-FIELDS:

Negative emission technologies

Energy transition

Advanced materials

Energy storage



SURVEY OBSERVATIONS:

The drive to reduce the amount of CO_2 in the atmosphere has been a global priority for a number of decades. Moving away from polluting fossil fuels has been a major focus of this effort, which is why energy transition was judged to have low anticipatory need. Despite being rated very highly for its transformational impact, the field has already received plenty of attention and is expected to reach maturity over relatively short timescales. In contrast, large-scale deployment of negative emission technologies is almost two decades away and has received less attention so far, suggesting a greater need for foresight in this area.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Among many publications in the aforementioned areas, four documents from 2019 provide a useful overview. Luderer et al review the likely co-benefits of decarbonisation[3]; the International Renewable Energy Agency has looked at innovations in energy storage[4] and the future of solar photovoltaic systems.[5]

Finally, there is the National Academy of Sciences, Engineering and Medicine's "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda".[6]

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

At the current CO_2 emission rate and its projected growth, it is projected that the world is headed for a catastrophic temperature rise above 3°C in this century.[7] In fact, there is already so much CO_2 in the atmosphere that simply reducing emissions is no longer sufficient; the effort now requires the implementation of "negative emissions technologies" (NETs) that can extract carbon directly from the atmosphere. NETs can both impact past emissions and also help manage those emissions from small, dispersed sources, like automobiles.

Examples of NETs include nature-based solutions such as afforestation, reforestation, and the use of agricultural soils that can take up and store carbon; of the various proposals made to date, these technologies are included in a short list of NETs that are sufficiently developed to remove carbon from the atmosphere for less than $100 per tonne.[8] Unfortunately, these technologies also require rapid and widespread changes in forest and soil management practices. Transforming how society manages its land is no small challenge. Given this, other proposals regarding NETs have been made. These include activities such as extracting CO_2 directly from the atmosphere using chemical interactions, a process called direct air capture (DAC). In this case, the CO_2 would be extracted from air and subsequently sequestered underground for long term storage.[9] Unfortunately, DAC is still in its early stages, making it too expensive at the moment. Like other NETs, DAC also must be combined with a robust carbon-pricing system, which mandates that emitters pay for the greenhouse gases that they produce as a cost for "clean up". Such carbon pricing is key, as it can help pay for the capture process and promote NET optimisation; the latter can reduce the economic cost associated with removing carbon from the atmosphere, and hence, help to eventually develop a CO_2 market that might further incentivise the adoption of NETs.

5-year horizon:

The development of a CO_2 market

With the anticipated reduction of the price of carbon capture for selected NETs to below $100 per tonne of CO_2,[10] the global CO_2 market will start becoming attractive for private actors. From a technology standpoint, experts do not expect game-changing developments at 5 years but rather incremental improvements to make those technologies more efficient and better integrated into the so-called circular economy. With continued reduction in the cost of captured CO_2, we can begin to move towards its utilisation in the production of a variety of value-added products. Nevertheless, investments into start-ups and scale-up activities will be increasing quickly, on the prospects of a commercially competitive market.

10-year horizon:

Mining CO_2 from the air is commercially viable

By combining solar energy and various CO_2 extraction methods, including newly developed approaches to DAC, the production of synthetic fuels from carbon is becoming commercially viable. DAC is boosted via economic and policy incentivisation.

25-year horizon:

Large-scale CO_2 capture and utilisation begins

Breakthroughs in DAC and conversion technologies now allow large industrial scale applications where CO_2 is captured from air and converted into synthetic fuels and other value-added chemicals.

Climeworks direct air capture plant to sky image is © Climework, Image by Julia Dunlop

3.1.2 Energy transition

Due to factors such as a growing global population, the demand for power is expected to rise by 50 per cent before 2050.[11] Nonetheless, greenhouse emissions still need to fall sharply, necessitating a rapid transition away from fossil fuels as a source of electricity generation and transport fuel. This can be made possible by leaving remaining fossil fuel reserves untapped and embarking on a rapid uptake of renewables such as wind and solar photovoltaics (PV), allowing these technologies to dominate power generation by 2050. In addition, fuels can be produced from CO_2 that is "mined from the air". In short, solar energy can be used to produce synthetic hydrocarbons from captured CO_2 and "green hydrogen". The latter is produced via solar-driven electrolysis that splits water into oxygen and hydrogen leading to an overall carbon-free fuel production process.[12] In parallel, nuclear fusion reactors remain a viable possibility in future decades.

5-year horizon:

Embracing the sun and wind

Record efficiencies are achieved in commercial solar photovoltaic modules and combined with reductions in device cost, make utility-scale solar PV cheaper than building new coal or gas-fired power plants in most of the world, boosting the adoption of solar technologies.
In addition, a new class of giant offshore wind turbines, with rotors over 220m in diameter and individual output up to 15 MW, are installed across the globe.[13]

10-year horizon:

Managing the energy transition

Intense planning allows existing fossil-fuel infrastructure, such as refineries and pipelines, to be phased out or repurposed.[14] The energy sector becomes somewhat decentralised, with advancing technology allowing smaller-scale production facilities (e.g. local solar and wind farms) to become viable options for communities.[15]

25-year horizon:

Renewable energy comes of age

Over 80 per cent of global energy comes from renewable sources. This reduces emissions fast enough to approach IPCC targets on climate change by 2050. The planet finally nears "net zero" CO_2 emissions.

3.1.3 Advanced materials

The elimination of global CO_2 emissions will require significant advances in the discovery and design of advanced materials that serve as the basis behind many decarbonisation technologies. Success in this regard will improve the practicality of the global implementation of many important technologies such as those related to clean energy production, carbon capture and utilisation, and energy storage. Moreover, scientists are working to provide new materials that can passively extract CO_2 from exhaust gas at power plants as well as ambient air, and others are actively designing new catalysts that might enable the efficient reuse of CO_2 after its collection for the production of synthetic fuels.

Despite all the effort, the rate at which advanced materials are being discovered, assessed, and actively implemented into decarbonisation technologies remains too slow. As things stand, applying the most mature capture technology to a coal-fired power plant would slash the net output of the facility by an estimated 30 per cent.[16] Moreover, all too often, when a new material is successfully made in the lab, there are few guarantees, that it can be subsequently used for the application that motivated its development. Thus, research aimed at the discovery of new advanced materials that can reduce the aforementioned cost of the carbon capture process is now making use of cutting-edge computer methods to screen, in silico, hundreds of thousands of materials that might make the separation process more efficient, before physically testing the best candidates.[17] This type of approach to the design of advanced materials enables scientists to screen hypothetical and existing materials, identify those with the highest potential for a given application, propose possible synthetic pathway to expedite the discovery process, and assess the CO_2 footprint and environmental impact of its implementation in a given decarbonisation technology on large scales.

5-year horizon:

Solar shines brighter

Continued development in perovskite solar technology continues to push the efficiency of solar cells, making them increasingly commercially attractive.

10-year horizon:

Towards a “Genome Project” for advanced materials

Breakthroughs in machine learning and high-powered computing accelerate the discovery of new advanced materials and hence their deployment in real-world applications. This in turn accelerates and unleashes innovations in technologies required for DAC and the conversation of CO_2 into synthetic fuels as well as many other decarbonisation technologies.[18]

25-year horizon:

Decarbonisation efforts accelerate

New advanced materials dramatically reduce the energy required for DAC allowing gigatons of carbon to be removed from the atmosphere every year. Breakthroughs in other classes of materials also spur massive improvements in battery performance that can help reduce their cost and promote an even greater penetration of renewables into the grid. Science is pushing towards the development of machine-run laboratories that are responsible for designing, making, assessing, scaling, and manufacturing the materials (also their corresponding devices and processes) that are required for decarbonisation technologies.

3.1.4 Energy storage

With the development of renewable energy sources, such as solar and wind, energy storage technologies must also grow in parallel. When the wind drops, or clouds move in, electricity is still needed. Thus, technologies such as batteries and stored hydrogen (from electrolysis, for example) are needed to enable energy storage when an excess is generated and hence help balance the system during times of limited to no energy production. Utility-scale storage capacity ranges from several megawatt-hours into the hundreds, with lithium-ion batteries being by far the most well-developed battery technology. However, upfront costs for utility-scale storage remains a barrier in the market, despite the steady decrease in the price of battery technologies. To facilitate the rapid scale-up that a decarbonising world requires, governments could help close this “viability gap” using subsidies and policy incentives — an approach successfully applied during the development of solar and wind technology. Chemical pathways — such as using renewable energy to produce synthetic fuels — are also an important technology for energy storage.

5-year horizon:

Money into power

Investments in utility-scale battery capacity sees record growth. There is increasing accessibility of the technology and more supportive governmental policies that help batteries seal their key role in the global transition to low-carbon economies.

10-year horizon:

Aggressive cuts to CO_2 lead to leap in installed renewable capacity

The European Union doubles its current installed capacity of renewables. This push, and similar initiatives around the world, results in installed utility-scale battery capacity increasing around four-fold from the 2020 level.

25-year horizon:

Energy storage diversifies

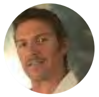
The explosive growth in renewable sources has propelled wide-spread developments in energy storage. Optimal energy storage depends on national resources and local factors, and how the power is to be used — for homes, infrastructure or industry, for example. As a result, developments are occurring not only in batteries, but also in mechanically pumped-hydro and superconducting magnetic energy storage systems.[19]

3.2 World Simulation

Humans exist embedded in complex "social-ecological systems" that are composed of interconnected physical, biological, and socio-economic systems. Understanding social-ecological systems (SESs) relies on integrating knowledge of the underlying disciplines, and the way that they interrelate. Holistic transdisciplinary understanding is vital to addressing the grand challenges and "wicked problems" facing society in the 21st century, such as those related to climate change, growth in the human population and disruptions to the global economy. Yet society lacks the capacity to measure and predict the relevant interconnections that would facilitate evidence-based policymaking and resource management, whether in urban planning or nature conservation.

However, this is now becooming possible through our increasing ability to integrate a wide variety of data and models into "world simulations" that leverage global networks of environmental sensors and ever-growing computing power. The ultimate ambition is an integrated planetary avatar that spans physical, biological, social and economic dimensions from local to global scales. As decision-support tools, the progenitors of such a system will model potential scenarios, helping us to safely navigate the Anthropocene; this unprecedented "social-ecological foresight" will serve society to protect and sustain our civilisation and the planet.

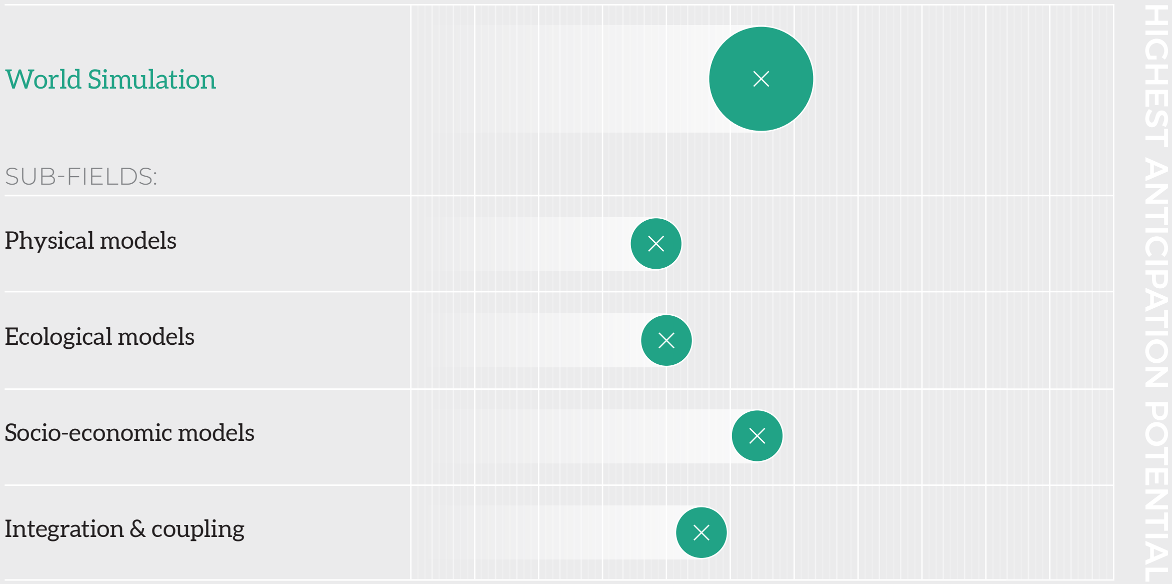
By developing such avatars and sharing data, these tools will one day allow not only government entities but also civil society — corporations, NGOs, and citizen groups — to explore alternative scenarios for the future of their region, and lead to better informed decision making.



Neil Davies
Director, University of California's Gump South Pacific Research Station on Moorea (French Polynesia); Research Affiliate, Berkeley Institute for Data Science; Vice President, Tetiaroa Society, USA

Anticipation Potential

EMERGING TOPIC:



SURVEY OBSERVATIONS:

Digital models are already becoming an increasingly popular tool among both scientists and policymakers. Physical models have the highest potential for disruption, but the field's relative maturity has lowered anticipation scores. Socioeconomic models and progress in the integration and coupling of different types of models were deemed to be around 12 years from maturity and in need of collaborative, interdisciplinary research, suggesting they would benefit from particular focus in the coming years.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

An early report by Young et al. surveyed the prospects of Socio-Ecological Systems and proposed the expansion of this field to cover the impacts of "mega-trends".[1] More recently, work by the IDEA Consortium[2] and Enders and Hoßbach[3] have provided detailed analyses of progress.

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 Physical models

Predicting the future state of the physical world under the influence of human activities includes sensing and modelling of weather and climate, ocean flows, terrestrial hydrology and erosion. Global climate models, seismological models and sea-ice models, for example, already draw on a vast web of physical-chemical observational and socio-economic data, giving us an unprecedented capacity to predict future states of land, sea, and air. The development of cheaper and improved sensors, increased availability of autonomous research craft, including underwater vehicles, and remote sensing from space will lead to an explosion of available data.

But we are just getting started — our data-driven physical models of Earth's systems are set to grow ever more refined. Consider, for example, Destination Earth (DestinE), a major initiative of the European Commission.[4] Its ambitious aim is to create “a digital twin of planet Earth that would simulate the atmosphere, ocean, ice, and land with unrivalled precision, providing forecasts of floods, droughts, and fires from days to years in advance.”[5]

5-year horizon:

High-resolution modelling enables urban weather simulations

Physical modelling is already an advanced science, utilising models at a planetary scale. But high-resolution refinements are on the horizon, initially for densely populated areas, including micro-climate weather simulations in urban areas. Global ocean flows are routinely modelled as part of climate models and can be coupled to increasingly accurate models of local scales and near-shore circulation patterns, including physical and chemical water properties, which are particularly complex, and important, for coastal ecosystems.

10-year horizon:

Abundant contextualised data becomes available

High-resolution models for physical processes, initially demonstrated for select locations, become both more accurate and more widely available. This is driven by increased availability of computational resources, but more importantly, by increased availability of well-contextualized FAIR data. That is, data which meet principles of Findability, Accessibility, Interoperability, and Reusability. As these FAIR data become linked to downstream use and reuse, value is unleashed throughout the data lifecycle, accelerating the deployment of machine learning.[6]

25-year horizon:

Accurate simulations extended to remote populations

The availability, spatial and temporal resolution of data continues to improve, with geostationary and stratospheric platforms for recording of high-frequency processes able to investigate even remote areas of the planet with high fidelity. Computing capabilities and modelling improves for even more accurate predictions at finer scales that will now be rolled out also to remote and less densely populated areas.

3.2.2 Ecological models

For understandable and entirely valid reasons, research has focussed on harvesting colossal amounts of observational physical data to feed into our climate models. The "biological layer" of our planet, however, remains under-sensed and less adequately modelled. For example, our observations of soils, their dynamism and the interactions of their microorganisms, are in many respects low-resolution.[7] Ecological modelling, the attempt to understand interactions and feedback mechanisms that shape ecosystems at a variety of scales, requires a full range of biological sensing platforms that have not yet been fully developed and deployed.

This situation is beginning to change. Advances in sensor technology (biological observations through molecular/genomic, acoustic, and imaging platforms) and computing power mean that ecological models are poised for rapid progress. These models start with scientifically tractable island ecosystems. The Island Digital Ecosystem Avatars (IDEA) Consortium is creating such a model for the intensively studied island of Mo'orea in French Polynesia, simulating links and feedbacks between climate, biodiversity, environment, and human activities across land and sea.[8] As improved models for the more complex biological world are built, they will become possible for more places and at ever larger scales. While ecological simulations (avatars) will never have the predictive power possible for physical systems, machines or the built environment (twins), they will provide valuable guidance, helping society evaluate likely opportunities and risks.

5-year horizon:

Developers create new sensing platforms

Technologies to measure additional key genetic, population, community and ecosystem attributes are developed or refined, and multi-scale sensing platforms begin to be deployed to produce a nascent, interconnected global network of biological observatories, expanding on the set of existing scientific field sites and sensor platforms — such as the International Long-term Ecological Research Network — that already are beginning to span from local to regional to ocean basin scales.[9]

10-year horizon:

We begin to predict ecosystem feedbacks

Fueled by data streams from the maturing global observatory network, advanced dynamic ecological models emerge that adequately predict ecosystem feedbacks, enabling the forecast of rippling effects through ecosystems. Quantitative 'risk management' tools will be developed for predicting ecosystem vulnerabilities and identifying tipping points and state transitions to inform sustainability policy.

25-year horizon:

Global observing systems come online

The integration of marine and terrestrial platforms into truly global observing systems is achieved. Ecological observations and models fully incorporated into digital avatars ranging in complexity and spatial scale that can be used for scenario modelling that powerfully supports policy- and decision-making.

3.2.3 Socio-economic models

By 2050, nearly 70 per cent of the world's anticipated 10 billion people will live in urban areas.[10] That is roughly equivalent to all the people alive today, so the governance of cities must maintain a sharp focus on environmental, social, and economic sustainability as they grow.

To date, much of the progress in the socio-economic domain has focussed on models of financial-market dynamics and the potential for creating "smart cities". A smart city is an urban area that uses extensive information and communication technologies to collect data from its citizens, buildings, roads and other infrastructure to monitor and optimise the management of a wide range of public services, systems and resources. Increasingly, "digital urban twins" are being developed to model, among others, the effect of climate change on the urban environment and test policies and actions to cool cities.

Modelling citizens' socioeconomic behaviour, and the evolving nature of the urban areas themselves, will also support initiatives to increase regional self-sufficiency (including in food supply and energy generation), boost the circular economy and optimise local traffic and mobility systems. Smart coordination is increasingly important — and possible — when so many people live in close proximity.

5-year horizon:

Large city models improve quality of life

Integrated models for places as large as Zurich, Singapore and Manhattan, begin to include simulation of city microclimates, including temperature, humidity and airflow. They allow the anticipation of the effect of architecture, urban design and planning on outdoor thermal comfort, promoting the design of more "liveable", cooler cities with lower energy needs and reduced carbon impact.

10-year horizon:

Digital twins of cities allow smart urban re-development

After successful deployment in select locations, digital twins are rolled out more broadly using agile data science and modelling platforms. They are used to plan new developments in rapidly growing cities and for the re-building of existing cities. Machine learning and data science optimise mixed-use city planning, traffic flows, local circular economies and renewable energy production for better quality of life. Smart cities, using digital twin technology, evolve into responsive cities, able to reconfigure their services and resources on the fly to account for the movement of people across the city, local weather conditions, or emergency scenarios.

25-year horizon:

Simulations alter the way we live

Digital twins become ubiquitous tools for urban and economic planning, expanding from cities to regions, and heading towards modelling the entire built environment. Thanks to foresight enabled through simulations, cities and their hinterland evolve into new types of settlement in which mixed-use renewable energy and food production fulfil about 70 per cent of the local population's needs. Transportation infrastructures are emission-free, but altered living-working environments and improved work-from-home technology mean that commuting is drastically reduced anyway.

3.2.4 Integration & coupling

If researchers are to create simulations that help inform decisions aiming to improve quality of life across the globe, they will need to not only generate models, or digital avatars, that reveal the key workings of socio-ecological systems (SES), they will also need to combine them in order to expose the feedback mechanisms that operate in the real world. This will allow us to pursue strategies more likely to protect and enhance those systems — be they fisheries, cities, countries, islands, oceans, or the entire planet.

This is clearly a huge challenge. Myriad feedback loops link the physical, ecological and socioeconomic worlds, so developing a digital simulation for an SES of interest requires the widespread coupling and integration of physical, ecological and socio-economic models, combined with cutting edge data science. However, urban digital twins — virtual replicas, updated in near-real time and primarily used for urban planning and smart city applications — offer a glimpse of what can be achieved when models are integrated. In Singapore, for example, extensive data on traffic volume and pedestrian activity are sent to the relevant government agencies for analysis and to coordinate services. In addition, National Research Foundation Singapore is creating Virtual Singapore, a dynamic 3D city model and collaborative data platform that will be made widely available to users from different sectors to develop and test new tools and services, and optimise planning and decision-making as Singapore evolves.[11]

The integration of these sorts of models with larger-scale SESs, including more aspects of nature, is a significant challenge in terms of international collaboration, but vital if we are to address the realities of life in the 21st century. The future well-being of humanity depends on regenerative rather than extractive systems and collaboration with nature, rather than domination over her.

5-year horizon:

First social-ecological avatars emerge

Coupled social-ecological avatars are created for a few places that are especially tractable and subject to intense, ongoing scientific research, such as oceanic islands. The Island Digital Ecosystem Avatars (IDEA) Consortium, mentioned above, for example, has now extended to other islands in Polynesia through the 4Site: Pacific Transect Collaborative, as well as coastal and island communities in Europe.[12]

10-year horizon:

Simulations anticipate effects of sea-level rise on coastal societies

Research efforts link observing systems and data archives across scientific disciplines and geographic regions, enabling social-ecological avatars to model the effects of climate change, such as sea-level rise, on island and coastal systems. Digital twins of urban areas are integrated into wider socio-ecological avatars, revealing how individual human behaviour scales up to system-level consequences and providing timely feedback on our socio-economic decisions.

25-year horizon:

World-wide simulations guide global decision-making

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 to guide inclusive and equitable decision-making at levels of governance appropriate to the scales of the processes they seek to influence.

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.

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Anticipation Potential

EMERGING TOPIC:

Future Food Systems

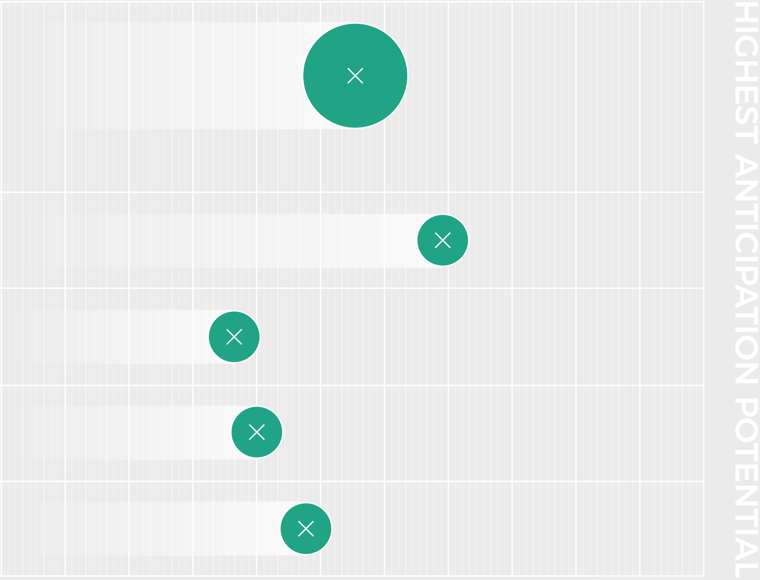
SUB-FIELDS:

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:

There are a number of extensive, well-researched overviews investigating the future of our food systems. The IPCC, for instance, included food security in its 2019 report "Climate Change and Land".[1]

In 2020, the Global Panel on Agriculture for Food Systems and Nutrition issued "Future Food Systems: For people, our planet, and prosperity", which lays out an extensive analysis of the issues for policymakers.[2]

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services issued a "Global Assessment Report on Biodiversity and Ecosystem Services" in 2019.[3] More recently, the International Panel of Experts on Sustainable Food Systems (iPES Food) published a report on ways to transform food systems by 2045.[4]

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/r3-3

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.

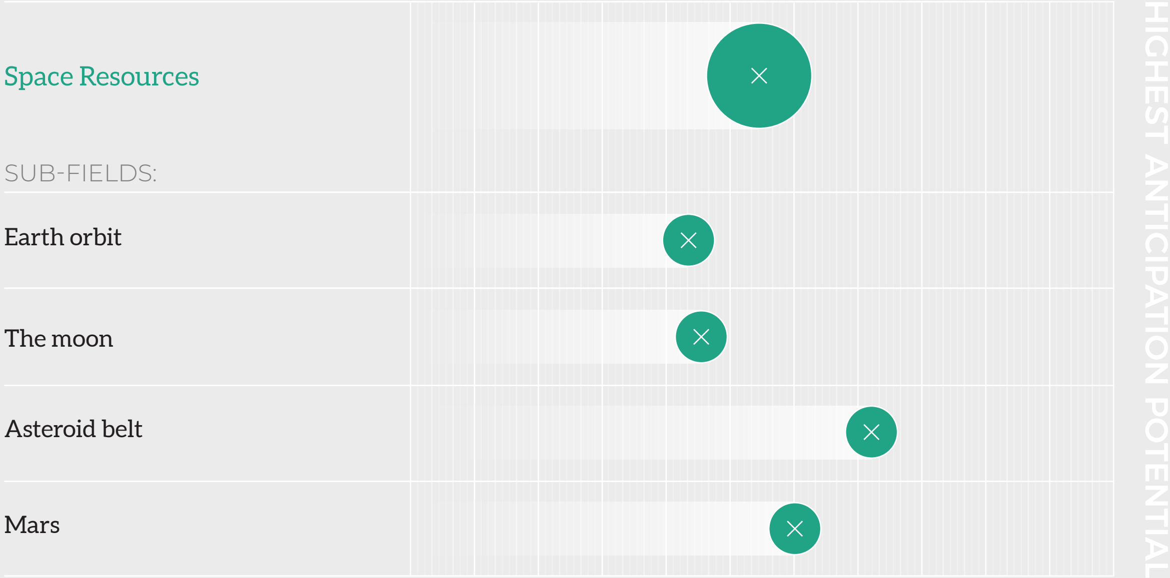
Important questions remain over the legal rights we have to exploit areas beyond Earth, how we should govern our behaviour in space and to what extent we should preserve what we find for the future. These questions are already being tackled in countries like the United States, which in 2015 became the 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:



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:

The European Space Agency recently published its "Voyage 2050" recommendations for future mission themes[1], focusing on the moons of the giant planets, potentially habitable exoplanets and better understanding the origin of the universe.[7]

The US National Academies surveyed space science priorities in its "Planetary Science and Astrobiology Decadal Survey 2023-2032".[8] NASA has considerable investment in human spaceflight with its Artemis programme expected to return humans on the moon within the next few years.[2,9]

In 2016, China set out its ambitions in space in an English-language white paper and has outlined its next five-year plan with the details expected later in 2021.[10,11] The United Nations Office of Outer Space Affairs explored the nature of space-related commerce in its "Space Economy Initiative 2020 Outcome Report".[12]

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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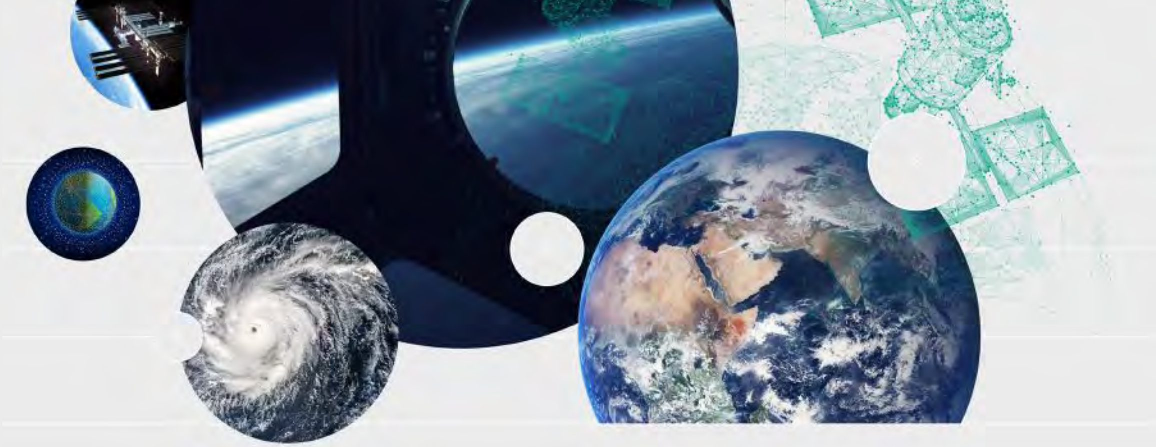


3.4.1 Earth orbit

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.

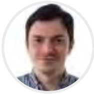
3.5

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]



Robert Blasiak
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.

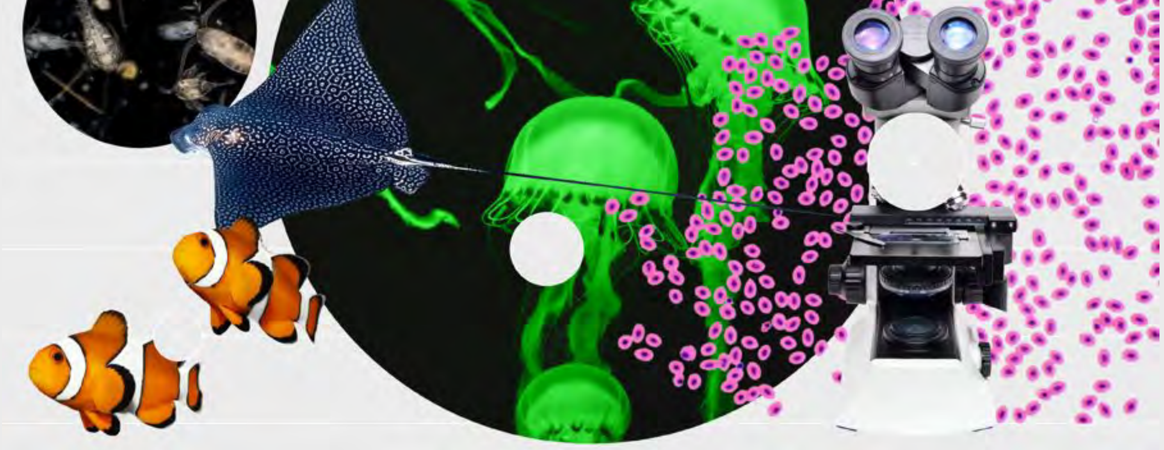
SELECTION OF GESDA BEST READS AND KEY REPORTS:

The 2020 report on the Ocean Genome from Blasiak et al is a result of efforts to help meet United Nations Sustainable Development Goals, and describes the state of understanding associated with equitable and sustainable use of the ocean's genetic resources in order to assist policymaking.[4] It has also been used as the basis for a scientific review paper.[5]

In 2019, Levin et al reported on the urgent need for ocean observation at depths greater than 200m.[6] Also in 2019, Rabone et al surveyed best-practice examples associated with the genetic resources found in marine biodiversity in areas beyond national jurisdiction.[7]

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

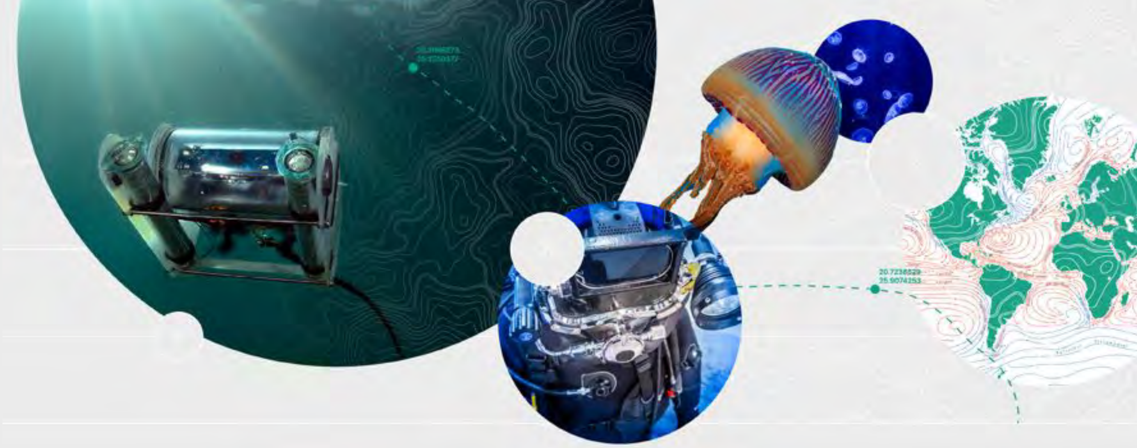
Improved monitoring, use of genomic technologies and other innovations result in a step-change in scientific understanding of ocean habitats and basins and their connectivity, which helps to explain the relationship between human activity and what happens in our deepest waters, informing policy-making. 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.

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Professor at the Center for Atmospheric and Oceanic Sciences Indian Institute of Science

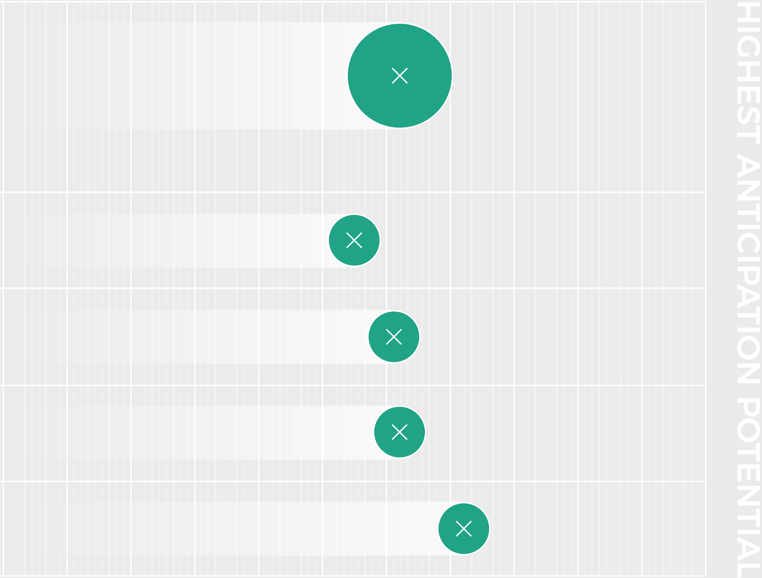
Anticipation Potential

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:

The 2022 IPCC report provides the most comprehensive summary of current climate change.[6] The US National Research Councils' Committee's report on Geoengineering Climate in 2015 focuses on the potential of geoengineering solutions.[7]
In June 2020, the EPFL International Risk Governance Center released a study drawing together relevant information and recommendations.[8] A 2018 report in Nature Communications provides a useful perspective.[9]

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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3.6.1 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.

Astronaut photograph ISS059-E-36734 . Image credit: Earth Science and Remote Sensing Unit, NASA Johnson Space Center, and NASA Earth Observatory.

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:

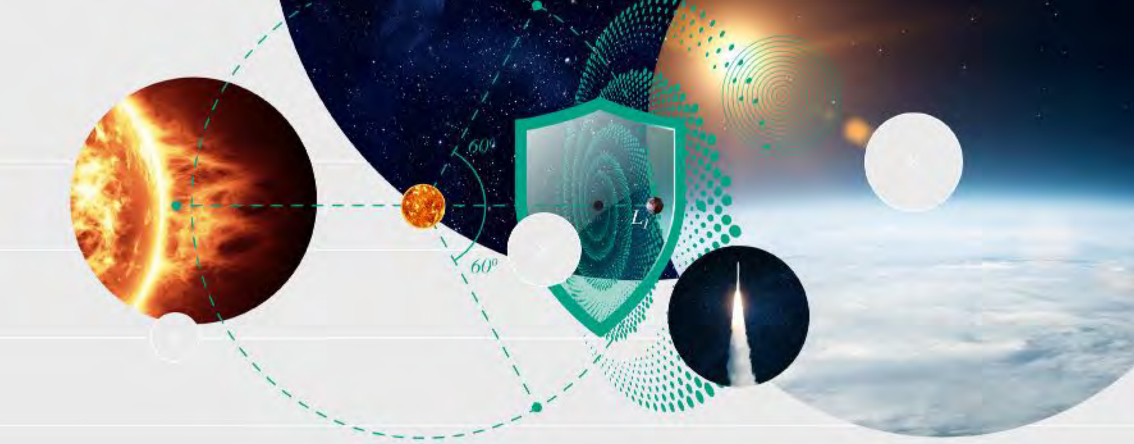
Building codes embrace albedo brightening

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
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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 2015, The Lancet published a set of policy responses discussing how to protect public health in an era of climate change.[5] In 2022, Carlson et al provided evidence of climate change's effects on cross-species viral transmission.[6] Lerner and Berg provided a useful comparison of One Health, EcoHealth and Planetary Health in 2017,[7] and the One Health High-Level Expert Panel published a new definition of One Health in 2022.[8] A useful set of studies of global parasite diversity was published in 2021,[9] and a 2020 overview of the history of disease vector mitigation argued for a return to a more thorough, evidence-based approach.[10]

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.

Rasmus Gjedssø Bertelsen
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Invited Contribution: Polar Resources

There is a long-standing misconception that the Arctic is somehow above international relations. However, what goes on at the top of the world has always reflected competition between great powers. As we enter a new period of geopolitical upheaval, there is every reason to believe that we might soon witness new and dramatic impacts on science, natural resources and the environment in this crucial region.

Recent decades have seen relative stability in the relations between the eight countries with territory in the Arctic Circle. But this is an historical anomaly, thanks largely to the unipolar world that arose following the end of the Cold War. American hegemony helped galvanise co-operation between the USA, Canada, Russia and the five Nordic countries in areas like science, human security and exploitation of natural resources.

The USA has devoted considerable effort to maintaining this status quo in the face of a rising China, putting pressure on allies to keep Chinese investment and scientists out of the parts of the Arctic controlled by allies. Russia, which has long preferred a multipolar world with a more balanced relationship between itself and the other great powers, sought balanced relationships with the West and China.

Unfortunately, the rapid deterioration in relations between Russia and the West over the war in Ukraine promises to upend co-operation in the Arctic. As the two sides decouple — both economically and politically — it seems worryingly likely that we will see division arise in Arctic investment, trade, and scientific co-operation.

The first casualty of this process will be the Arctic Council, the intergovernmental forum that mediates between the eight nations with interests in the region. Russia remains chair of the organisation until Spring 2023, but the other seven member states have frozen collaboration with Russia as chair and resumed cooperation without Russia. It seems unlikely that Russia will continue to attend as an ordinary member once it hands over the baton to Norway.

The loss of one member out of eight may not sound like a death knell for the Arctic Council. However, the Russian territory makes up nearly half of the Arctic — and it is the more valuable half, containing rich deposits of oil, gas and minerals as well as the critical Northeast Passage shipping route, which connects the Atlantic and Pacific oceans. The raising of a new Iron Curtain between Russian and Western Arctic territories could therefore lead to a cascade of negative outcomes.

One of the most obvious impacts will be on the exploitation of polar resources. Russia's north has enormous oil and gas reserves, but also contains huge deposits of valuable minerals. Europe has long been highly reliant on Russian fossil fuels; but even now, as Western economies transition to renewable energy, many of the key minerals required to make batteries and other green technologies are still sourced from Russia.

A breakdown in economic ties between the two sides could therefore lead to a major change in Western attitudes towards Polar resources. The West has so far been keen to avoid mining and drilling for fossil fuels, which is a dirty business with many adverse impacts for the environment and local communities. But loss of access to Russian resources could create increasing pressure to exploit similar deposits in Scandinavia, Greenland and the Canadian High Arctic.

The situation is further complicated by new Western sanctions, imposed after Russia's invasion of Ukraine. They are putting Russia under enormous economic stress, and are likely to force an expansion in efforts to tap whatever natural resources it can, potentially leading to increasing industrialisation of its Arctic territory. The same sanctions limit co-operation with Western companies, which currently have the most advanced technology and management practices in terms of human health and environmental standards. Russia's ramped-up exploitation of the Arctic is therefore likely to be a potentially more dirty and dangerous affair.

As a result of all this, we could be about to see a dramatic acceleration in the exploitation of Polar resources and a qualitative shift in Western attitudes towards the Arctic region. What is more, an equally worrying breakdown in scientific dialogue between the two sides will make it increasingly difficult to understand the impact of these shifts.

Norwegian government regulations permit interpersonal contact with Russian academics, but institutional contact is forbidden. While highly disruptive, this still allows room for a very limited amount of dialogue between social scientists such as myself and my Russian counterparts, but not highly qualified discussions with key foreign and security policy bodies. For those working in the natural sciences, continued collaboration is impossible as they need access to data, instruments and terrain, which are all mediated through institutions.

The result is that Western Arctic science has lost access to half of the terrain it purports to study. While remote sensing from satellites can fill some of the gaps, the value of the data collected is greatly diminished by scientists' inability to visit regions under study to calibrate instruments. Given the central position of the Arctic in efforts to understand and prevent climate change — not least the vast amount of methane that could be released by the melting of the Siberian permafrost — this could lead to significant gaps in the evidence we use to set sensible environmental policy.

These issues are highlighting both the importance of science diplomacy and its inherent fragility. While science has often been seen as a way to bridge political divides, recent events have shown that politics can also create scientific divides. And it is important to remember that the current impetus to sever intellectual ties is coming from Western governments.

It seems to be a Western trait to eschew attempting to understanding an adversary because it might be seen as sympathising with them. There is also a tendency to imagine that communication with an adversary should only happen if and when they exhibit good, co-operative behaviour. This is a short-sighted approach. I have seen first-hand, in discussions about Arctic security, what happens when Russian and Chinese voices are shut out. Homogenous forums quickly succumb to groupthink, confirmation bias and fear of standing out, which leads to less qualified analyses and decisions. We need diversity of opinions if we are to do our best work.

Cultivating intellectual ties is a long-term process and the connections young academics make today may not bear fruit for 10 or 20 years. If we want people who can help bridge the divide between different cultures when it matters most, we need to do that homework today. Given the critical place the Arctic will play in all of our futures, that's something we should commit to.

Anders Meibom
Professor at the Laboratory for Biological Chemistry EPFL

Invited Contribution: Coral and Ocean Renewal

Coral reefs are in free-fall around the world. This year, for instance, the Great Barrier Reef in Australia — the world's largest and most iconic coral ecosystem — saw more than 90 percent of its reefs bleach.

Bleaching occurs when corals expel the symbiotic photosynthetic algae that they rely on for food, often in response to environmental stress such as abnormal elevated temperatures. Reefs can recover from bleaching events, but the process is uncertain and can take years — frequently corals die from bleaching on a massive scale.

Such events are becoming worryingly common as climate change causes rapid warming and increasing ocean acidification. From a biodiversity perspective this is a disaster, because although they only account for a very small area of the ocean, coral reefs host an enormous amount of biomass and a dazzling array of species.

It is therefore not just a question of losing some interesting and colourful corals. The corals are the base of many critical ocean ecosystems, and when they die the whole system they support comes tumbling down. This can lead to rapid declines in fish stocks and major losses for tourism activities related to the reefs; around the world, hundreds of millions of people depend upon these ecosystems.

The losses are happening very fast. By the middle of this century coral reefs are expected to shrink to just ten percent of their pre-industrial extent. This is an ecological catastrophe, but there is a glimmer of hope: recent breakthroughs in both science and diplomacy suggest we may be able to create a refuge for these critical ocean ecosystems.

One cause for optimism stems from scientific discoveries in the Red Sea. Pioneering research by Professor Maoz Fine from the Hebrew University in Israel found that corals in the Gulf of Aqaba, which is bordered by Egypt, Israel, Jordan and Saudi Arabia, are remarkably resistant to heat stress. The region is heating twice as fast as global averages, but has not yet experienced any major bleaching events. We now know, from exhaustive experimentation, that the corals of the Gulf of Aqaba can tolerate as much as five degrees of warming above their summer maximum, far in excess of even the most pessimistic climate predictions.

These projections were made possible by projects such as the Red Sea Simulator, a large system of experimental aquaria in which researchers can control any environmental parameter they choose, including temperature, salinity, pH and pollution levels. A suite of sensors and measurements also permits monitoring of the corals' health, photosynthetic performance, protein content, oxidative stress and even how the genes they express change in response to rising temperatures.

The Transnational Red Sea Centre (TRSC), a scientific organisation based at EPFL, builds on Professor Fine's groundbreaking work. Our goal is to coordinate research efforts and help preserve one of the world's major reef ecosystems. The first step will be to establish the biodiversity baseline of the Red Sea's coral reefs: from 2022 to 2025 we will be carrying out expeditions across 4,500 km of coastline of the Red Sea system.

Beyond that, it will be crucial to give governments and scientists in the region the capacity to continually monitor their reefs. To that end, we are creating a monitoring system that combines low-cost GoPro cameras with machine learning-based video analysis. This will assess coral cover, what genera are present, whether they are healthy, and the presence of plastic and pollution.

Sophisticated sensors will help us monitor the photosynthetic performance of their algae, which is a key indicator of stress. Furthermore, we are developing new seascape genomics techniques that will help us determine the regions of the reefs that are best adapted to warmer climates and responsible for seeding the rest of the reef with heat-tolerant coral.

This is not science for science's sake: all of our efforts are directed towards gathering the information that will be required to preserve these reefs into the future. That is why we have committed to Open Science principles and make all of our data freely accessible. More importantly, we are actively translating this data into common formats that anyone can access and use for further analysis.

However, none of this will be of any use unless we can motivate the governments and the communities in the region to act on our findings. That is why our mission is as much one of diplomacy as it is of science. Our efforts will only succeed with regional-scale collaboration; if just one country in the area doesn't follow agreed protocols, the reefs of the entire region could be put at risk.

Nonetheless, we are optimistic. Promoting collaboration in this geopolitically complicated region is undoubtedly one of our biggest challenges. But in many ways, science can be an avenue for dialogue that would be impossible elsewhere. For once, everyone's interests are aligned and there is a common understanding of what we will lose unless the countries in the region work together. As such, our project is not only an experiment in how to save coral reefs, but also a demonstration of how science can help find ways out of political impasse.

Whether our project provides hope for coral reefs elsewhere in the world remains to be seen. Experiments into assisted evolution, where scientists attempt to "encourage" corals to develop greater tolerance for a warming world, will no doubt have much to learn from the corals of the Red Sea. Personally, I am not convinced that this approach will provide solutions fast enough to deal with the rapid changes our oceans are experiencing.

Perhaps more important will be the impact of the model that we develop at the TRSC. The Coral Triangle, which spans more than 6 million km^2 of tropical waters around Indonesia, Malaysia, Papua New Guinea, the Philippines, the Solomon Islands and Timor-Leste, faces different but comparable challenges in terms of both science and diplomacy. In this region the corals have enormous genetic diversity, and while they do not exhibit the exceptional heat-tolerance of corals in the Red Sea, any help this region can get to prolong their life-time and perhaps save their reefs could be enormously important.

4

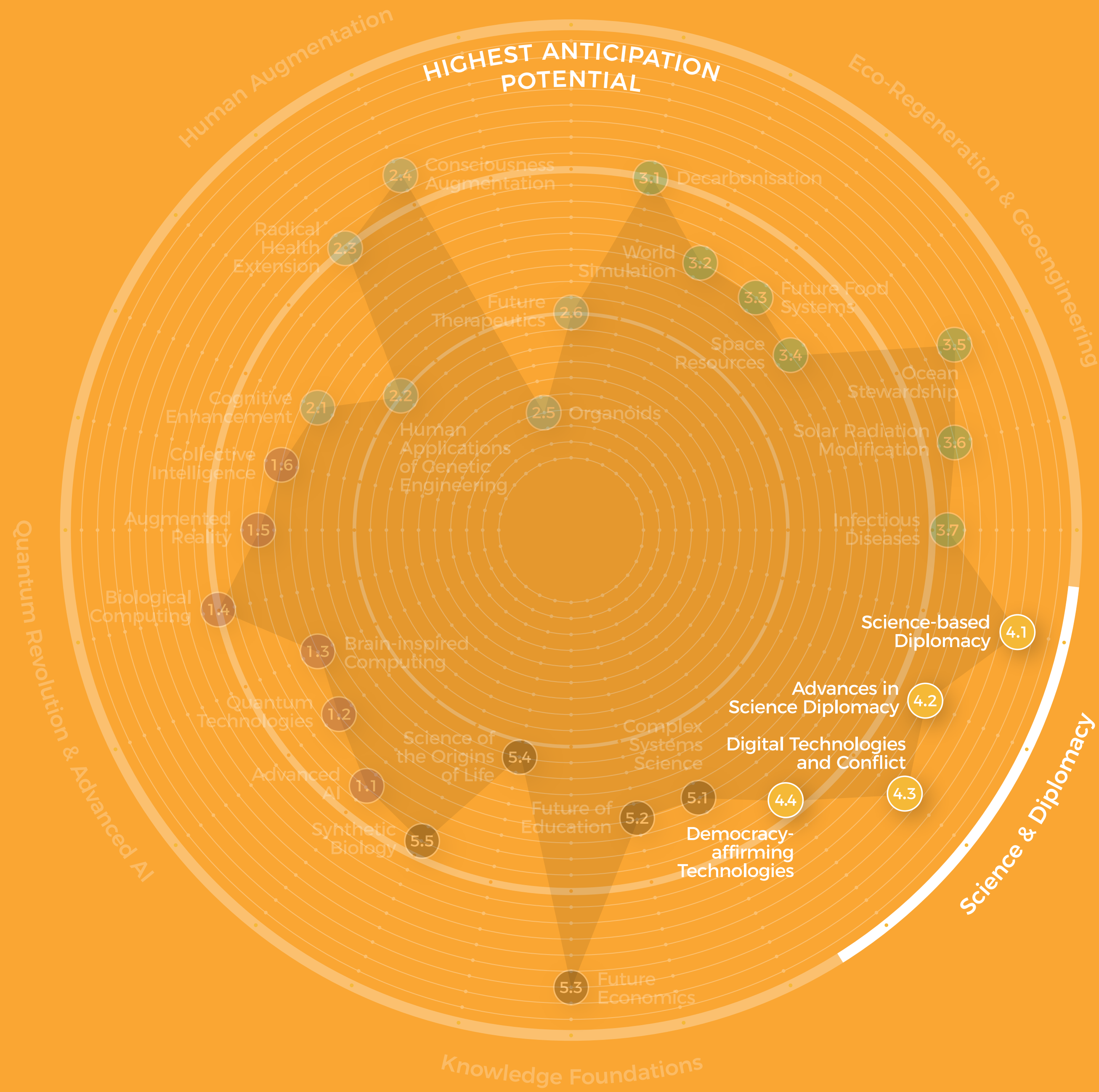
Introduction to Science & Diplomacy

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 creators of wealth creation. These advanced technologies are now becoming part of the currency of international negotiation and diplomacy, an effort that will be ever-more vital in the 21st century. **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 and from non-governmental organisations. Big science projects themselves are becoming increasingly part of this landscape. Together these groups must find ways to manage the global commons fairly and effectively.

The increasing power and availability of digital technologies is fundamentally changing the nature of conflict in the 21st Century and the interactions of **digital technology and conflict** are an urgent subject of research. The war in Ukraine, for example, is being hailed as the first "hybrid war", a concept long talked about in policy circles in which conventional battlefield tactics are combined with cyber-attacks and information warfare to achieve military goals. Perhaps the most impactful use of digital technology in the Ukraine conflict has been the exploitation of commercial satellite imagery for military and propaganda purposes by both state and non-state actors. Surveillance technology is also rewriting the nature of modern conflicts, and there is growing concern is the increasing convergence between biosecurity and cybersecurity.

Much has been written about the potential of technologies like social media and data analytics to spread disinformation and polarise society, thus weakening democracy, but there is now a countervailing movement. A Summit for Democracy hosted by the US in December 2021 highlighted these threats; in an attempt to counter them, the White House Office of Science and Technology announced a new grand challenge competition designed to spur the development of **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
Quantum Revolution & Advanced AI
Knowledge Foundations
Science & Diplomacy
2.4 Consciousness Augmentation
3.1 Decarbonisation
Radical Health Extension 2.3
World Simulation 3.2
3.3 Future Food Systems
Future Therapeutics 2.6
Space Resources 3.4
3.5 Ocean Stewardship
Cognitive Enhancement 2.1
2.2 Human Applications of Genetic Engineering
2.5 Organoids
Solar Radiation Modification 3.6
Collective Intelligence 1.6
Augmented Reality 1.5
Infectious Diseases 3.7
Biological Computing 1.4
1.3 Brain-inspired Computing
Science-based Diplomacy 4.1
Advances in Science Diplomacy 4.2
Quantum Technologies 1.2
Science of the Origins of Life 5.4
Complex Systems Science
Digital Technologies and Conflict
Advanced AI 1.1
5.1
4.4
4.3
Future of Education 5.2
Synthetic Biology 5.5
Democracy-affirming Technologies
5.3 Future Economics

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.

Nicolas Levrat
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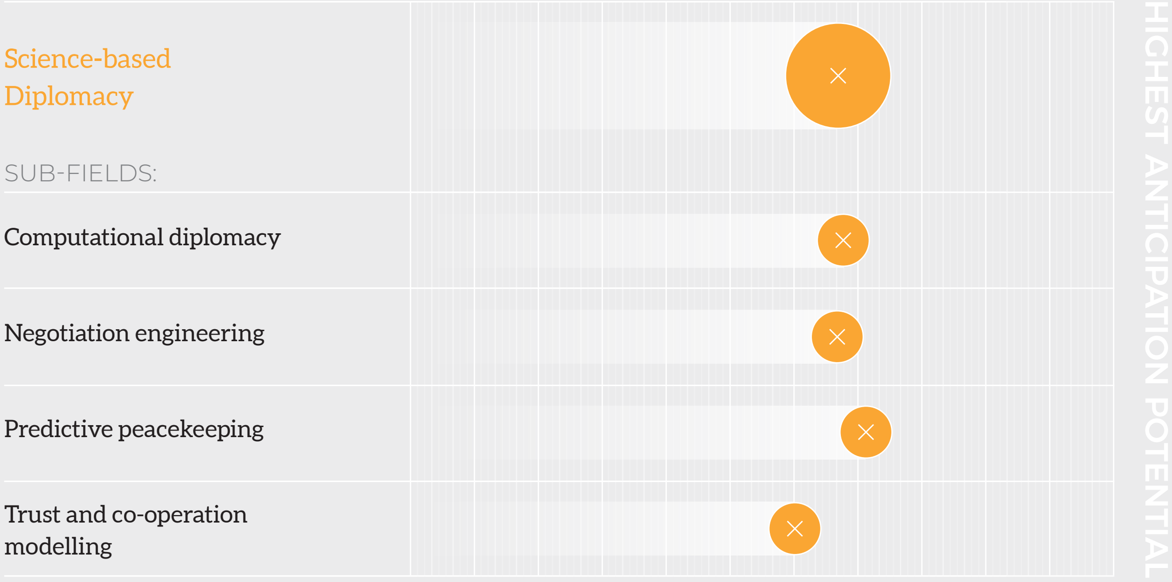
Michael Ambühl
Professor at the Chair of Negotiation and Conflict Management at ETH Zurich

Anticipation Potential

EMERGING TOPIC:



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 2018, the Royal Institute of International Affairs at Chatham House published a report: "Artificial Intelligence and International Affairs: Disruption Anticipated".[1] This examines some of the challenges that AI may bring for policymakers in the area of diplomacy.

The Emirates Diplomatic Academy's "Diplomacy in the Age of Artificial Intelligence" investigates similar issues.[2] The role of computational diplomacy and its evolution in recent years is covered in "Computational Diplomacy: Foreign Policy Communication in the Age of Algorithms and Automation".[3]

An overview of Negotiation Engineering is given in "Negotiation Engineering: Why Quantitative Thinking Can Also be Useful in Negotiations".[4] "Computational trust and reputation models for open multi-agent systems: a review"[5] provides some of the technical basis for models of this kind.

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 in particular has highlighted the role of science on the international stage, how it rapidly advanced novel vaccine technologies, and how these vaccines became a crucial part of the currency of international negotiations, diplomacy and geopolitics. The emerging discipline of science diplomacy seeks to establish an evidence-based, anticipatory foundation for this kind of endeavour.

This foundation will support and empower the increasingly diverse set of stakeholders who practice science diplomacy, though there are numerous challenges ahead. One issue is how to train and incorporate these actors at state and non-state levels — these actors will come from government, academia, global companies, grass roots and non-governmental organisations, and so on. These actors are currently in siloed communities that have little reason or incentives to interact, and often speak different "languages" in the sense of the jargon and concepts they rely on. A challenge will be to find ways to bring them together to find a common "worldview" and to train individuals and institutions with the technical multilingualism they need to communicate effectively across boundaries. "Big science" projects are becoming 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.

Marga Gual Soler
World Economic Forum Young Global Leader
Founder SciDipGlobal

Anticipation Potential

EMERGING TOPIC:

Advances in Science Diplomacy

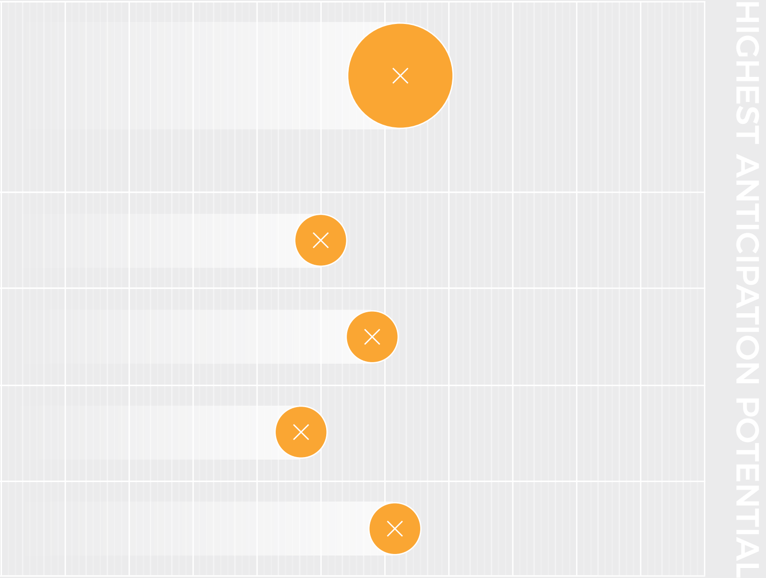
SUB-FIELDS:

Multistakeholder technology diplomacy

Integrating non-state actors

Diplomacy for big science

Managing the global commons



SURVEY OBSERVATIONS:

The importance of diplomacy in science and vice versa is becoming increasingly accepted. Nowhere is this more apparent than in our efforts to better manage our global commons, which was judged to have by far the highest potential for impact of the four topics investigated. Breakthroughs in this area are still some way off, however, with respondents predicting that maturity won't be achieved for another 14 years. Getting there will be a long-term project and will be impossible to achieve without breakthroughs in multi-stakeholder diplomacy, which will require considerably more attention going forward.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Science diplomacy is a relatively new discipline with a broad and multidisciplinary skill set. In 2008, the American Association for the Advancement of Science established a Center for Science Diplomacy as a focal point for discussion, publication and training in this field.[1]

In 2010, AAAS and the UK's Royal Society published the report "New Frontiers in Science Diplomacy", which proposed the first conceptual framework for science diplomacy.[2] The European Union Science Diplomacy Alliance, established in 2021, brings together the members of several research projects on science diplomacy.[3]

In 2018, S4D4C published a useful review of work and approaches in this area,[4] and Timothy Legrande and Diane Stone published "Science diplomacy and transnational governance impact", which presents a research agenda for influencing politics and international studies with science.[5]

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 Multi-stakeholder technology diplomacy

Technology plays a fundamental role in 21st century society, enabling communication, finance, industrial development and much more. But this role requires multistakeholder commitments. It involves numerous actors in society, from policymakers and grassroots campaigners to technology companies and their customers.

These actors often exist in siloed communities. Bringing all these actors together will be increasingly important to map out the future of technology, to set standards and common frameworks and to ensure these technologies embody the societal values we want them to have. A key goal for this kind of diplomacy will be to find ways to balance competition against strategic co-operation. This is important because the potential fragmentation of some of the most important technologies threatens to limit international co-operation and stability.[6] For example, the political conflict over Huawei's 5G infrastructure threatens agreement on standards for 6G and beyond, raising the possibility that China and its allies could take a different technological trajectory in future. The same could happen for gene editing technologies, brain-computer interfaces or climate-altering technologies. Gathering the information and technology nous[4] to tackle these issues and then bringing together the relevant stakeholders to establish global governance frameworks would be key goal for science diplomacy.[7]

5-year horizon:

Potential conflict galvanises action

Fragmentation of certain technology standards such as 6G triggers efforts to bring together the multistakeholder groups required to find solutions.

10-year horizon:

Science diplomacy begins to shape technology platforms

The fruits of multistakeholder technology diplomacy begin to appear in the form of social media platforms that are designed to limit the prevalence of hate messages on topics of race, gender and so on. Ironically, these new technology models increase demand for services that allow anonymous hate messaging.

25-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.

4.2.2 Integrating non-state actors

The key role that science and technology play in our lives and our futures makes a wide range of non-state actors crucial players in this landscape. For example, technology companies determine how we communicate and increasingly how these communications should be censored.

Pharmaceutical companies decide which diseases to pursue for drug development, while grass-roots organisations such as pressure groups can have a powerful effect on public opinion. And regional and city actors play an increasingly important role in many negotiations.[8] Bringing these non-state actors together in a way that gives them an effective voice will be a key part of the process for finding solutions.[9] This new generation of actors will require training with the relevant diplomatic skills and with technical knowledge. They will also require forums that bring them together. This kind of capacity building will be a crucial part of next-generation diplomacy.[10]

5-year horizon:

Higher education institutions take the lead

Universities and institutes develop courses teaching the unique combinations of multidisciplinary skills for science and technology-related diplomacy. Innovative immersive pairing schemes between politicians, engineers and scientists foster the mutual transfer of skill sets in a broad range of countries.

10-year horizon:

Non-state actors achieve diplomacy success

Non-state actors begin to play significant roles in preventing fragmentation of technology and the alignment of international technology trajectories.

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.

4.2.3 Diplomacy for big science

The infrastructure for many modern scientific experiments is multinational in scale. For example, CERN, the European particle physics laboratory, is a collaboration between 23 member states with further links across the planet.[11] Similar multinational science projects include the ITER fusion project, Eumetsat and COVAX.[12] These projects require long-lasting engagement, on an international scale, between actors with detailed knowledge of the science and engineering challenges ahead. Also crucial is a good understanding of the potential outcomes from these projects, their significance and their impact on science, business and society.

Future collaborations of this sort will require individuals who are equally at home in the world of science and the world of diplomacy. The importance of these skills has been brought into sharp focus by the COVID-19 crisis, which forged collaborations on unprecedented scales between a wide range of actors, creating new models of cooperation and rapid research and development. The development of highly effective vaccines in record time is a huge success. But there have also been failures of science diplomacy, such as vaccine nationalism and the inequitable distribution of medical equipment and treatments.

While the COVID-19 crisis has highlighted the power of science and diplomacy to achieve collaboration on a global scale, it is likely that growing nationalism and trends towards strategic autonomy will challenge future large-scale science collaborations. This threatens to limit knowledge sharing, the free movement of people and ideas, and funding for international collaboration.

5-year horizon:

Science diplomacy curricula include tools for large-scale efforts

Training courses for science diplomacy highlight the skills necessary to operate in this space and in particular focus on the technical multilingualism needed to converse with actors in the scientific and diplomatic fields. The collaborations forged during the COVID-19 crisis provide a template for a new generation of research and development projects with global relevance.

10-year horizon:

Trained science diplomats are spread through relevant organisations

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.

25-year horizon:

Blocked projects increase awareness of challenges

Severe delays to several big science projects are finally resolved. These projects involve many state and non-state actors and depend on complex, multi-layered negotiations. The deadlock is broken thanks to key groups of experts with skills spanning diplomacy and science.

4.2.4 Managing the global commons

The oceans, the atmosphere, the polar regions and outer space are part of the global commons that humanity relies on for a wide range of resources and activities.

They are governed in part by international treaties and environmental laws but new technologies and better understanding of these regions often reveal serious shortcomings in this system of governance.[13,14] Tension over these commons is often a potential source of conflict and finding ways to reduce these tensions will be a significant goal for science diplomacy.[15,16] At the same time, new forms of digital commons now underlie much of our society and provide an increasingly important environment for communication, for economic activity and for virtual conflict. An important role for science diplomacy will be to anticipate the effects of science and technology on the global commons and to find innovative ways to avoid or mitigate the shortcomings in governance.

5-year horizon:

National bodies call for action over resources held in common

Studies of large parts of oceans protected from exploitation — Marine Protection Areas — provide evidence that international action can bring about significant beneficial change to global commons. Cyber commons are increasingly exploited in ways that threaten the stability, freedom and utility of the online world. Academic efforts in science diplomacy begin to formulate solutions.

10-year horizon:

Unilateral geoengineering creates science diplomacy challenges

Non-state actors begin pumping sulphur dioxide into the upper atmosphere to reduce the amount of energy reaching Earth from the Sun. The move tests the limits of environmental law and challenges conventional governance models and climate justice processes. Non-state actors begin to recruit staff trained in science diplomacy.

25-year horizon:

Science diplomacy limits damaging exploitation of commons

State and non-state actors working with science diplomacy experts, come together to formulate and update international agreement on some global commons exploitation, such as active cooling of the atmosphere.

4.3

Digital Technologies and Conflict

The 2021 Science Breakthrough Radar anticipated that the interaction between politics and digital technologies would create disruptive, unanticipated effects, radically altering the character of conflict and the strategic landscape. In the year that has since passed, it has become clear that the future trends suggested in the 2021 timeline have accelerated due to ongoing geopolitical shifts and the further destabilisation of the international security landscape. The increase in defence expenditures in emerging and disruptive technologies, including in advanced computational methods and digital capabilities, seem to confirm those forebodings.

As this year's Radar goes to print the current landscape is dominated by competing narratives, strategic ambiguity, hybrid models of collaboration, diverging interests and converging technologies. Non-state actors are assuming increasingly significant, and often unexpected, roles and functions. These developments will continue to raise ethical and normative questions, as well as questions around decision making-transparency and supply chain accountability. Decisions by non-state actors or entities — notably private technology firms — on how they engage with a conflict or other contested issues will be increasingly framed in geopolitical terms, influencing their public standing as well as revenue streams.

With the onset of so-called immersive environments, human enhancement practices and cognitive warfare, the battlefield is expanding into the human body and mind. Information, hedging and influence operations and other such subversive activity is likely to become more intense and divisive over the coming years due to advances in life and neurosciences and greater insights into behaviour modulating technologies and their perceived strategic value in conflict.

Looking 25 years ahead, it appears that we are heading toward a great systemic decoupling with mutually incompatible normative and technological trajectories and with significant implications for global trade, multilateralism and international cooperation, as well as for preventive diplomacy and conflict management. The 2023 Radar will feature a deep-dive into these and related issues. Here, we offer a visualisation of the Anticipation Potential of this field, and reprint the 2021 Radar's invited contribution on the Digitalisation of Conflict from Myriam Dunn Cavelty, Anja Kaspersen and Camino Kavanagh.

Anticipation Potential

EMERGING TOPIC:

Digital Technologies and Conflict

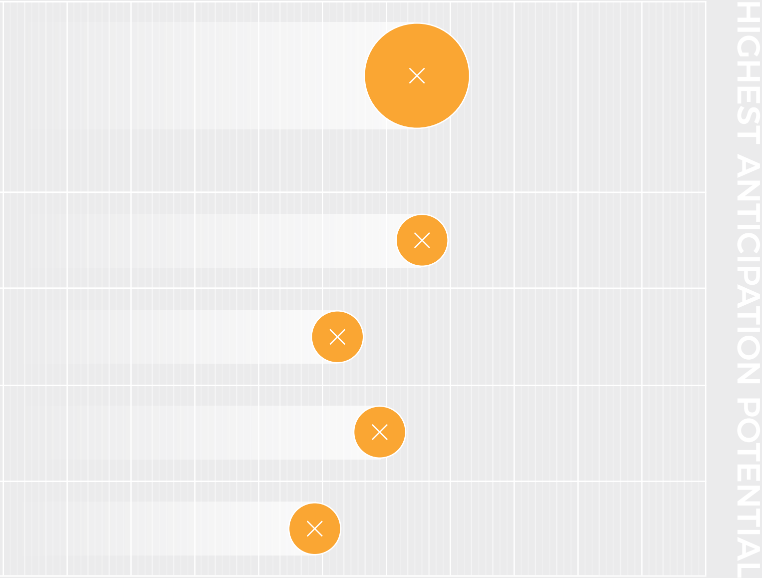
SUB-FIELDS:

Non-state actors in conflicts

Autonomous systems, AI and the metaverse

Weaponization of the bioeconomy

Perception of capabilities



SURVEY OBSERVATIONS:

The digital revolution has changed the character of conflict, from the way humans disagree to the way warfare is conducted. Awareness of this topic — in particular weaponisation of the bio-economy and the role non-state actors play in conflict — remains relatively low. Low awareness, the need for interdisciplinary working and the relatively high disruptive potential of these technologies has placed this topic near the top of the list. It will require considerably more attention going forward.

SELECTION OF GESDA BEST READS AND KEY REPORTS:

Conflict parties use digital technologies for a range of different purposes in conflict. The European Commission's Knowledge for Policy platform has attempted to categorise the threats on a broad level.[1] The European Institute for Security Studies regularly publishes briefings on this and related issues, including "Digital Technologies and Civil Conflicts" by Camino Kavanagh.[2] A variety of academic institutions or civil society organisations track the emergence of digital weapons or capabilities, the way they are used and their societal impact. Such entities include The Citizen Lab at the University of Toronto and The Berkman Klein Center for Internet & Society at Harvard University.[3,4] Many newspapers also report on the use and abuse of digital technologies in conflict, such as this report on the use of facial recognition technology in the Ukraine conflict for the Washington Post.[5] International organisations, too, are taking a closer look at how digital technologies are changing the character of conflict and affecting existing mandates. The work of the UN General Assembly's First Committee (including the OEWGs and GGEs) on ICTs in the Context of International Peace and Security; the GGE on Lethal Autonomous Weapons Systems; the UN Secretary-General's Strategy for the Digital Transformation of UN Peacekeeping and the work of the UN Department of Political and Peacebuilding Affairs on Digital Technologies and Mediation in Armed Conflict are a case in point. Regional organisations, too, are increasingly working on these and similar issues.

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/r4-3

Invited Contribution:

Digitalisation of Conflict

Myriam Dunn Cavelty
Center for Security Studies at ETH Zurich

Anja Kaspersen
Senior Fellow, Carnegie Council for Ethics in International Affair

Camino Kavanagh
Nonresident Scholar, Carnegie Endowment for International Peace

Digital technologies are playing a twofold role in conflict. On the one hand, they are used to extend power politics into the poorly regulated domain of global data exchange, where they are used to exploit and exacerbate existing political tensions, posing significant risks and potential harms to individuals, communities and businesses across the globe; on the other hand, they can contribute to better understanding and monitoring of conflict and, if accompanied by the necessary political momentum, agency and effort, to preventing and even resoling various sorts of conflicts, thus mitigating the aforementioned harms. It remains to be seen whether existing institutions traditionally tasked with building and maintaining international norms for security and stability and relevant structures, tools and processes will suffice to both understand and manage the challenges emerging around digital technologies, including the escalatory potential of certain uses, or whether the world needs alternative governance structures.

Many parts of the technological infrastructure, algorithmic systems and data flows that we rely on every day can be **exploited for criminal or political purposes**. The bigger the societal reliance on the uninterrupted, trustworthy operation of digital technologies for essential services and other functions deemed crucial to our collective well-being, the higher the disruptive potential. While the world has yet to see a large-scale destructive global attack on a critical infrastructure, non-state, semi-state and state actors' cyber operations cause minor to major disruptions on an almost daily basis. Apart from hacking into technical systems to extract data or cause other types of damage, algorithmic technologies are being deployed to influence opinion, to spread distrust and to undermine faith in traditional social-political structures. Understanding the significance of this, the roles of international actors and how manipulation techniques will change in future is a major challenge.

At stake is the nature of trust and trustworthiness, which, already under significant pressure due to non-technological drivers, has become badly eroded in many communities, increasing extreme polarisation. Undoubtedly, different uses of digital technologies are contributing to this growing trust deficit which continues to weaken some of the fundamental pillars of social cohesion and civic order.

On the other hand, digital technologies, when used in support of existing human analytical capabilities, has proven effective in enabling a enhanced understanding of certain forms of conflict and have significant potential for early warning, the monitoring of peace agreements and other such arrangements in the event of armed conflict. Computational social scientists have begun to simulate conflicts on local and regional levels using agent-based models in order to develop early warning systems. These models capture the simultaneous interactions and movement of multiple actors and simulate the complex behaviour that emerges.

This is made possible by developments in several key technologies: a rapid increase in computing power, improved computational based simulations and methodologies such as AI and machine learning, the development of intelligent agents and the availability of ever-larger datasets to train these systems on a multitude of conflict vectors. Together, these have created a significant opportunity to model broader social, political and economic systems and to study conflict at unprecedented scale and resolution. However, issues about data access and quality, the complexity of modern conflicts that engage a broad range of international and external actors make real and impactful progress in digital conflict modelling difficult. To date modelling falls short of offering explanations, culturally sensitive understanding or strategies for engagement. As with earlier developments regarding the opportunities that can be derived from information technologies for conflict prevention and resolution purposes, such opportunities need to be accompanied by a political will to engage, technology literacy , agency, investments, of which there appears to be a significant shortage at present, adding to the growing strains on the international system.

Whether digital technologies are used with positive or malicious intent or something in between is not inherent to the technologies themselves but depends on human decisions. The intentions, norms, and value structures of technological developers find their way into the artefacts during the design stage, while existing power structures influence the desirability of specific aspects, forms or functions of technology. Given the disruptive potential of digital technologies, state and non-state actors are discussing voluntary and binding norms to balance the opportunities and risks of global society's ongoing digital transformation and shape behaviours relevant to the development and uses of the technologies. Due to enduring uncertainties about the scope and pace of ongoing socio-technological transformations, the growing centrality of digital technologies and data to great power rivalry, an increasing willingness to use disruptive tools in the context of accelerating great power rivalry, and significant fragmentation of authority and accountability on different levels, managing digital insecurities continues to be a most challenging governance issue in contemporary international affairs.

Future trends with a 25 year perspective

With the expected increase in data availability, advances in machine learning as well as better understanding of the relation between digital information flows and behaviour, it seems likely that monitoring and modelling performances will improve. At the same time, the world might see an extension of manipulation, militarisation, weaponisation and targeting capabilities. The convergence between cyber- and bio-technologies will potentially result in further threats to the individual and society, including new encroachments on personal privacy and fast growing commercialisation of bio data flows involving the body and the brain. That said, future developments are uncertain: the interaction between politics and digital technologies often creates disruptive, unexpected effects.

Monitoring and modelling conflicts

The widespread deployment of sensor technologies and progress in data gathering will allow for better monitoring and managing of live conflicts and drivers of conflict. To be effective and trusted by all parties, this will require more transparent data gathering and storing practices and a shift in the collaboration of private actors and security agencies.

The ability to simulate conflicts through digital (machine learning, simulation) techniques will allow actors to create plausible scenarios and to take part in joint problem-solving exercises or use modelling as a tool for both conflict prevention and resolution efforts. Monitoring online activity, machine learning algorithms will be able to anticipate potential crises. Trust in the models depends on their vetted ability to simulate complex systems, in an imperfect environment, including actors and organisations involved and their perceived legitimacy.

Manipulation

Psycho-social strategies enabled by digital and algorithmic technologies will play a greater role in manipulating and controlling narratives and populations. Current trends in monitoring and surveillance by private, largely unregulated entities will trigger moves to regulate these forms of interference, and over time may induce drastic shifts in the business models of social media companies and other relevant corporations, cementing the legitimacy of the state against the backdrop of pursuing counteractions.

Convergence between cyber- and bio technologies

Health sector entities and research institutions that focus on data gathering — pharma, nutrition, personal sensors etc — will risk becoming more deeply and directly involved in conflict and will continue being the target of malicious cyber activity. In addition to new personal privacy encroachments on bio data flows and brain interfaces, such a scenario can will give rise to important personal safety and national security concerns as unauthorised access to certain types of health data (human genomes for example) may allow them to micro-target specific groups with biological weapons. Accountability and regulatory action will become a bigger issue for private actors, such as biotechnology, digital and social media companies, as these and other challenges to existing models of self-governance emerge.

Why do they matter?

The impact of digital technologies and digital flows of information on societies across the globe is evident, even more so in fragile societies with historically poor or nonexistent digital infrastructure and data regulations. As the power of digital technologies increases through more precise data gathering and more applied uses of algorithms, the potential of digital technologies for conflict prevention and resolution increases. At the same time, however, more elaborated and wide-reaching destabilisation strategies and capabilities can be deployed. This raises a series of essential questions to the wider security establishment: how do we protect societies against the destabilising potential of technologies alongside targeted attempts of using technologies to destabilise the geostrategic order?

How can the multilateral system adapt to manage extant and emerging challenges associated with digital technologies and better leverage the opportunities they offer for conflict prevention and resolution?

Complex, dynamic frameworks already govern some fields of digital technologies. Some of these are contested and others remain under-developed or are under development, and most lack any implementation framework. All while new risks and vulnerabilities relevant to the technologies and how they may be exploited in conflict continue to emerge. Some involve just states, while others involve a range of other critical actors. Some may be anchored in hard or soft law while others may involve a mix of binding, non-binding and self-regulatory elements.

Looking to the future, responding to the attendant risks and challenges of digital technologies, particularly how they may be used in conflict, requires more than an understanding of these frameworks and the relevant organisations, tools, structures and processes. It will require a deeper understanding of how they interact with each other; an appreciation of the overlapping social, cultural, economic, environmental and (geo)political contexts against which they are crafted; a firmer grasp of the overarching questions of power and conflict that tend to shape our relationship with digital technologies; and moreover, a much deeper and informed public debate at every step of this journey.

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.

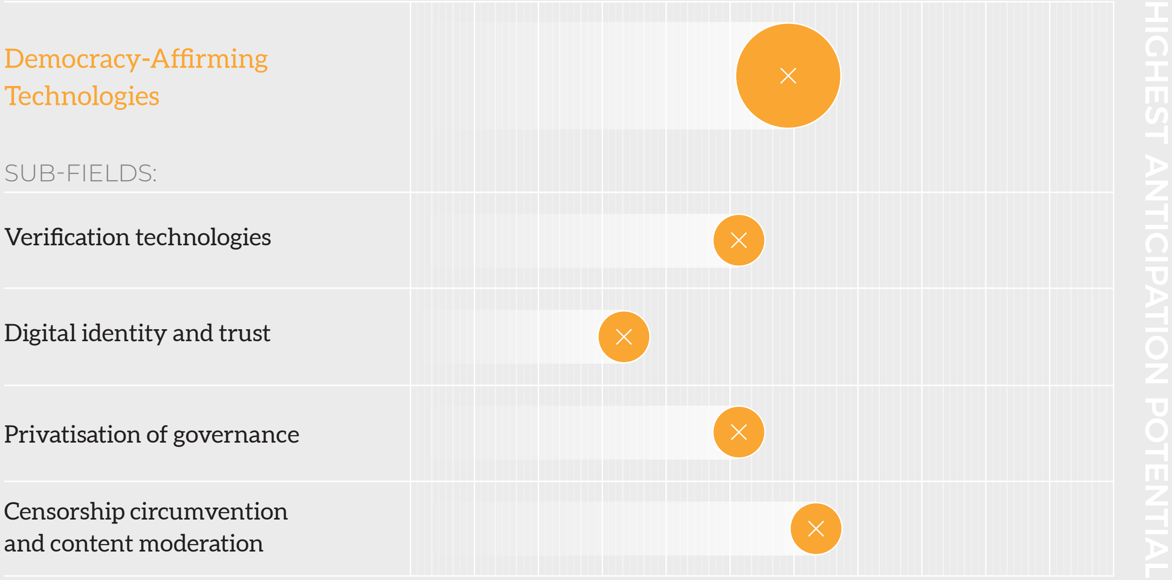
All this sits within a broader debate about the veracity of information, and how to identify and counter misinformation. The ways in which information can and should be moderated is a topic of significant debate, with much agreement that misinformation and hate speech cannot be allowed to spread largely 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:



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 Europe, the Digital Services Act and Digital Markets Act drawn up by the European Commission have placed significant markers for the way online behaviour and activity will be regulated in future.[3] However, China has taken a different approach with mass surveillance and a social credit system that bodes ill for personal freedom and free expression.[4] The potential for digital technologies to protect freedom of expression and promote civic engagement has been explored by Freeman Spogli Institute at Stanford University.[5] Many of the potential pitfalls of digital societies have been highlighted by Reetika Khera's study of India's Aadhaar system of digital identity.[6] Paul Nemitz has also explored the way AI can be exploited to support democratic institutions.[7] Francis Fukayama and colleagues have also asked how democracy can be saved from technology.[8]

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 trust it 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.

Rajna Gibson Brandon
Professor of Finance, Geneva Finance Research Institute,
University of Geneva

Invited Contribution:
The Challenges and Opportunities of Sustainable Finance

Investors today are looking for much more than just a risk-adjusted return on their money. With environmental and social concerns high on our list of priorities, we want to make an impact in these areas too. However, finding good ways to measure these impacts and achieve consensus on them will be crucial if markets are to help us achieve our goal of sustainable development.

The last decade has seen a dramatic shift in people's conception of what a company is and what it should do. Businesses are increasingly being judged by what have become known as Environmental, Social, and Governance (ESG) criteria, a framework used to assess the extent to which firms are contributing to the greater good of society rather than simply maximising risk-adjusted returns for shareholders.

Although such judgements are often imprecise and subjective, this framework is increasingly being used to inform "sustainable investing" decisions. The trend is already starting to change the behaviour of large companies, which increasingly disclose things like their environmental and social performance and are increasingly reactive to developments that would traditionally sit outside the remit of corporate boards.

So far, environmental concerns have received the bulk of attention in sustainable investing. That is thanks largely to the fact that climate change presents clear systemic risks to the global economy. This is driving firms to think harder about corporate issues such as the company's carbon footprint or the ecological impacts of its supply chains. But social concerns are quickly gaining traction too, as evidenced by the growth of the FairTrade movement and the large number of companies pulling out of Russia in response to its invasion of Ukraine.

Perhaps even more fundamentally, a renewed focus on how to make corporate governance more socially beneficial is driving a shift from prioritising the interests of stakeholders to also thinking about other stakeholders in a company: the workers and customers, for example. This is helping lay the groundwork for a new form of "responsible capitalism" that optimises for long-term benefits for both shareholders and society at large.

Early evidence suggests that companies that score highly on ESG criteria often outperform those that don't. However, results are far from conclusive and the question of whether there is a clear positive link between environmental, social and governance positioning and financial risk-adjusted performance remains open.

Despite the potentially transformative impact of sustainable investing, it faces numerous interlocking challenges. Solving these will be crucial to ensuring that the ESG framework helps push markets in a more socially beneficial direction, and that it doesn't result in purely performative acts and announcements — "greenwashing" and "social washing" — designed to hide the fact that companies are continuing with business as usual.

One of the biggest problems is measurement. Almost all of the outcomes sought by sustainable investors take years, if not decades, to achieve, be that net zero climate emissions or ending child labour. Quantifying many of the ineffable qualities tied up in ESG criteria, such as equity or justice, can also be incredibly challenging.

Even if we could come up with a good metric, gathering data in a useful and comparable form from thousands of different firms is very difficult. The fact that ESG ratings from different ratings agencies often disagree markedly is indicative of the scale of the challenge. The proliferation of products aimed at sustainable investors is only likely to muddy the waters further.

These are complex financial instruments that we currently have little experience in valuing or assessing. Take "sustainability-linked bonds" (SLBs), for example. Traditionally, so-called ethical investments have focussed on simply buying equity in companies with good ESG credentials. But in the last couple of years there has been substantial growth in buying bonds that are used to directly finance the company while reaching environmentally or socially beneficial targets. The issuers of SLBs set key performance indicators that determine whether the issuer lives up to the commitments they made, normally on a horizon of between 5 and 10 years. If they fail to deliver on reaching the KPI then the issuer has to pay an increased amount of interest to the investors.

Early evidence suggests that a non-negligible fraction of the first sustainability bonds were overpriced, essentially giving companies a source of cheap capital due to the huge demand from institutional investors eager to enter the market. A lack of understanding of how such instruments work could also make greenwashing and social washing easier, a growing concern as increasing numbers of less sophisticated retail investors enter this market.

Solving these problems will be difficult without some kind of harmonisation on the standards and metrics by which we create and judge ESG criteria. Markets certainly tend to push towards the certainty and security offered by disclosure and standardisation, but a certain amount of regulation seems likely to be necessary. The fact that research has found greenwashing to be more common in the light regulatory environment of the US than in the more heavily-policed EU makes a compelling case for more government oversight.

The good news is that some efforts are already underway. The EU Taxonomy for Sustainable Activities, for example, helps investors and companies to judge the impact of different businesses behaviour. The EU is also pushing for countries to adopt common accounting principles, which could make it easier to compare progress on environmental or social issues.

But this will only work with global harmonisation of these efforts. If one part of the world regulates and the other part doesn't, loopholes will quickly appear and companies are likely to engage in regulatory arbitrage to circumvent the more onerous ESG requirements.

Given the current geopolitical situation, hopes for such harmonisation currently seem slim. There are big question marks over the future of globalisation, and the fragmentation of the world economy into different blocs operating on different rules is a distinct possibility. When it comes to ESG criteria, it's also important to remember that attitudes can vary significantly across different cultures. Whether we have an effective platform for common dialogue that can unify these disparate voices remains unclear.

The onus is likely to fall on governments and companies in the West, particularly large multinationals with large global footprints. Enforcing a unified set of standards, whether a company is operating in a developed democracy or a developing country with less robust institutions, could help set the tone for a more responsible approach to business worldwide.

Another hindrance to progress is our current understanding of the impact and design of ESG initiatives. At the Graduate Institute of International and Development Studies (IUHEID), in collaboration with several Swiss universities including the University of Geneva, we recently launched the "Swiss Sustainable Finance Lab" to help with this situation. It will have a particular focus on driving progress in understanding and quantifying the social dimension of ESG, but this will require truly interdisciplinary research that brings together scientists, economists, social scientists and policymakers.

As a hub of international finance, cross-disciplinary research and multilateralism, Switzerland has a crucial role to play in driving innovation and adoption of ESG approaches. Given the urgency of the challenges the world faces, we certainly must do everything we can to ensure financial markets are pulling in the same direction as we try and achieve a new more sustainable approach to economic development.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Introduction to Knowledge Foundations

This year we have introduced a new platform: Knowledge Foundations. This will cover areas of foundational knowledge, which are transversal to the four other 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.

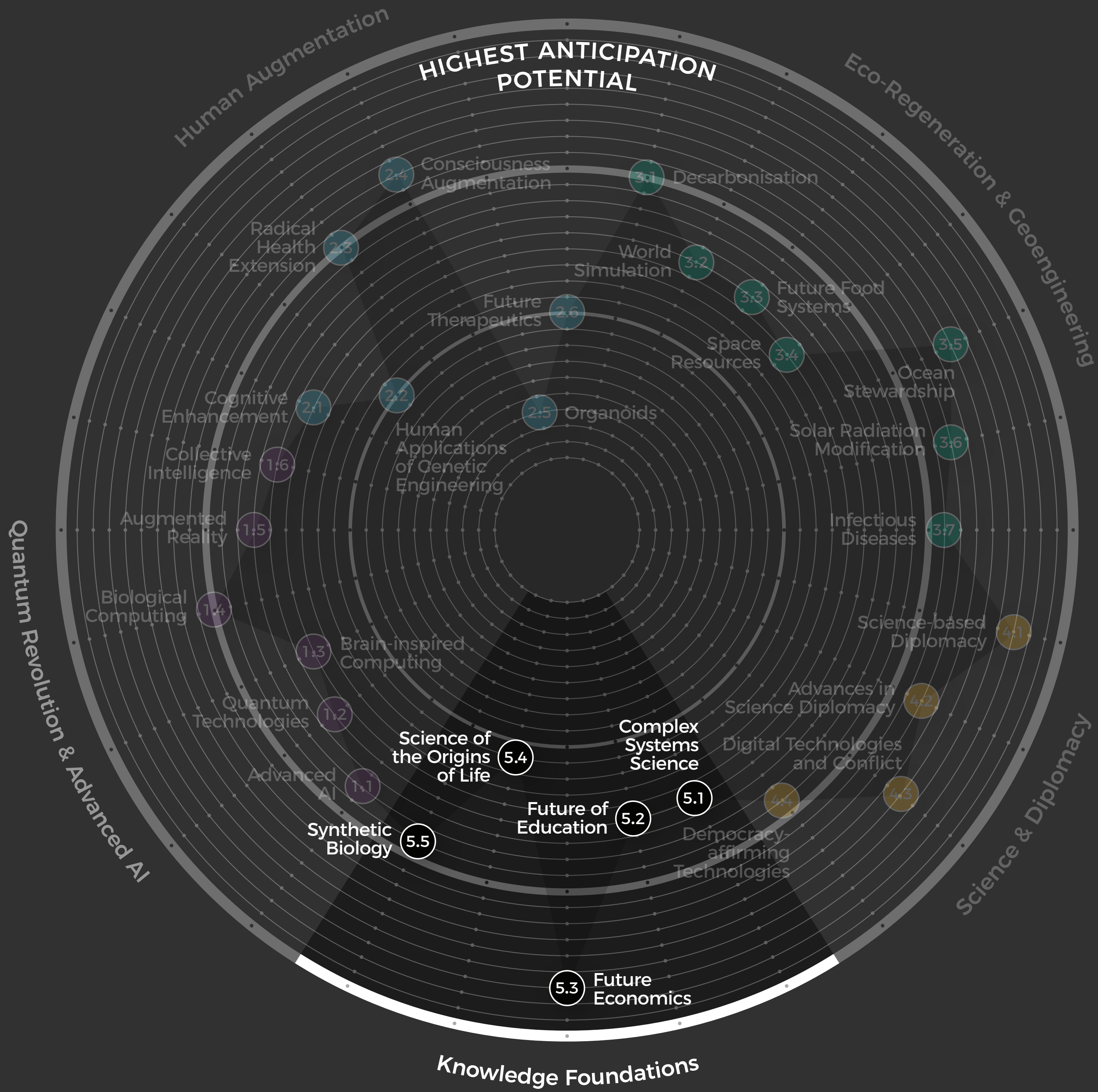
Much of the progress in all fields of research over the next quarter-century will depend on the knowledge we gain, exploit and pass on to our children. But the need for **innovations in education** goes much wider: we need to find ways to exploit educational technology for individual, lifelong learning 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 **future economics**. 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; a central driver for its inclusion as a new Radar topic. There are already around 400 scientifically feasible use cases for synthetic biology that could have a direct economic impact of $4 trillion.

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
Quantum Revolution & Advanced AI
Science & Diplomacy
Knowledge Foundations
2.4 Consciousness Augmentation
2.3 Radical Health Extension
2.6 Future Therapeutics
2.1 Cognitive Enhancement
2.2 Human Applications of Genetic Engineering
2.5 Organoids
3.1 Decarbonisation
3.2 World Simulation
3.3 Future Food Systems
3.4 Space Resources
3.5 Ocean Stewardship
3.6 Solar Radiation Modification
3.7 Infectious Diseases
4.1 Science-based Diplomacy
4.2 Advances in Science Diplomacy
4.3 Digital Technologies and Conflict
4.4 Democracy-affirming Technologies
1.6 Collective Intelligence
1.5 Augmented Reality
1.4 Biological Computing
1.3 Brain-inspired Computing
1.2 Quantum Technologies
1.1 Advanced AI
5.4 Science of the Origins of Life
5.1 Complex Systems Science
5.2 Future of Education
5.5 Synthetic Biology
5.3 Future Economics

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

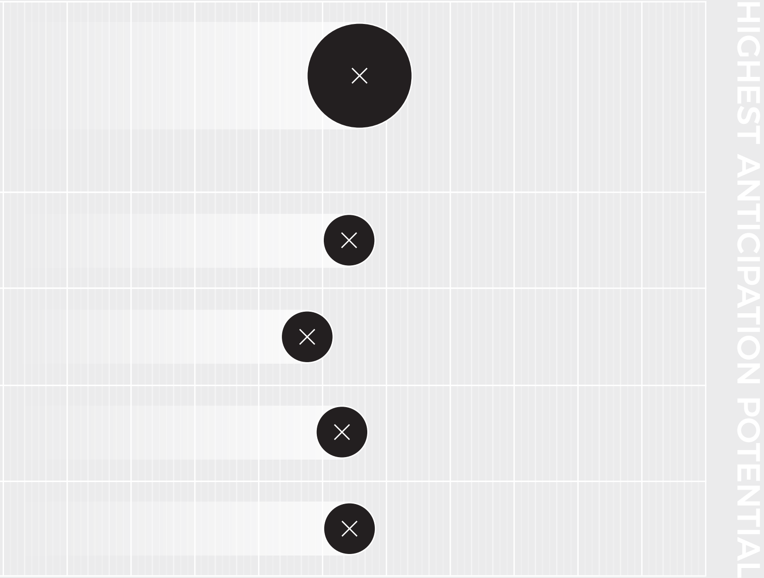
Anticipation Potential

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:

The fragility of many aspects of our networked society has been highlighted by numerous authors. Joseph Stiglitz highlights the failures of modern macroeconomics in "Crises, Contagion, and the Need for a New Paradigm".[1]

Dirk Helbing reviews the problems and challenges associated with complex social systems in "Globally networked risks and how to respond".[2] Reinhart and Rogoff study the networked links between financial crashes and debt crises.[3]

In "Values for the Future",[4] the European Union explores the values that European and global governance should embody.

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.

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Anticipation Potential

EMERGING TOPIC:

Future of Education

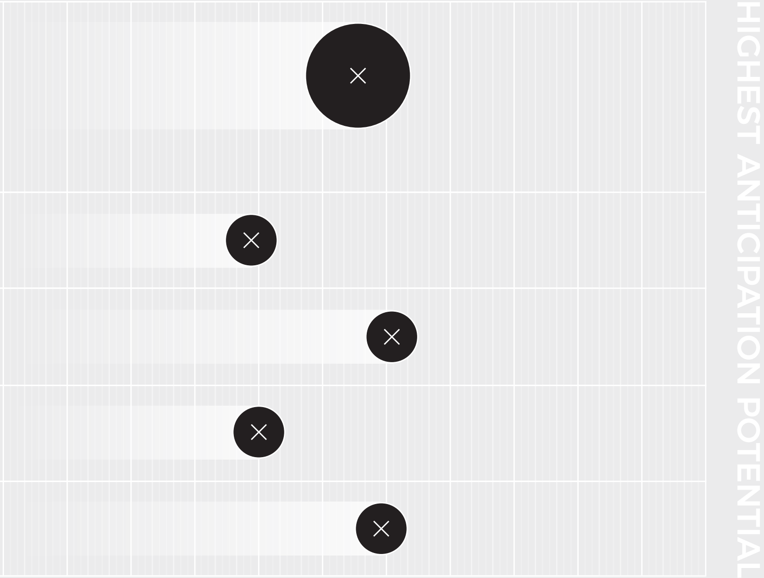
SUB-FIELDS:

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:

In recent years there have been numerous efforts to track the potential of technology and other tools to transform teaching and learning.

In 2017, for instance, the US National Bureau of Economic Research put together a working paper, “Education Technology: An Evidence-Based Review”, synthesising and discussing the evidence of effectiveness gathered in developing and developed countries.[1] “Innovation in education: what works, what doesn’t, and what to do about it?” focusses on the US experience and delivers a number of interesting conclusions, particularly about the need for scalable innovation.[2]

EdTech Hub is a globally focused evidence library and tools database that aims to assist decision-making regarding educational technology.[3]

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

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. 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.

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Anticipation Potential

EMERGING TOPIC:

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 2015, the United Nations set out a list of 17 Sustainable Development Goals to be achieved by 2030, and in 2019 it published a supporting document that lays out policy, incentive and action recommendations.[2]

Environmental considerations for sustainable development are analysed in a report by Polasky et al.[3] Strategies to create circular economies are proposed in a European Commission circular economy action plan[4] and the Ellen Macarthur Foundation is championing further action on a global scale.[5]

In 2018, "Charting Pathways for Inclusive Growth" outlined ways to ensure that people living in poverty were not left behind by developments in frontier technologies.[6]

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. For some parts of the Earth, that could be catastrophic, leading to the collapse of farming, and significant water shortages. That raises the prospect of mass migration away from these regions. Urgent international attentio is required to better understand, predict and plan for these mass movements.[7,8]

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.[9] 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.

5-year horizon:

An era of progress

Governments come up with a real plan to get to zero emissions by or before 2050. A growing awareness and experience of the negative consequences of climate change lead to implementation of a global CO_2 tax. Circular economy strategies continue to be implemented on key issues such as plastics and waste, if only at a local level.

10-year horizon:

Farming requires intervention

Some parts of Africa become too hot and too dry to support traditional crops, while efforts to commercialise heat-resistant crops have stalled over intellectual property rights and the limited potential for recouping costs. Nevertheless, the success of some genetically modified crops in extreme conditions provides momentum for a global research effort to develop other heat-resistant crops. After the success of covid-19 vaccine development, this work is funded by governments rather than by commercial profit.

25-year horizon:

Crisis is avoided through forward thinking

The global effort to develop heat-resistant crops largely prevents mass starvation and civil unrest in countries whose traditional crops have failed due to climate change. The retraining of workers in these economies, funded through global co-operation, 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

The prospect of more intelligent and more capable machines has generated fears that machines might replace humans entirely while concentrating wealth in the hands of a tiny minority of people.[10] 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.[11]

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.[12] The fraction of the workforce that becomes unemployed will need to be looked after and retrained where possible. And this will have to be paid for by governments, who will need to find new ways of gathering and redistributing the wealth generated by machines.[13] 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

Automation technologies become more widespread, and governments put policies in place to create incentives for employing human labour and innovating with labour-augmenting technologies, supported by a change of taxation in favour of human labour and against capital, which smooths the transition.

10-year horizon:

Governments tax automation

There is significant displacement of jobs because of machines powered by artificial intelligence. Governments implement policies that ensure human capital is not wasted: education and retraining is common, preparing workers and rising generations for a changing workplace.
A wide range of economies begin trialling universal basic income paid for by the taxation of capital and automation.

25-year horizon:

Machines alter the human experience

The workplace has changed substantially, with new jobs and tasks in place. People are working significantly less, thanks to the productivity 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 ensure that automation technology becomes available to a wide swathe of smaller-scale employers to avoid any 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.[1] 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.[14]

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.[15]

5-year horizon:

Circularity efforts gain momentum on local scales

City-level 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.

10-year horizon:

The first entirely closed-loop economic processes appear

International agreement on material pricing creates the financial incentives that make some small-scale circular economies viable. The first of these begin to emerge.

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 still needed to bootstrap more circularity. Implementations of artificial intelligence identify and react to eventualities that might cause crisis or unsustainable practices in the global supply chain.

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. Although globalisation is generally considered a positive force, rising tensions over some of its consequences threaten its future.[16]

There are many reasons for these tensions.[17] One is that globalisation displaces local employment opportunities, and even entire industries, to other parts of the world. This has been a factor in the rise of nationalism, which threatens to disrupt international trade and cooperation. Anticipating the effect of global trade on local industry and preparing the local workforce accordingly may help to mitigate some of the most serious disruptions.

Another problem, highlighted by the covid crisis, is the fragility of supply chains.[18] 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, and blockchain technology will help to secure this information, making trade more transparent.[19] In the longer term, this transparency will make supply chains more sustainable too. 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:

Post-covid recovery focuses on more resilient supply chains

In the aftermath of the covid-19 crisis, most high-income countries and global companies increase the resilience of their supply chains. Some governments attempt to re-shore their industries making supply chains shorter. These shorter chains are not always more sustainable, however. Blockchain and smart contracts allow global supply chains to become more resilient, despite the arresting effect of rising nationalism.

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. Fossil fuel use in the supply chain drops significantly, and in a sustainable manner that means it will not rise again.

25-year horizon:

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

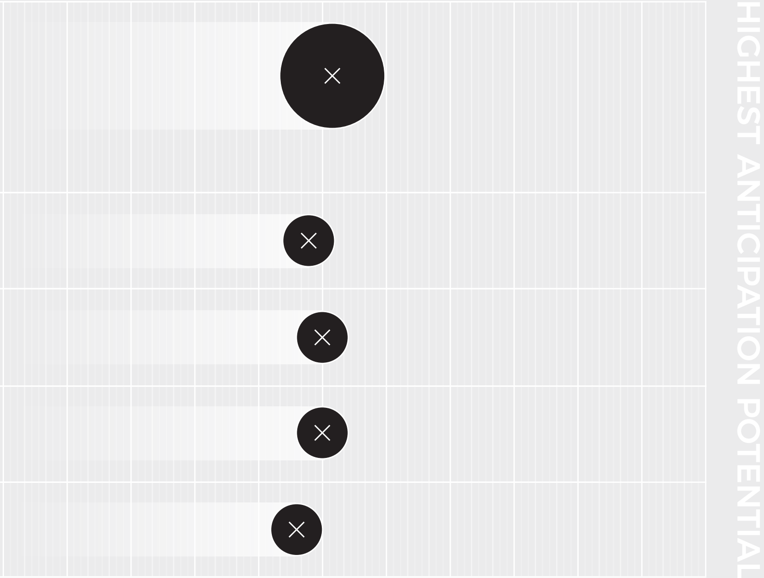
SUB-FIELDS:

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:

Martina Preiner and a large group of researchers have attempted to find ways to bridge the gaps between sub-fields in a 2020 paper.[4] A 2017 report “Re-conceptualizing the origins of life” aims to bring together a number of approaches.[5] “A Strategy for Origins of Life Research” is a white paper resulting from a 2015 workshop at the Tokyo Institute of Technology that offers “a guide and stimulus to the solution of the most urgent and important issues”.[6]

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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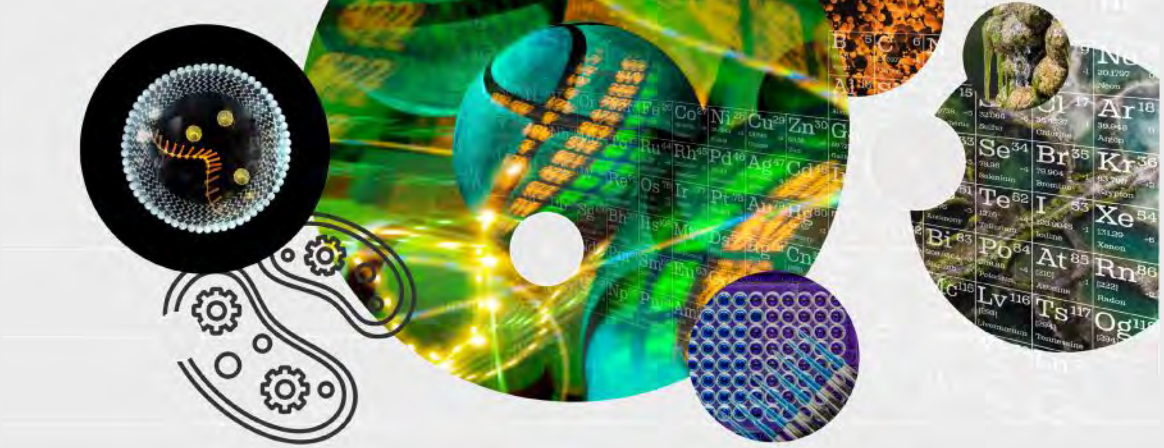


5.4.1 Prebiotic chemistry

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:

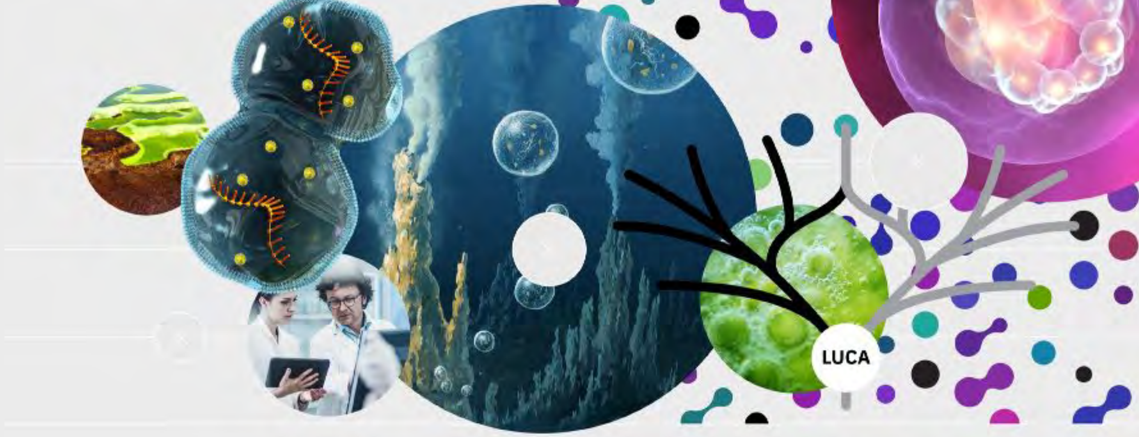
Chemical computation becomes possible

"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.

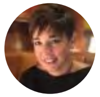
5.5 Synthetic Biology

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 CO2 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:

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 2022, Schmidt Futures published a useful report into the US bioeconomy.[6] "Synthetic Living Machines: A New Window on Life" provides a review of the 2021 status of bioengineering of novel multicellular living bodies.[7] "Future Trends in Synthetic Biology—A Report" is a 2019 synthesis of a conference on the field's direction of travel.[8] A 2018 National Academies report discussed possible malicious uses of synthetic biology.[9]

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/r5-5

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 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.

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The Philosophical Lens: Moving landscapes in the humanities and social sciences

The vision of GESDA is to use the future to build the present, through the anticipation of future science advances and breakthroughs. The GESDA Board of Directors recognised from the start that, if we want those advances to ultimately lead to a better life for humanity on a healthy planet, three essential questions must be kept in mind throughout the process. Those questions are:

1. **Who are we, as humans?** What does it mean to be human in the age of robots, gene editing and augmented reality?
2. **How are we going to live together?** What technology can be deployed to help reduce inequality, improve well-being and foster inclusive development?
3. **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 anticipatory mapping of the scientific advances of the next 5, 10 and 25 years that could have a strong bearing on the answers to these questions. However, it is not enough to anticipate trends in natural sciences, medicine, and engineering. Reaping the benefits of anticipated science advances and emerging technologies requires that we also anticipate and understand the trends, schools of thought and strategies within the rapidly evolving landscapes of philosophy, social sciences and the humanities. In other words, we also need to formulate the right questions and considerations about the future of the human, given anticipated advances in these disciplines.

This section aims to do just that, extending the initial reflections of a group of scholars from philosophy, social sciences and the arts developed in the 2021 edition of the Science Breakthrough Radar. Here we present a short summary of two workshops convened in Geneva and Brussels on 7-8 and 9 June 2022, introduced and chaired by Mark Hunyadi and Wendell Wallach. It is divided into three parts:

A. Moving landscapes in philosophy: three intellectual approaches. This describes how philosophy and social sciences are approaching their subjects as they relate to anticipated science developments.

B. Being human: philosophy and social science for a moving landscape. These are the questions raised by philosophy and social sciences about the human — at the level of the individual and of society, and in relation to our planet.

C. Tools for navigating a successful planetary life. Here, we offer initial reflections about a way forward.

"There is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination", as Daniel Dennett said in Darwin's Dangerous Idea.[1] One role for philosophy is to bring to light underlaying assumption, and to provide an appreciation for how change alters or makes obsolete existing theories and beliefs. Another role for both philosophy and the social sciences is to offer frameworks for understanding scientific discovery and technological development. Finally, philosophy, ethics, and the social sciences each play an essential role in shaping the deployment of a technology to facilitate the realisation of shared goals.

Our conceptual, epistemic, and moral frameworks are not immutable; they have a history, and it is the responsibility of philosophy to continuously rethink and rebuild them. Science and technology play an important role in shaping these frameworks ; deep philosophical questions about the human as an individual and as a collective (that is, "society"), and the human relationship with the planet, are now shared by all sciences, natural and social. Philosophical naturalism — the necessity of philosophy to take science into account — is growing and must be nurtured. Today, science is integral to gaining a better understanding of subjects formerly in the exclusive domain of philosophy — for example, consciousness studies can involve mathematical modelling, experimental psychology, and neuroscientific imaging. Finally, ethics must be re-envisioned so it is better able to address complex challenges and uncertainties where many values come into play, and are often prioritised differently by various stakeholders.

Moving landscapes in philosophy: A. Three intellectual approaches

1. The machinic condition

For millennia, humans have built machines and put them to work in the world. This has, in turn, acted upon and transformed humans themselves. But the unprecedented pace, scale and transformational power of today's digital technologies is different: it has fundamental implications for our human condition. Below, we explore how workshop participants saw the implications of this new "machinic condition".

The first implication is for our senses of time and desire. For the past three decades, we have been experiencing a change in our relationship with time; essentially, we have been attempting to dismiss the infinity of time. The result of this is that the modern promise of gradually accumulated progress has been replaced by a philosophy of carpe diem. The vision of progress traced back to the Enlightenment — the slow emancipation of the individual towards an ideal — has been replaced by "presentism" and instant gratification. Postponing the satisfaction of desires — sacrificing ourselves today to preserve the interests of our children, for instance — is either treated as absurd or dismissed.

In the digital universe, each user assigns to the system the function they expect from it, given their immediate desire. They thus become administrator of their own well-being: it becomes the norm that desires are fulfilled, unquestioningly, with a single click. This is how the digital world suppresses time: by satisfying impatient desire as quickly as possible, instigating a libidinal reflex.

The second consequence of the machinic condition is the problems that come with what is known as "desymbolisation". Humans are beings of language, and this is affected by the dialectical relationship between man and machine. Through language, we break with immediacy and reactivity; we leave the present in order to conjugate our existence with the future. However, when we reduce language to information, as happens in the technological world, this reduces the symbol to the signal, and language loses its symbolic function of semantic representation. This crushing of symbolic dimensions, or desymbolisation, leads to a reduction of human beings and social interactions, as well as to a new fatalism.

2. The new materialism and humanism

In the 1980s, Bruno Latour and colleagues went beyond the anthropocentrism of social sciences and showed that the world is made up of interactions that involve humans, animals, plants and micro-organisms, as well as countless technical objects.
At the heart of this new materialism is the decision to take into account the active role of non-humans in the constitution of social systems, refocusing social science research on the agency of non-humans and their material and environmental dimensions. This new materialism proposed to replace categories and oppositions such as nature versus culture or human versus non-human. It opposes a reductionist "machine" conception of life and makes it possible to restore the "living" as distinct from the machine, freed from the cybernetic control paradigm. As a consequence, our belonging to planet Earth becomes the only universalism possible.

The new materialism participates in a redefinition of the human and its boundaries because it proposes a conception of human existence as one in which non-humans play a central role. This blurring of boundaries raises the question of "animality". If biology is the motor of history and the smallest bacterium a source of autonomy, each species introduces exceptions, which makes the distinction between human and animals obsolete.

But humanism also invokes autonomy and responsibility for humans. In this respect “animalisation” refers specifically to non-dynamic automation: animals instinctively remain on the same course of action without changing direction, whereas human beings know how to take charge of their destiny. In this perspective and in the context of the climate crisis, nothing is gained by this “animalising”.

The concept of humanism is obsolete in the Anthropocene: the influence of humans on nature has become such that we are witnessing a fusion of natural history and human history. This implies a “redefinition of the human being” that cannot be satisfied with notions that predate our geological era. This offers a conceptual opportunity to re-establish ontologies, particularly that of the living: an obligation to reconstitute borders and categories. This is the proposition of radical materialism; it requires “de-centring”: we become relational beings, dependent on living beings, water, bacteria and so on. This can offer us an alternative normative basis to humanism.

This has serious implications. In the Anthropocene, the concept of environmental catastrophe can only be considered in terms of the human being capable of representing it. To subsume the human view into the animals’ point of view is, in the context of the ecological crisis, to declare a generalised sauve-qui-peut: this would merge the human being into the great whole of living beings that will, whatever happens, continue to exist.

3. Mathesis universalis – or the cyberspace as new metaphysics

The digital world is a succession of 0s and 1s to which algorithms are applied. It is a metaphysical reality because it aims at unification as “cyberspace”. Cyberspace realises the Cartesian and Leibnizian project of mathesis universalis – a universal science modelled on mathematics. This “informational paradigm” is applied to everything and extends to the humanities and social sciences. The result is a de-complexification of theory, and a normalisation of practices resulting from the confrontation between machines, organisms, algorithms and even thoughts. This normalisation can be termed “ordinary transhumanism”.

To deal with this appropriately, cyberspace has to be conceived as a new environment, one with the primary impression of having the whole world at our fingertips. This total presence is a central element of our condition in cyberspace. The digital model is marked by an extreme objectivism: all reality is reduced to a code, with the result that borders are erased, particularly the one that separates the human from the machine.

B. Being human: philosophy and social science for a moving landscape

Technological development is a social process; science and technology are necessary conditions of this process, but they are, by no means, sufficient to determine its direction or performance. Once a technology is introduced into a social context it becomes an integral part of a sociotechnical system. “A sociotechnical system includes people, relationships between people, other artifacts, physical surroundings, customs, assumptions, procedures, and protocols,” according to Huff.[2] The technology is in a dynamic relation with other elements of that system, transforming their actions, and in turn being transformed by their activity. For example, social media not only transformed the larger society, but was transformed as users perceived new ways in which it could be used, many beneficial but some that have been societally detrimental.

In other words, the relationships between the development of the social and the technical are not deterministic but contingent and entangled. There is no invention which does not constitute a novel pattern of human action: every invention is an intervention into nature and society. That is the reason why technical development is equivalent to social change. To say it with the words of Karl Marx (1856): “Steam, electricity, and the spinning machine have been revolutionaries much more dangerous than the citizens Barbès, Raspail and Blanqui [named revolutionaries of his day].”[3]

Whereas many design activities aim to develop concrete technical solutions, a philosophical lens (that is, a meta-design) and an appreciation of social dynamics provide frameworks within which sociotechnical systems can be developed.

A first requirement is to un-silo the conversation and build it both in a strong transdisciplinary manner and with a collaborative approach to problem-solving. The framework should include support for cultures of participation that put the owners of problems and those most affected by the proposed solutions in charge.

In a socio-technical system, in the dialectic of society and technology, 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. Utilising experts with that sensitivity as members of the team developing and deploying the technology enables value-added design geared at nurturing the desirable impacts of a technology (and defusing negative impacts) all along its life-cycle.

This is the required collective, collaborative, multidisciplinary stewardship of emerging technologies.

Where the individual is concerned, our technologies are apparently exacerbating a sense of dissociation. Science and technology seem to be exploding the concept of "human" at all levels, while opening up a range of options for people's conception of what they "want to be" and can potentially become. In view of this, ethics and social sciences should explore the central points of tension, frame questions, and eschew simplistic answers. Are the distinctions made between being human and being a machine sufficient for the challenges we are confronting? Are the things we are producing, whether digital or biological, objects or subjects? Such questions challenge our preconceptions and definitions of humanness and personhood.

Two "conservative reflexes" lurk in the background. First, the status quo bias: today, many believe we are in an optimal moment for being human. While concerns have been expressed that we modify this at our peril, we should not overlook that we might just be at a local optimum. Second, human beings have value for both what they are and can do, and tinkering with human capabilities could destroy this value. In anticipating these technological impacts, many social scientists will naturally focus on challenges and risk; but they must also examine the positive possibilities that technology can enhance our existence.

Given current challenges for humanity, there are new questions the social sciences must ask in many new areas:

Mental Health and autonomy: In the attention economy, mental health and mental autonomy are becoming a "limited biological resource". Better definitions of what constitutes a "good state of consciousness" will be required, and we must ask, considering the blurring of self and other: what are the ethics and responsibilities of this blurring? Mental autonomy should be protected in the same way that we protect freedom of expression — that is, it must remain a "rebuttable presumption" — and we must integrate, through law, the idea that brains are to remain "unviolated" by means of neural computation. Will it be possible to keep the "founding principle" that nothing should interfere with the individual's ability to take responsibility?

Immortality: With the development of the Metaverse, the dead will remain among us in palpable, directly accessible and maybe even responsive ways, even in secular societies. This will entail deep changes in our family relationships. What considerations should we have for these VR identities ? And radical life extension of the living, a dream pursued by many high-tech companies will compound the challenge of redefining the roles of human generations.

Machines (AI, automation, artificial consciousness): The legal system must think about neurotechnology creating machines that prevent crime, or identify potential deviants from their thoughts. How do we determine the liabilities of the machines or of those who deploy the machine? And do we need a moratorium on synthetic phenomenology — "artificial consciousness"?

Existential risk: As nano-, bio- and info- sciences and technologies converge, we increasingly have the capacity to tinker with the operating system of reality. It is not unreasonable to think about this as an existential risk for humanity. In response to this concern, we need to urgently develop safe "sandbox" spaces for innovation that can facilitate a better understanding of such existential risk, and to explore methods to ameliorate them.

When it comes to questions about society and life on the planet, we must acknowledge that, through digital platforms and infrastructures, technology is segmenting and reordering individuals within societies, and society as a whole. At the same time, it is unifying humanity, diffusing pervasive values throughout society. Work has always been central to humanity, but automation is redefining labour markets. What's more, technology is regionalising and segmenting the planet but is also allowing risks to be mutualised at a global level.

This values shift forces us to expand the vocabularies of ethics, and ensure that they become anticipatory. There is a need for new tools to address global ethical issues. However, our intuitions are not well naturally developed to address such issues. How can we develop values and new ethics — incorporating solidarity, community, democracy and truth — at the social level and at the planetary level, empowering sustainability and security?

There are also new questions about our individual rights and the evolution of the rule of law. Given the pace and implication of science and innovation, the rule of law is constantly lagging behind. There is a need to rethink legal rule-making — in advance of issues arising — with a focus on human rights and human centricity. But how do we anticipate which entitlements and responsibilities come with the new machines, new life or new hybrids that humanity will create? What responsibilities, for example, do we have when we blur the real and the virtual to the point they are undistinguishable. Do we have a plan for extra-planetary self-determination and rights?

Anthropogenic climate change is certainly a pressing issue. Humanity is losing the fight against climate change: we have already lost control, and can only strive to limit the damage. What are the implications of humanity realising that it is a failing species?

We are at a point in human history where we can sit down and engineer our future, and have the potential to redesign, re-engineer or simply hack what it means to be human. It is exciting to think that we can engineer the future we want — but what might we lose? Discussions of trade-offs in such a complex and uncertain space are central to the honest brokering of science and technology.

C. Tools for navigating a successful planetary life

Much of contemporary ethics can be considered as individualistic-centred ethics in the sense that it focuses on the rights and freedom of the individual. It is a legacy of the liberal tradition of the enlightenment, enshrined in the universal declaration of human rights.

However, the moving landscapes we encounter in the context of the Anthropocene as well as the cumulative impacts of emerging technologies forces us to re-envision ethics, as Joel H. Rosenthal and Wendell Wallach have argued:[4]

"Collectively, information technologies, biotechnologies, and nanotechnologies have given birth to an inflection point in human history: the Information Age. Re-envisioning ethics will be helpful for all realms of human endeavour, but it is particularly essential for addressing the challenges posed by emerging technologies that are rapidly transforming daily life, reshaping human destiny [and that of our planet] ...A re-envisioning of ethics is certainly not a rejection of the past. Ethics will continue to be grounded in shared principles as goals to strive to fulfill. The Golden Rule or something like it exists in all traditions and offers a good starting point. The dignity and rights of each individual has become sacrosanct. What exactly those rights are and require of us and our governments remains a subject for debate and further elucidation."

We may have to rethink traditional values of Western liberalism, such as the primacy of the subjective individual and their freedom to act, so that we can go beyond small ethics and move towards "global ethics".

This is particularly important when we face the fundamental questions raised by the deployment of emerging and next-generation technologies.
As we have seen, these technologies profoundly alter humanity — in its individuality, in its relation to others (in society, in other words) and in its relation to the planetary ecosystem. The world currently lacks the philosophical and political tools but, as Rosenthal and Wallach go on to say, it also "requires input from a variety of perspectives and experiences as well as collaborative problem solving across disciplines and professions" to understand and deal with these implications.

The Geopolitical Lens: Moving landscapes in geopolitics

GESDA's ambition is to allow humanity to benefit from scientific advances through anticipatory science diplomacy — to use the future to build the present, in other words. The GESDA Science Breakthrough Radar is an essential tool in this endeavour. It provides a mapping of which scientific advances in the coming 5, 10 and 25 years could have strong implications on humanity.

This is not enough, however. As recent events show, the world is entering a new era of geopolitics, where science and technology play an increasingly important role.

For GESDA to be successful, it will also have to anticipate where geopolitics as a science is heading. This requires understanding the flow of thoughts within the discipline and an ability to formulate the right questions, from a geopolitical perspective, about the future of the human, of society and of the planet. Such a "geopolitical lens" will equip GESDA with frameworks and tools to navigate this moving landscape.

The geopolitical lens of the 2022 GESDA Science Breakthrough Radar is a discussion with key scholars of geopolitics across three areas:

A. **Moving landscapes in geopolitics:** What are the field's various approaches and lines of thought?

B. **Questions and considerations formulated by geopolitics in this moving landscape**

C. **Tools to navigate uncertain times:** What might the new geopolitical frameworks for science and diplomacy look like?

This section provides a selection of responses collected via interviews conducted in July 2022, laying a foundation for more in-depth analysis in the 2023 edition of the Radar.

A. Moving landscapes in geopolitics: What are the field's various approaches and lines of thought?

Jean-Marc Rickli, Head of Global and Emerging Risks at the Geneva Centre for Security Policy (GCSP) :

We see a very complex world emerging. There are still elements of classical multilateralism and states continue to co-operate within the framework of the UN on very important and uncertain issues. But we see a growing polarisation on issues that have to deal with global leadership and international security. Some people would say that we are moving back towards a Cold War era. I don't think that's the right depiction of the world we are moving to. [...]. For me it is rather **an apolar system**: this is a system where you no longer have actors with the ability to prevail across all dimensions of power. And the reason I argue this is that we need also to zoom out from a very state-centred perspective to one that includes non-state actors. Take multinational companies, for instance. If Apple were a country, it would be the eighth richest country in the world. Microsoft would be the twelfth. And they don't just have more access to data and the latest technologies; they also provide critical infrastructure for nations: in this respect they actually have much more power than a country.

My problem is that traditional theories of International Relations are based on states. If you wanted to understand the international system, you had to understand the dynamics between the most powerful states, whether it's two states in a bi-polar world or 5, 10 or 25 of them in a multipolar world.
But now, with emerging technologies — and especially digital technologies — once something has been translated into lines of code, it's impossible to prevent proliferation. This gives any group of people on the planet access to means of power at a level that has never been seen in the history of humanity.
So when thinking about approaches in international relations and geopolitics, one needs to change the way we look at power, politics and state dynamics. They need to include outliers that can hijack those kinds of capabilities for their own agenda and project power onto the real world. [...] No wonder it is much more difficult to predict the future of geopolitics: the dimensions of power and the number of actors have expanded dramatically.

Let me also mention **technological decoupling**. The West realised during the COVID-19 pandemic that the model of globalisation that had been pushed since the end of the Cold War was no longer working. Just-in-time production, for instance, is only optimal — from an economic point of view — if the global system is stable. This highlighted the West's hyper-dependence on selected countries and regions, and the danger this brings in times of crisis. What's more, the trade war initiated in 2018 between the United States and China means that the Chinese are trying to reduce their dependency on the West as much as possible. They are catching up on key technologies such as microchips — and at the same time they are trying to make the West's access to certain raw materials and resources much more complicated. The West retaliates in a similar manner with China, if you think about the smear campaign against Huawei. This technological decoupling is a driving factor in international relations, and it needs to be taken into account. [...] Take the setting of norms and standards for emerging technologies, for example: it is becoming more and more like a battlefield, where two visions of the world clash. If we consider the future of the internet, the West has traditionally pushed for values around free access to information for all and has seen the internet as a technology for emancipation. With actors such as China, it is all about bending the future of communication networks to national regulations and values, as well as tight control by national governments.

Arancha González Laya, Former Minister of Foreign Affairs, European Union and Cooperation of Spain and Dean, Paris School of International Affairs, Sciences Po:

The big question for our time is the geopolitical competition between the US and China. In my view, that is the framing that we have to use because it will have consequences and determine a number of secondary dimensions. As an example, consider the question of how we will be able to deal with the global commons or manage our interdependencies. To answer that, we need to understand what is motivating this geopolitical contest. Is it an imperialist desire for pre-eminence? Or is it the consequence of China wanting to improve the standards of living of its population? Current schools of thoughts do not agree about the primary factor driving this competition.

From a geopolitical point of view, the biggest risk is the danger of fragmentation across economic, social, environmental and political dimensions. This could lead to a world where we do not have a common system that can ensure financial stability, international trade or governance frameworks for things like Artificial Intelligence. How then do you ensure that there are enough commonalities to engender international co-operation?

> "the biggest risk is the danger of fragmentation across economic, social, environmental and political dimensions"

The third important dimension in the geopolitical competition is the evolving definition of power. Power — in a geopolitical sense — used to be about territories, military capacities and national narratives of conquest. In the 21st century, however, power is becoming much more about the capacity to manage interdependencies at many levels, and to ensure resilience. Exploring the evolving notion of power, its layers and interdependencies as well the variety of actors involved will be critical for thinking about future mechanisms of governance.

Prof. Nayef Al-Rodhan, Head of the Geopolitics and Global Futures Programme, Geneva Center for Security Policy :

Traditional International Relations theory presupposes the rationality of the state in the pursuit of national interests. However, there is ample evidence in contemporary and historical records that, some of the time, some states will act in ways that are not rational. This will lead to misunderstandings and potential conflict, thereby sabotaging the very national interest they aim to serve and preserve — and creating serious geopolitical stress points.

I have theorised that humans can best be described as "emotional amoral egoists". This is the default position for most people, most of the time, accentuated by stress, alienation and fear. It is not a reductionist or deterministic account but a pragmatic one. It is also neither optimistic nor pessimistic, “A good geopolitical reflection today must manage to connect international relations with intranational and transnational dynamics. ”

but neutral. As I have also previously said, states can have the same characteristics: the primary goal of the state is self-preservation and accumulation of power through intrinsic capacities and alliances, and it does this in emotional, amoral and egoistic ways. This is to be expected given the absence of an overarching authority in a self-help global system.

It is partly governed by strategic cultural practices, applied history and the skewed and cumulative historical narratives about a state’s own history, values and triumphs and those of other states.
This allows states and their policy makes and citizens to propagate narrow national historical narratives and current unilateral national interests which may include exploitation, subversion, dominance, alienation, xenophobia, dehumanisation, cultural stratifications and conflict.

Jean-Marie Guéhenno, Arnold A. Saltzman Professor of Practice in International and Public Affairs; Director of SIPA’s Kent Global Leadership Program on Conflict Resolution; Director of International Conflict Resolution Specialization:

The war in Ukraine is providing a kind of magnifying glass for a number of geopolitical questions today. It is often said that traditional geopolitics are back — the classic realism of international relations. This is a superficial analysis that ignores the interaction between international politics and domestic politics ; the Ukraine conflict is less a confrontation of political systems — autocracies versus democracies — than a test of the resilience of societies. For us in the West, the big question (beyond the battles on the ground) is how much our societies will hold up and for how long? In Russia, the situation is different. President Putin’s power is based on depoliticising the country, but the longer the conflict lasts, the more he will have to politicise and to mobilise.

We live in a deeply networked world, composed of fragmented societies that have a fragile internal coherence. If societal resilience becomes a key driver of international relations, the future of geopolitics will be much more about the capacity of human beings to live together and to recognise each other as a group than about a “clash of civilisations” or a “clash of nations”. This links to the second fundamental GESDA question: how can we all live together?

In this case, the distinction between relations between states — between international and domestic affairs — becomes less and less relevant. This is what makes geopolitics so complicated today, and this is where the classical analyses in international relations no longer work. A good geopolitical reflection today must manage to connect international relations with intranational and transnational dynamics.
Those transnational dynamics can be cultural, financial or economic, and will become increasingly important. Transnational communities built around shared values, norms and language are becoming stronger, and they compete with territorial-based communities on which national identities are based. The increasing power and diffusion of communication technologies play a key role here.

Joseph D’Cruz, former Special Advisor for Strategic Planning and Futures to the Administrator of UNDP and CEO of the Roundtable on Sustainable Palm Oil:

Right now there is a sense of de-globalisation occurring. A sense that we are moving away from a world which was becoming more interconnected and more unified in its worldview, towards a decoupling of countries and societies from a universal global order. This fracturing exists on multiple levels: in the area of technology for instance, it could lead to competing or even incompatible standards, with different economic groups and ecosystems of companies competing for their own norms and visions to be the global standard.

There is also a decoupling around culture. In Southeast Asia it has become evident over the last generation that cultural products, norms, aspirations and worldviews are moving away from a primary focus on trends from the West, with more attention paid to cultural signals from East Asia. Malaysia, for instance, is shifting from its historically western-focused cultural worldview towards the South Korea, Japan and China nexus. Younger people now often look to Korea, Japan and China for music, fashion, entertainment and other cultural trends. This cultural decoupling is a very important issue to recognise in international relations and geo-politics, because it ultimately impacts which viewpoints and perspectives are seen as having legitimacy across many sectors including geopolitics and international relations.

“a world process of internationalisation, invention and development, industrial and commercial usage, transfer and diffusion of technologies”

A Western perspective tends to frame this decoupling as a struggle between liberal democracy and authoritarianism. This is not entirely untrue but it is insufficiently nuanced. From the perspectives of China but also from many other countries in South East Asia and Africa, it is sometimes seen as choosing between a socio-political system that provides stability, order, dependable delivery of services and economic growth, and one that promises individual freedom but might also lead to chaos, a lack of direction and therefore a lack of sustained growth and predictability.

It also important to recognise that there is quite a depth and sophistication in the intellectual, cultural and philosophical frameworks that are being created to underpin a more state centric, quasi-authoritarian view of the world — even if they seem to stand against traditional liberal values. At the level of individual choice, for example, many of the more authoritarian worldviews see unconstrained individual choice as suboptimal at a societal level. Recognising that for many in this part of the world these are different perspectives, rather than just a “right” or “wrong” perspective, is key.

Pak Nung Wong, Senior Lecturer, Politics, Languages & International Studies, University of Bath:

Techno-globalism refers to “a world process of internationalisation, invention and development, industrial and commercial usage, transfer and diffusion of technologies”. Techno-globalists regard technological innovation the venue for international cooperation and emphasise “the role of market principles over state control”. In contrast, techno-nationalism can be defined as “the idea that technological strength is an effective determinant of national power in a harshly competitive world”. The techno-nationalists suggest that technological autonomy is central to national security, which is “dependent on a country’s overall technological capacity”. Beneath the U.S.-China trade war, there is actually a more deep-seated structural rivalry between the two powers for global economic supremacy, which is underpinned by technological leadership, that is we have a “U.S.-China techno-geopolitical containment and counter-containment”.

The long-term strategic competition between China and USA therefore involves a marathon struggle not just for political influence in the international system but also for defining the present and the future of technology, which enables the economic superpower to set the standards and therefore can show the world the best future directions for global development. During the Trump administration, the focus of the US was still very much on China. Under the Biden administration, and with the war in Ukraine, the US have entered a dual containment strategy, against Russia and China, with a growing entente between China and Russia as a consequence.

The smaller and mid-size countries will need to devise a new strategy trying to cope with this new reality. In the emerging — if not already formed — techno-digital interdependency between China and other parts of the world, many countries try to get the best from “both sides”, like the Philippines, Indonesia and Thailand. For example, they have not outlawed outright the Huawei 5G technology, but still remaining close to the US. Even the president of the Solomon Islands, while signing a security pact with China, said that he would not exclude a future security cooperation with Australia. As Europe, Asia and Africa will no longer be completely contained by the US, the future communication technologies will become the parallel great-game space for great power competition and containment. This not only will mitigate geopolitical pressures but also could open up unlimited co-developmental space.

B. Questions and considerations formulated by geopolitics in this moving landscape

Jean-Marc Rickli, Head of Global and Emerging Risks at the Geneva Centre for Security Policy (GCSP) :

If we look at what happened from 2013 to 2017 with the Islamic State in Syria, you have an example of a non-state actor that conquered territory the size of the UK in just six months. The Islamic State was the first organisation to understand how to weaponise social media, and the first group ever in the history of warfare to win tactical air supremacy over traditional state actors for a limited time by weaponising commercial drones available in any discount shop. They were also the first non-state actor to develop an active chemical weapon programme with experimental human guinea pigs and produce their means of delivery.

The power, and low barriers to entry, of emerging technologies — especially in synthetic biology, or linked to the emerging developments of neurotechnologies — and sometimes the low barrier to entry for certain techniques, such as CRISPR in synthetic biology or deepfakes in artificial intelligence, could be easily misused by similar groups in the future.

In my 2019 book Surrogate Warfare I argued that, in the 21st century, warfare will extend the use of human surrogates to technological ones, a consequence of progress in artificial intelligence and autonomous agents. This makes technology itself increasingly an actor in future conflicts. These technological surrogates can be used as force multipliers by both state and non-state actors. This makes the reading of the international situation much more complicated. We will still have great powers calling the shots, especially when we consider technological decoupling between power blocks. But this is only a partial view: depending where you look or how you consider a conflict, the set of actors to include in any analysis is completely different. This makes the reading of international relations — and geopolitics — much more complicated that it used to be.

"in the 21st century, warfare will extend the use of human surrogates to technological ones, a consequence of progress in artificial intelligence and autonomous agents"

Prof. Nayef Al-Rodhan, Head of the Geopolitics and Global Futures Programme, Geneva Center for Security Policy:

Outer space security, a serious upcoming geopolitical challenge for the global community, is intimately linked to terrestrial security. It is therefore a perfect geopolitical domain to apply new governance paradigms — what I call Multi-Sum Security and Symbiotic Realism. Outer space is a new domain of potential geopolitical conflict due to the nature of its existence as a global commons: there are gaps in space law and unresolved issues over space debris, militarisation, celestial resources and so on. This is further complicated by the exponential and irreversible over-dependence of humanity on outer space for our daily needs in peace and war. I have previously advocated that if outer space becomes critically unsafe, it will not be selectively unsafe, but unsafe for everyone.

"the future of war and peace can go in two completely opposite directions, driven by emerging technologies."

Jean-Marie Guéhenno, Arnold A. Saltzman Professor of Practice in International and Public Affairs; Director of SIPA's Kent Global Leadership Program on Conflict Resolution; Director of International Conflict Resolution Specialization:

From what we see today, the future of war and peace can go in two completely opposite directions, driven by emerging technologies.

First, artificial intelligence and data management, if they are harnessed by strong states, can manipulate minds in a much more powerful way than traditional propaganda. This could create collective perceptions much more effectively than anything in the past. This could lead to a shock of nationalisms which would be even more brutal and massive than what we saw at the outbreak of World War One.

I think the second direction is more likely, however: our societies will move towards more fragmentation. Even a strong state finds it difficult to exert total control over the information space in a connected world. It is less difficult to weaken the social coherence and resilience of adversaries than to increase one's own. Using the conflict in Ukraine as an example again, we can see how Russia tries to fragment and polarise Western societies but may have difficulties mobilising its own.

That means that there are several possible futures: at one extreme, one of mass confrontation of manipulated masses; at the other, fragmented violence, where societies dissolve in internal conflict and the most resilient country prevails.

Joseph D'Cruz, former Special Advisor for Strategic Planning and Futures to the Administrator of UNDP and CEO of the Roundtable on Sustainable Palm Oil:

Warfare is not something that is defined by geographical borders any more. It has become much more about contesting the integrity and cohesiveness of societies. Rather than attacking your opponent at the border, adversaries now have the capacity to reach into the systems and structures and sinews of the opposite society and undermining those. You undermine trust, you undermine social infrastructures. In the worst case, you use biological tools to undermine physical well-being and health. That becomes the reality of warfare increasingly as we move forward. And I think we're seeing elements of this in many places already. [...]

We may need to accept a world where peace is no longer something that's guaranteed by strong international institutions. The actors of the international community need to be able to manage peace by anticipating where and how tensions can erupt, and by accepting that there will be cases where these tensions unavoidably erupt into active warfare, be it actual fighting or economic, cultural, or misinformation-based conflict.

Here, the notion that peace could be imposed by coalitions of actors, or by external great powers, vanishes. The opportunity and the ability to undertake warfare now exists at so many levels, and with such low barriers to entry, that almost any actor can engage in quite sophisticated attacks against countries and societies. Therefore, peace can't be imposed, neither by use of force nor by structured multilateral global accords, because the ability to disrupt peace and to wage war is no longer managed by the state through the use of conventional military force.

"Warfare is not something that is defined by geographical borders any more. It has become much more about contesting the integrity and cohesiveness of societies"

Pak Nung Wong, Senior Lecturer, Politics, Languages & International Studies, University of Bath:

From my point of view, when we are thinking about future generations, we need to find a new geopolitics beyond the Earth, driven by the increasing competition for resources, markets and economic development. Therefore, I would see the future of geopolitics tightly connected with science and technology, under the larger framework of interstellar studies. But different cultures have different understanding about how to approach space. China, for example, has much more of an economic point of view on space, very much tied up with seeking for and exploiting new resources and rare minerals — because China faces an acute problem of environmental degradation and of resource depletion. The US and European approach to space is more cautious and inclined to scientific questions and explorations that advance knowledge and leadership. Another peculiar difference is that the Chinese are sending signals to the outer space and they are receiving signals back; they are not afraid of attracting potential newcomers to the earth. The U.S. has a very different approach: although they listen for signals, the U.S. has warned China to stop sending signals because of the risk that it might provoke a war with unknown entities. Interstellar geopolitics, or geopolitics beyond the Earth, is certainly an area that will define war, peace and conflict in the future.

C. Tools to navigate uncertain times: What might the new geopolitical frameworks for science and diplomacy look like?

Jean-Marc Rickli, Head of Global and Emerging Risks at the Geneva Centre for Security Policy (GCSP)

What we have now in international relations is a situation where one country, the United States, is a hegemonic power that emerged from the Cold War but is perceived as being in decline. [...] With the world in this state of transformation, revisionist actors such as Russia and China are challenging the status quo by using all the different levers of power available to contest this hegemony.

In the 21st century, science and technology are becoming key levers of power. One could even say that they are the most important ones, because these emerging technologies are so transformative that they provide huge amounts of power to those who are actually able to master them and control them. And so there is a race to dominate in these fields. Take microchip technology, for example. This is a key area: when you are no longer able to have access to the most efficient microchips, you have a strategic disadvantage. Another example is advanced AI: the first actor able to master Artificial General Intelligence will have a significant competitive advantage — not only in the technology, but also in terms of defining norms and how the technology can be deployed — and so the race to get there intensifies. Not only science and technology create new means of power: the norms and standards that regulate these technologies are also becoming the key enablers to disseminate strategic national values and therefore worldviews, intensifying further more international competition and rivalry.

"In the 21st century, science and technology are becoming key levers of power. One could even say that they are the most important ones"

> "states are in competition with private companies, with virtual communities and all sorts of structures that bring human beings together."

Arancha González Laya, Former Minister of Foreign Affairs, European Union and Cooperation of Spain and Dean Paris School of International Affairs, Sciences Po:

Science and technology are built around a common belief in rationality. This common belief can also help the conversations that we are not fostering at the global level. It could be a unifying force that creates spaces for collaboration and provide safe havens for collaboration on important global issues. Imagine, for example, a huge global programme to fight cancer. In a world that is very power-driven, with rising geopolitical contests and the risk of fragmenting, keeping channels of collaboration open through science and technology will be critical.

> "with rising geopolitical contests and the risk of fragmenting, keeping channels of collaboration open through science and technology will be critical."

Prof. Nayef Al-Rodhan, Head of the Geopolitics and Global Futures Programme, Geneva Center for Security Policy:

Current and future statecraft and diplomacy will require a broader geopolitical lens that employs transdisciplinary approaches and subscribes to collective security and prosperity approaches here on earth and in outer space. This needs to include Multi-Sum Security — a security framework that takes into account interdependency of all state actors, replacing zero-sum paradigms — and Symbiotic Realism, a neurobiologically based framework that attempts to explain and predict the behavior of states and advocates. Going forward, humanity will either triumph together or fail together. This prospect is too consequential for our species to allow narrow geopolitical lenses of states to dictate relations and operate dangerous power politics, with the rest of humanity on the receiving end. It is time for decision-makers and concerned citizens throughout the world to realise that the only way forward for humanity is to head towards collective, equitable and sustainable security, peace and prosperity for all, at all times and under all circumstances, both here on earth and in outer space.

Jean-Marie Guéhenno, Arnold A. Saltzman Professor of Practice in International and Public Affairs; Director of SIPA's Kent Global Leadership Program on Conflict Resolution; Director of International Conflict Resolution Specialization:

Classic international organisations such as the United Nations have difficulties adapting to this world because they are institutions that are based on geography. The United Nations, as its name indicates, is an organisation composed of nation states. It suffers from the same fragility of the states that make it up. These states are in competition with private companies, with virtual communities and all sorts of structures that bring human beings together. The states are no longer the only actors that shape geopolitics, as they may have thought they were in the past. Therefore, when we speak about peace and war, we need to take this multidimensional world into account. This is what Pascal Lamy would call polylateralism. This articulation of power between groups of a different nature raises difficult questions about legitimacy. Territorial legitimacy is evident, but what legitimacy do self-proclaimed communities have? This is a political issue that will be increasingly present in our mind and in our societies. We can see this already in today's debates; in the reactions of people to (for example) the legitimacy of science; in the mistrust towards entrepreneurs and private companies, and in the mistrust of political institutions. The self-evident territorial communities of the past are under stress, and there is no clarity on their articulation with the virtual communities of the future.

Joseph D'Cruz, former Senior Advisor for Strategic Planning and Futures to the Administrator of UNDP and CEO of the Roundtable on Sustainable Palm Oil.

Scientists have been trained on the idea that there is a purity to science, and therefore all you need to do is chase the question down to find the answer. But we now live in a world where scientists have to be much more acutely conscious of the political implications and ramifications of the questions they ask, the answers they find, and how those answers are shared and disseminated. We need to go back a little bit to the kind of world we had where science was very enmeshed with questions of philosophy: questions of use and value and purpose and risk and implications.

Meanwhile, diplomacy needs to recalibrate, becoming more focused on the active management of risks and the avoidance of conflict (as well as the pursuit of national interests), rather than creating structures and institutions through which interests and risks can be mediated. This will lead to a much more organic diplomacy, which is perhaps more tactical rather than institutional. It is a diplomacy that has to be able to understand and weigh the multi-layered and often competing or conflicting interests of a country in terms of where and how it engages with other conflicts. There is a need to build a diplomatic corps able to recognise and engage with all the complexity of the world.

Anticipation and foresight are critical tools to navigate this uncertainty, in order to develop the frameworks that will inform how decisions are made and how you build the necessary tools and skill sets. Scientists, technologists and diplomats all have to recognise that we must navigate today by looking to the future, not the present or the past.

"Scientists, technologists and diplomats all have to recognise that we must navigate today by looking to the future, not the present or the past."

Jean-Marie Guéhenno
Arnold A. Saltzman Professor of Practice in International and Public Affairs;
Director of SIPA's Kent Global Leadership Program on Conflict Resolution;
Director of International Conflict Resolution Specialization

Invited Contribution: The Future of Peace and War: The vital role of debate and difference

As the British historian Michael Howard has brilliantly explained, conflict is always a mirror of a particular society. The wars of the knights had little in common with the wars of the professional soldiers of the 18th century, or with the wars of the French Revolution and the Napoleonic era. More recently, the Industrial Age made "total war" a reality, culminating in the possibility of mass annihilation of the nuclear age.

What will the wars of the future look like, as the age of data is transforming societies in ways not seen since the Industrial Revolution? Two trends are emerging that point into two opposite directions.

On the one hand, technological progress leads to an unprecedented potential empowerment of the individual. We have all the knowledge of the world at our fingertips, and with ever more effective connectivity we can insert ourselves in the production processes, ensuring that products are tailored to our specific needs. With 3D printing, we can even produce our own products, from clothes to less benign possessions such as guns. This extreme individualisation reflects a broader trend in science as well as in society. As knowledge gains ever more specificity, medicine can be increasingly tailored to individual profiles. And most societies — especially but not only in the West — celebrate the agency of the individual as the master of their own destiny.

On the other hand, the mass collection of data gives the collecting organisations the capacity to shape collective perceptions in a way that is much more powerful than traditional propaganda. Individuals can now be easily manipulated by corporations or authoritarian states that collect and manage data. Meanwhile, the volume of data that we generate is growing exponentially, as the digitalisation of the world ensures that every moment of our lives leaves a trace. Moreover, the volume collected is so vast that only algorithms can effectively manage it. Most of these algorithms are self-learning, raising the question of who has ultimate control over them.

The trend towards ever greater individualisation may usher in ever more fragmented societies, deprived of a shared common space. The decline of collective values makes the avoidance of risk the absolute priority. And the emphasis on the supreme value of the individual increases the potency of terrorism, as the protection of each individual life trumps any other societal consideration. Societies fragment into self-referential groups united by fear rather than shared values, and public debate withers. This is already in evidence in many western societies. In the absence of conflicting but nevertheless collective visions structuring societies, traditional politics is in decline, replaced by atomised violence and radical populist groups whose appeal rests on symbols rather than genuine programs. Over time, such societies will become increasingly vulnerable, as they find it more and more difficult to raise the revenues that fund public services. A vicious circle sets in, whereby the declining legitimacy of collective institutions erodes their capacity to support themselves, which in turn leads to the deterioration of the services they provide.

The opposite trend, reflected in the concentration of power resulting from the mass collection of data, generates a huge inequality between the entities that collect and manage data and the individuals who provide them. Today there is a great difference between societies in which the state is the main collector and manager of data, and those in which corporations are the main actors. China is the prime example of the first category, and it uses the data to ensure its stability, by suppressing dissent, but with the greater ambition to create a "harmonious" society in which perceptions are so tightly controlled that the people won't even feel their chains, living happily in a manufactured bliss. The giant American corporations that thrive on data have a different goal: they want to maximise their profit. Social media companies have found, unsurprisingly, that people prefer to be reinforced in their opinions rather than challenged, resulting in the formation of groups which self-radicalise and have little time for contrarian views. These companies, therefore, tend to amplify difference without facilitating discussion.

In theory, the virtual space of the internet could foster a virtual agora in which various views could be discussed. However, the reality is the opposite, and the cacophony of opinions is generating a dangerous backlash: the easiest way to avoid damaging polarisation is to suppress controversial views, and there are increasing demands for stricter regulation of the opinions that can be expressed on the internet. It is possible, if not likely, that western societies might eventually embrace their own version of the Chinese model, suppressing any opinion that triggers controversy, thereby fostering homogeneous conformist societies. The end-result would be the consolidation of societies where there is little dissent, with the risk that governments could use the power of data to mobilise their societies on the basis of strident nationalism and identity. Instead of the fragmented violence of hyper-individualistic societies, the world could face not the clash of civilisations foreseen by Huntington, but a clash of closed societies incapable of relating peacefully with anything different from them. Domestic dysfunctionality may be a predictor of international conflict. Russia today illustrates how a violent society can turn into a violent international actor. In an age of weapons of mass destruction, such mass thinking could be catastrophic.

We can do better than those two dystopian futures, but we need to work out how. How do we prevent the slide from dysfunctional societies to a dysfunctional international system? Political institutions are lagging behind scientific and technical progress, and the gap that has opened is at the root of the crisis of trust in collective institutions. The legitimacy of traditional institutions is already being challenged: the enormous expansion of knowledge inevitably increases the separation between political and technical decisions at the same time as power and wealth are being captured by new actors. Rebuilding trust under such circumstances is a difficult but necessary process. It will require new institutions to restore accountability, and a better and more transparent articulation between competing legitimacies. The strength of democratic societies has been to welcome debate and differences. Their challenge is now to ensure that differences don't turn into violent conflict.

Invited Contribution:

The Future of Peace and War: Warfare at the Technological Edge

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Technological innovations have always shaped conflict and war. In the 20th century, technological developments in the military realm mainly concerned conventional weapons, such as fighter jets, missiles, and tanks as well as nuclear, biological and chemical weapons. The end of the last century brought through cutting-edge technologies such as satellite communication and digital tools. The beginning of the 21st century has accentuated the developments in these fields and continues to produce the technologies of the future, such as artificial intelligence (AI), nanotechnology, and human augmentation. Given these technologies' novel features, their military use will most likely have considerable influence on future conflict and war.

New technologies in conflict and warfare

Several new technologies on the horizon are likely to impact future conflict and warfare. Armed forces and other actors already rely heavily on **digital tools**. These technologies have enhanced the speed, quantity and quality of information, thereby enabling a connected battlefield. Cyber-operations further allow states and non-state actors to attack military forces and critical infrastructure, as well as retrieve sensitive information from the adversary. While cyber-operations have thus become a full feature of warfare, they also tend to precede the outbreak of conflict. In the future, it is possible that with the increased sophistication of digital tools, cyber-operations will take on dynamics of their own — dynamics that are different from those in the other military domains. To date, offensive cyber-operations have not yet led to the outbreak of war in the physical world, for instance. The damage that cyber-operations create tends to be very real, however, as prominent attacks against oil, healthcare and nuclear facilities have shown.

New technological developments also impact the militarisation of **outer space**. Armed forces have used outer space for several decades now, but both civilian and military use of outer space has significantly increased recently, making outer space congested, contested and competitive. This increases the risk of confrontation, inadvertent incidents and escalation. Yet modern societies' strong reliance on space technologies also implies significant vulnerabilities. From a military perspective, outer space assets are crucial for the conduct of modern military operations, thereby making them potential targets. A challenge in this regard is "dual-use" of civilian assets for military purposes, as this makes civilian assets legitimate targets with potentially serious consequences on societies. Given the military value of outer space technology, it is very likely that states will conduct cyber-operations against others' assets in outer space to hamper them without causing damage to their proper assets. While no placement of kinetic weapons in outer space has been confirmed so far, several states have operational anti-satellite weapons that they can launch from the ground or air. As such, these states have the ability to disrupt the space technologies on which modern societies rely. Recent tests of anti-satellite weapons have caused problematic debris, for instance.

Artificial intelligence is another emerging technology that is likely to be increasingly used in warfare. AI applications can be used to produce and disseminate "deepfakes" for the purpose of subversion, for instance. In addition, AI enables increasingly autonomous systems, allowing ever more delegation of tasks to algorithms and machines. This reduces the need for human soldiers and increases the speed and complexity of warfare. Already today, armed forces use AI applications in the context of reconnaissance and communication. Other applications that are likely to see further development are AI systems that guide drones with limited human interaction, including their coordination in swarms. Early applications of AI-enabled swarming and autonomous drones have already been used in recent military operations, such as in Palestine and Libya. Technologically advanced states' recent decisions to enhance their investments for developing, procuring and integrating military AI applications make the wider and more substantial use of such technologies in all military domains and levels very likely. This competition for developing military AI may require the dynamics, costs, and risks of traditional arms races.

Quantum computing, nanotechnologies, human augmentation and **synthetic biology** are further technologies that may be used in future warfare. To date, publicly available information on the development of these technologies for military purposes, and on their sophistication and readiness for operationalisation, is scarce. Therefore, anticipating how they will affect the future of warfare remains very difficult. It is thus necessary to monitor the civilian development of these technologies very closely in order to infer potential military uses from their defining features and their concrete advantages for military operations. If these technologies are to be properly developed for military purposes, it can be assumed that they will lead to better-performing armed forces and combatants, which will further increase the speed and complexity of the battlefield. As with all technological developments in the military realm, any such progress will likely increase modern armed forces' dependence on technology; this may become a vulnerability of its own.

Outlook and broader implications

Today's and tomorrow's rapid technological developments will impact the future of conflict and warfare. A general trend is that technological innovation is usually driven by civilian research and development. **Civilian technologies** are then oftentimes adapted and integrated for military purposes. This poses challenges to civilian developers, who may not wish that their products be used for warfare. This also poses challenges for states' procurement processes, which tend to be complex and slow, because the technologies may be outdated by the time they are acquired. Hence, it is very likely that states will further increase their investments in research and development specifically for military purposes and in close co-operation with civilian partners.

A further trend is that new technologies enable states to be engaged in warfare, conflict and military confrontation less directly. Technologies and non-state actors — there is often no clear distinction between military and civilian tools and actors — are increasingly used by states as surrogates. **Hybrid warfare, surrogate warfare** and **remote warfare** conceptualise such modern forms of warfare that are likely to be employed in the future, notably in the context of tensions and confrontation between great powers. Yet, private actors may also access and use new technologies for their own objectives — hacktivists and terrorist organisations using civilian drones being obvious examples.

As new technologies emerge and are used for military purposes, their impact on the future of peace and warfare needs to be closely observed and evaluated. This also requires exploration and debate on how **international law, norms** and **standards** apply and need to be developed, since the military use of new technologies brings numerous ethical challenges. As such, the future is now.

Riel Miller
Head of Futures Literacy UNESCO

Invited Contribution: Futures Literacy

Life exists in our universe, as does time, hence it is no surprise that all living things incorporate the "later-than-now" in their functioning. Anticipatory systems and processes, the fruit of serendipitous evolutionary wanderings, express an amazing diversity of reasons and methods for taking into account the not-yet-existing future.

Humans possess a wide range of such different capabilities, ranging from the non-conscious immune system that mobilises in response to various provocations that might threaten the body, to our ability to imagine futures, our primary form of conscious anticipation. Conscious and semi-conscious anticipation also takes many diverse forms, including the learned response of a child that cries to be fed or absorbs the lesson that it is a matter of survival to look both ways before crossing the street. What is perhaps most striking is that there has been relatively little direct scientific inquiry into these many anticipatory systems and processes, in particular the performative attributes of conscious imagining that constitute the dominant form of the expression of the "future" in the present.

Advancing the exploration of the diversity of reasons and methods humans use to imagine the future has been the driving force behind a decade-long action-research/action-learning initiative that UNESCO has conducted in its role as a global laboratory of ideas. In collaboration with people around the world, we have been running specially designed experiments that we call Futures Literacy Laboratories.

These Labs are designed to probe the processes and assumptions at play when humans make use of the future. They are designed on the basis of two theoretical frameworks — one that proposes principles for the generation of knowledge through collective intelligence, and the other anchored in a framework for categorising anticipatory systems and processes. Working with participants from all walks of life and corners of the planet we have been able to co-design Labs that reveal the diversity of conscious human anticipatory systems and processes.

Peeling away the layers and taken-for-granted attributes of why and how people actually use the future constitutes an action-learning process that not only tests the hypothesis of anticipatory diversity but also initiates learning voyages that provide participants with a better understanding of nature and role of the future in what they perceive and do. We call this latter fruit of the action-learning aspects of Labs "Futures Literacy". This capability is accessible to all people in as much as all people are constantly using the future and are therefore able to recognise and refine their use of different anticipatory systems and processes.

Since 2012 we have co-created over 100 such Labs. We have been able to show that, despite the fact that initially most people are unaware of the richness of human anticipatory systems and processes, they rapidly leverage the power of the future as a constant presence in their lives, shaping their hopes and fears, perceptions and choices, in order to begin to distinguish different kinds of future.

From this perspective Futures Literacy is similar to the more familiar "reading and writing" literacy: it is a capability that can be learned by simply beginning with what people are familiar with in their everyday lives. Reading augments our capacity to speak. Futures Literacy augments our capacity to imagine the future. What is crucial to realise is that, like reading and writing, there is no way to know what people will do with the enhanced capacity to understand why and how they imagine the future. Capabilities are open, without any particular necessity or causal relationship to an outcome. That said, humans are accustomed to using the future in specific ways. The most dominant reason for imagining the future is to predict what will happen. From oracles to prophets to visionary leaders, humans have long relied on probable or desired images of the future to guide their decisions. Today is no different, as attested to by the horde of forecasters, pundits and planners who make their living by trying to predict what will happen in business, the economy and politics.

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ANITI, University of Toulouse.

Invited Contribution:
How Machine Learning is Transforming Regional Economic Development

It is no mystery that human societies are extremely complex, defined by many variables and interactions that cannot be simplified or reduced effectively. Such complex systems show emergent properties — that is, characteristics or behaviours whose existence at the macro scale cannot be traced back to micro- level mechanisms. An example might be weather patterns: it is impossible to explain the weather using a glass of water. In important ways, the economy is a complex system, like the weather, with macro-level behaviours that are hard to predict and nearly impossible to control.

But the explosion in big data and machine learning is providing us with tools that are helping us improve our understanding of these complex systems data with the granularity needed to trace the identity of many components and the techniques needed to make more advanced predictions based on this data. For more than a decade now, the field of economic complexity has pioneered the use of machine learning and network science techniques to answer questions of economic growth, regional diversification, and inequality. While those questions

are not new, the use of machine learning expands the toolbox methods by allowing researchers to avoid the need to aggregate data into broad groups.
This helps account for the non-fungibility of physical and human capital, since surgeons cannot be replaced by pianists, nor are harvesting machines interchangeable with rollercoasters. These methods can capture an economics where structure is not limited by coarse concepts such as agriculture, manufacturing, and services: but where we can literally distinguish apples from oranges, and oranges from fertilisers, packaging, and farming equipment.

The data-rich approaches of economic complexity are increasingly embraced by policymakers around the world, because of their ability to explain changes in regional diversification patterns and explain international variations in inclusive green growth. These approaches are useful to those looking to understand the economic opportunities of narrowly defined regions and industries. Not what is good in general, but what is specific to the city or region of concern for a policymaker.

This can be intellectually refreshing, especially for the policymakers who have been told countless times to focus on good governance, education, and institutions, without too many specifics of what these broad concepts mean, or how they apply to their distinct conundrums. However, the real politik of their work requires estimates of the economic potential of specific regions and industries. Maps of the competitive landscape and their chances of success in any particular industry, research activity, or innovation. As a result, they look for estimates that take into consideration information such as a region's specific portfolio of industries, export products, and patents — the kind of information that economic complexity methods can tackle well. These are not abstracted categorisations, but granular indices that give way to an augmented form of policymaking, where data-rich platforms empower economic analysts in their quest to fulfil specific economic objectives.

Consider the case of Data Mexico, the official economic data distribution and visualisation platform of Mexico's secretary of the economy. The government of Mexico has been using Data Mexico for the last two years to train their embassies and regional governments: it allows analysts to quickly retrieve visualisations about thousands of municipalities, industries, and occupations, and provides them with the information they need to promote commercial relationships. Do you need to, say, meet with shoe manufacturers from Vietnam? Data Mexico has detailed information about the shoe industry in Mexico and about current commercial relationships between Mexico and Vietnam, and can inform your decision. In this way, by pairing up a data platform with professional analysts, the secretary of the economy of Mexico is demonstrating a new model of economic intelligence support that radiates from the central government to regional units and diplomatic missions.

Today, the field of economic complexity is growing fast as young scholars continue to enter the area, developing and introducing new methods and ideas. These advances involve both empirical work — such as more nuanced measures of complexity that are better at predicting growth, inequality, and emissions — and theoretical work involving deep connections with traditional economic growth literature.
But more importantly, the field is helping bring together expertise from a range of disciplines, such as economic geography, computer science, and physics. This is how we can best understand the economy: not in theory, but in its natural complexity.

Actions & Debates

Taking the Pulse of Society


Nicola Forster
President Swiss Society for the Common Good,
President Science-et-Cité, Co-Founder Foraus


Valentine von Toggenburg-Bulliard
Global Shaper World Economic Forum,
Curator, Global Shapers Zurich Hub

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, their potentials 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. Again, these will inform the direction of future work.

For example, we have identified that the future of economics is being discussed extremely widely, while the conversation about anticipated applications in augmented reality is primarily dominated by younger age groups. Ethical concerns about artificial intelligence are being strongly voiced on social media, but there is very little recognition of actual or potential regulatory measures. Military applications of science and technology such as biological weapons, AI and quantum computers are viewed very critically. On the other hand, there is positive sentiment about new technologies that promise to improve teaching outcomes, the rapid expansion of educational technologies and the way that people can exchange tips about upskilling opportunities on social media. More insights from this machine learning-based analysis are written up in the body of the report.

This year we have also innovated with a tool for monitoring civil society and private citizen activity around the scientific emerging topics included in the radar. We looked at four areas of activity: raising of public awareness; entrepreneurial endeavours; policy-oriented 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. These insights are updated on a monthly basis on the radar's digital platform.

Our monitoring found that a significant share of the actors monitored do indeed act in the areas of the advanced topics considered in this report. This ranges from the creation of open-source and sandbox initiatives to spur entrepreneurial activities for the metaverse and artificial worlds, to crowdfunding for negative emission technologies in the context of decarbonisation or do-it-yourself science in the area of genetic engineering.

Our monitoring demonstrated that it is indeed possible to monitor public opinion and activity in a useful way; the results are discussed within the Actions & Debates section.

Quantum Revolution & Advanced AI

What do people say?

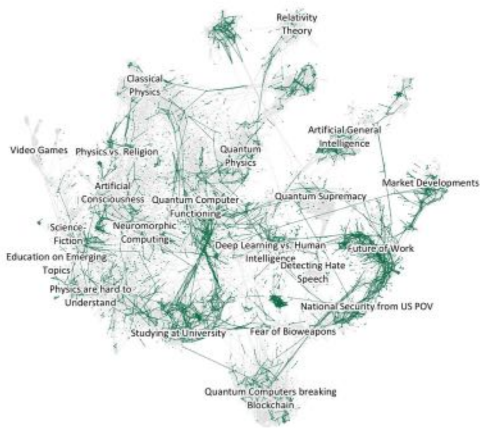
There is geographic variation in the tone and nature of this global discussion about Quantum and AI, with authors in Asia the most positive about the technology and how it could be integrated into society. In posts from authors in Europe and the US, there is more hesitancy around using the technology and more discussion over side effects and ethical considerations.

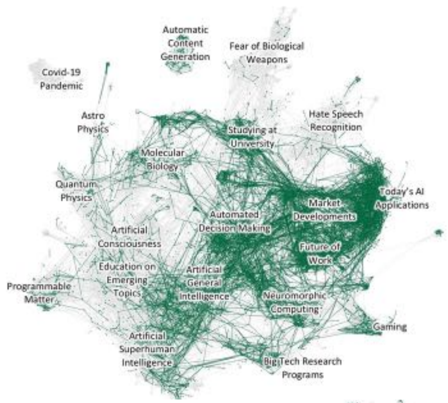
The age group dominating the conversation varies across continents. Older age groups are more active in North America and Europe, while younger voices dominate in Latin America, Africa and Asia. Authorship is mostly male, academic and North America based, particularly for hype topics like quantum computing or quantum cryptography. Social implication topics tend to be from female authors, who are underrepresented globally but strongly overrepresented in Asia. Younger voices are dominating the discussion around Collective intelligence and augmented reality.

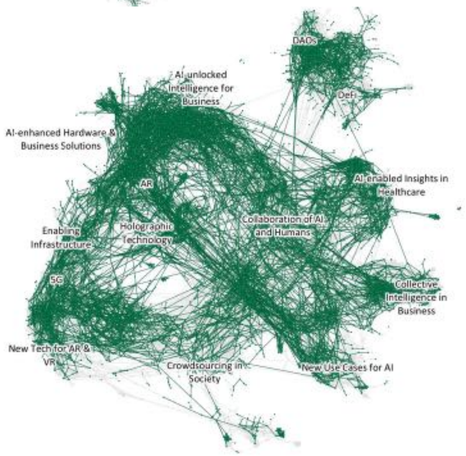
Sentiment towards these technologies tends to vary depending on the forum of discussion, with discussions on social media platforms like Twitter and Instagram more negative than long-form forums. Discussions vary across continents, but with positive sentiment centred around supporting infrastructure and new technology rather than implementation.

For AI, discussions differ depending on how it is being used. Authors become more sceptical when it comes to obvious collaboration between humans and technology — for example, if AI provides instructions that could determine human behaviour, some concerns around liability emerge.

Within the sentiment analysis clouds below each node represents one article and the linkages between dots show relations between topics in the analysed data.







Positive sentiment is centered around:

The quantum revolution, with emerging applications of quantum technology, and its potential to change the world in a positive way.

● 1.2 **Quantum Technologies**

Quantum-safe cryptography may be among the technologies closest to realisation and offers a route to highly desired increase in security.

○ 1.2.1 **Quantum communication**

The potential of biocomputing (mainly DNA computing) and its expected performance.

● 1.4 **Biological Computing**

Neuromorphic computing as an enabler for AI use-cases in demanding environments.

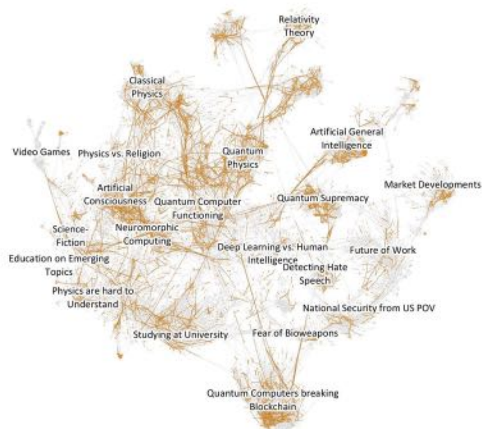
○ 1.3.2 **Neuromorphic systems**

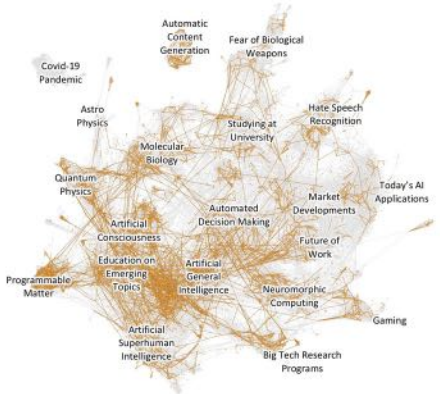
The accelerating deployment of 5G, which offers never-seen use cases for augmented reality and combining edge-computing and AI-analytics.

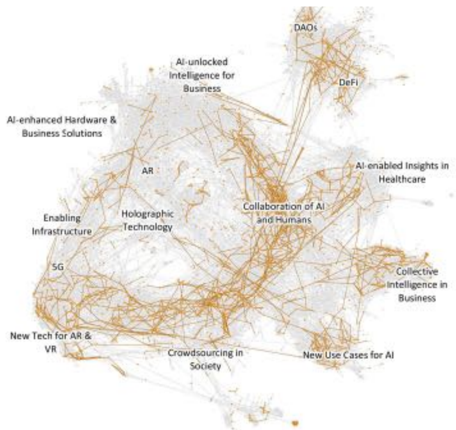
○ 1.5.1 **Augmented reality hardware**

AI and AR enhanced hardware and business solutions, which will result in remote industrial working or cutting edge image analysis and computer vision.

○ 1.5.1 **Augmented reality hardware**







Neutral/mixed sentiment is centered around:

The companies achieving quantum supremacy — though they are being applauded, they are also criticised for sharing premature results.

1.2.2 Quantum computing

The impact of AI on the future of work. This is a polarised discussion, based on whether AI will augment humans, replace cumbersome work, or replace humans entirely.

5.3.2 Automation and Work

The tipping point in AI, when the technology will irrevocably change its role for society: it contains scenarios ranging from Armageddon to superhumans.

4.4.3 Privatisation of governance

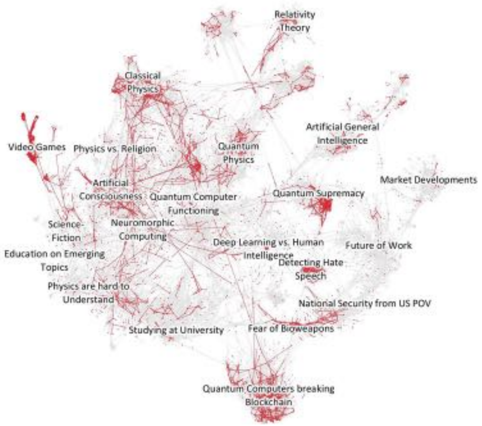
4.4.2 Digital identity and trust

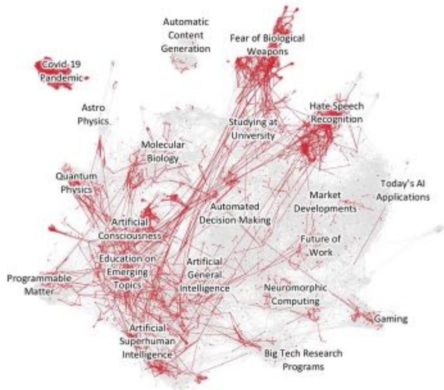
5.1.4 Design for values

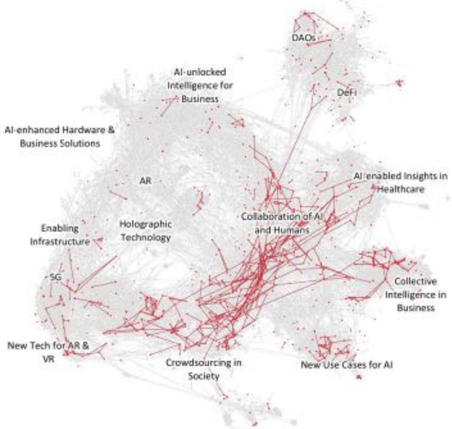
Use cases of AI in forecasting, decision-making in policy, and military applications. These have led to research and development grants, and concerns over regulation.

1.6.2 Smarter teams

AI-directed decisions, with concerns around liability.







Negative sentiment is centered around:

Emerging cyber-threats if standard encryption protocols become crackable through quantum algorithms.

1.2.2 **Quantum computing**

AI entering areas of life, such as automated credit scoring, where ethical questions arise due to built-in AI biases.

Emerging military applications, such as hostile AI and biological weapons. These are viewed very critically.

4.3 **Digital Technologies and Conflict**

What do people do?

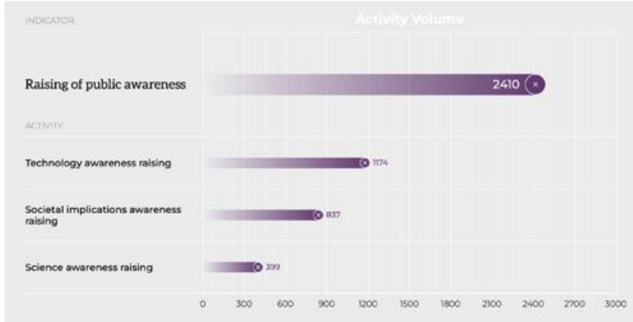
Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected 5239 “actions” in the field of Quantum Revolution & Advanced AI in the first six months of the year. Compared with the other Platforms of Human Augmentation, Eco-Regeneration & Geoengineering and Science & Diplomacy, this represents a below average citizen engagement.

The emerging topic of Augmented Reality saw the most engagement within the field of Quantum Revolution & Advanced AI, with nearly 60% of all monitored activities, followed by Quantum Technologies (25%) and Advanced AI 10%).

The strong activity around augmented reality is linked to recent metaverse announcements and the promise it holds to establish new business ventures and communicate.

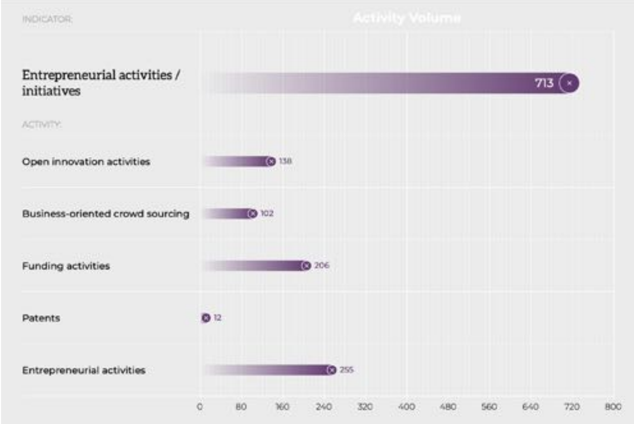
Monitored activity was divided into four indicator categories: raising public awareness, entrepreneurial activities, policy-oriented activities and contributions to science and technology. This data will be updated quarterly on our digital platform. Further details on the indicators can be found in this section’s introduction, while information on the tools and its limitations and biases can be found in the appendix.

Raising public awareness had by far the most data points, corresponding to the need to inform, communicate and popularise advances in digital technologies. These discussions are very much connected to the perceived “hype” around the metaverse and the low entry barrier to being active in this area.



The large majority of activities detected by this indicator are directly related to the need to raise awareness about the implications and opportunities related to these domains, with a big focus on augmented reality and the metaverse. Monitored civil society actors agree that artificial worlds provide a huge space for entrepreneurial and communication opportunities, as other indicators show. Considering that real-time applications are anticipated in 10 years, some citizens and organisations are starting to raise awareness of the impact that augmented reality will have on specific communities and legal issues, for example the ownership of assets in virtual worlds or how to safeguard people’s rights. Science awareness-raising activities focus on understanding and communicating about quantum research and what it means for our society. This touches fundamental aspects of quantum science, as well as understanding potential applications of quantum computing, quantum sensing and quantum cryptography.

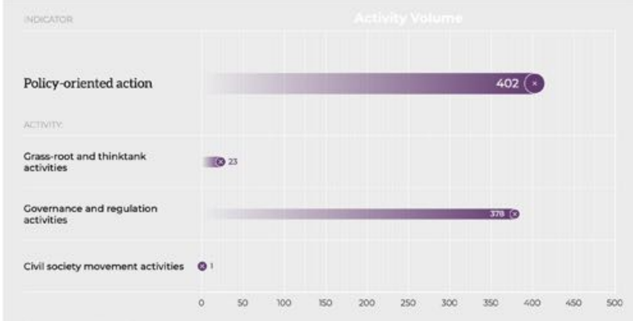
- 1.5 Augmented Reality
- 1.5.1 Augmented reality hardware
- 1.5.2 Augmented experiences
- 1.5.3 AR platforms
- 1.5.4 Human factors of AR
- 1.2.1 Quantum communication
- 1.2.2 Quantum computing
- 1.2.3 Quantum sensing & imaging
- 1.2.4 Quantum foundations



Entrepreneurial actions in this field are split equally between entrepreneurial and open innovation activities. The entrepreneurial activities are linked to the announcement of competitions for startups focused on future metaverse applications and business models and next-generation quantum technologies, especially linked to quantum computing. There were also many calls for the establishment of virtual and augmented reality standards by the developer community to speed up innovation.

Finally, activity detected under business-oriented crowdsourcing is linked to the launch of business development challenges for applications in the metaverse, but also access to national quantum computing platforms such as the Singapore Quantum Engineering Programme for the joint development of quantum applications. This data indicates that many civil society actors understand the business potential of the technology and are developing entrepreneurial strategies. As is highlighted in the opportunities section, this assessment is shared by representatives of the academic, diplomatic and business communities that participated in the respective summit session. They stress the need to maintain access to a level-playing field that allows smaller actors to access and develop quantum applications.

- 1.5 Augmented Reality
- 1.5.3 AR platforms
- 1.2.1 Quantum communication

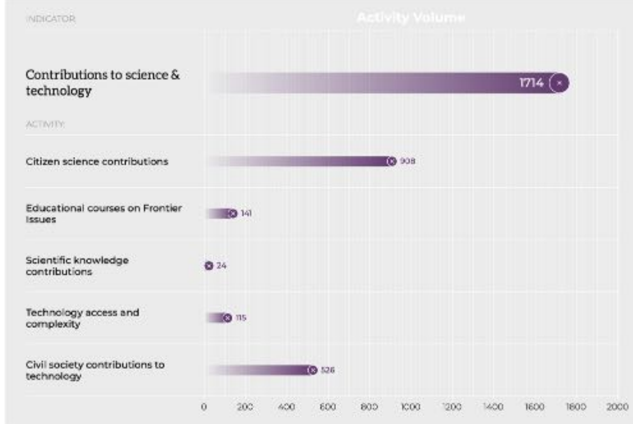


Unsurprisingly, most policy-oriented activities detected by our tool are linked to governance and regulation. These deal mainly with increasing privacy concerns over the development and deployment of AR technology. This challenge has also been identified in our analysis of what people are talking about online and in the trends sections, where anticipated breakthroughs in Augmented Reality directly mention potential implications at 25 years of the technology.

Civil society actors are raising questions about rights and obligations in an augmented or artificial world, and what will be done with personal data. These concerns — and related governance activities — are shared by our brief on Digital Technologies and Conflicts, where the manipulative power of advanced immersive technologies is described. This also links with anticipated developments around Democracy-Affirming Technologies which highlights how advances in Augmented Reality and the metaverse could challenge trust in democratic institutions and provide new ways for citizens to engage, but also raise the question of the balance of power between actors in society.

On quantum computing, civil society actors questioned the capacity of the technology to resolve large societal challenges, but also highlighted access and education issues to ensure inclusive use of the technology (link to the opportunities section). Grass-roots and think tank activities stressed the need for citizens, companies and government agencies to make their data systems quantum-ready and limit the potential for malicious activity.

- 1.5.4 Human factors of AR
- 4.3 Digital Technologies and Conflict
- 4.4.2 Digital identity and trust
- 4.4.3 Privatisation of governance
- 4.4.4 Censorship circumvention and content moderation
- 1.2.1 Quantum communication
- 1.2.2 Quantum computing



Contributions of civil society actors to science and technology are primarily driven by citizen-science activities and the contribution of non-academic actors to science and the production of knowledge. In contrast to the other indicators, the scores here are linked to developing open-source libraries for advanced AI. In the area of Augmented Reality, most activity was focused on educational courses about potential opportunities in the metaverse and other virtual worlds. Finally, in the area of quantum technologies, the activities were centred around the need to understand quantum science and related applications, as well as new ideas for quantum applications.

- 1.1 Advanced AI
- 1.5 Augmented Reality
- 1.2 Quantum Technologies
- 1.2.4 Quantum foundations

Human Augmentation

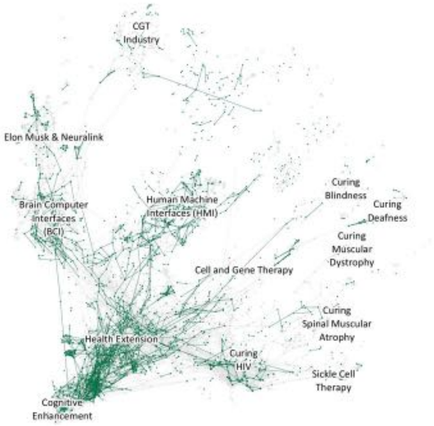
What do people say?

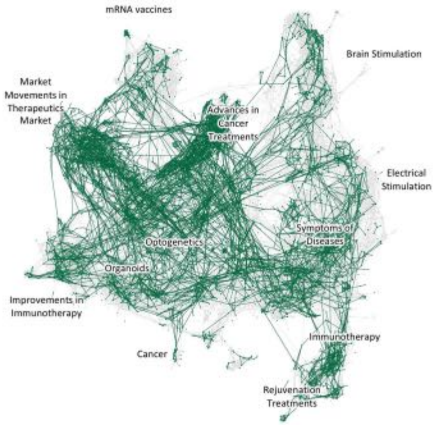
The global social media discussion of human augmentation is multi-faceted, with older age groups dominating in North America and Europe, while young groups hold the majority of discussions in Africa, Latin America and Asia.

Younger age groups were primarily interested in how brain-computer interfaces could be used to enhance healthy individuals. However, although most of the discussion is positive, mRNA vaccines, particularly their use in experimental gene therapies, face scepticism in Europe and North America. People in Africa are more focused on social inequality and conflict arising from human augmentation, while in Central and South America, concerns centre around cyber threats to the body. Discussions of the high costs of gene therapies dominate in Asia.

It is worth noting that our new emerging topics for 2022 — future therapeutics and organoids — received more negative sentiment than other fields within Human Augmentation. The COVID-19 pandemic (and in particular mRNA COVID-19 vaccines seems to have overshadowed the acceptance of new treatment innovations involving synthetic biology.

Within the sentiment analysis clouds below each node represents one article and the linkages between dots show relations between topics in the analysed data.





Positive sentiment is centered around:

Research and development efforts underway in immunotherapy, and in the use of organoids and bioprinting for personalised regenerative medicine and to study human evolution.

2.5 **Organoids**

2.6.4 **Immunome-based therapies**

Current market developments in therapeutics, such as the collaborations between smaller and large players to realise next-generation treatments and set up their pipeline for future success, and the recent approval of a multitude of new treatment options targeting different cancers.

2.6.4 **Immunome-based therapies**

The potential of biocomputing (mainly DNA computing) and its expected performance.

1.4 **Biological Computing**

The first successes in clearing legal/ethical hurdles for technologies in selected geographies, such as China and Chile.

The prospect of using Brain Computer Interfaces (BCI) to "augment" humans and prolong life.

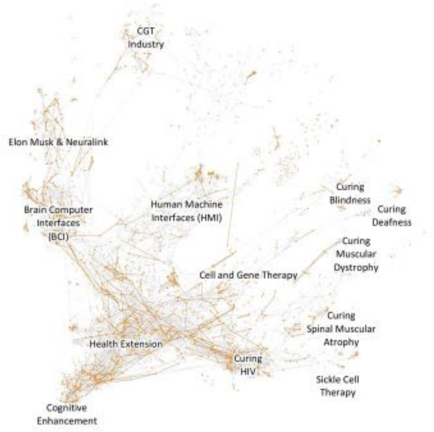
2.4.3 **Brain-machine interfaces**

The potential for using Human Machine Interfaces (HMI) in business processes and consumer products.

2.2.3 **Novel bioengineering approaches**

The promise and reported success of using gene-based treatments to treat a multitude of diseases and conditions.

2.2.2 **Gene therapies & enhancement**



Neutral/mixed sentiment is centered around:

Application possibilities of using light and genetic engineering technologies (optogenetics) to control and monitor cells (discussions around human applications were more cautious than more fundamental applications, such as controlling insects or nematodes).

2.4.4 **Sense-expanding technologies**

Personal experiences with immunotherapy treatments and the discussion surrounding the benefits, side effects, complexity and length of such treatments.

2.6.4 **Immunome-based therapies**

Using electrical stimulation to regenerate nervous systems and treat spinal cord injuries or restore sense of balance through in-ear implant.

Brain stimulation and its application possibilities in cognitive diseases including depression, autism, Parkinson's, OCD, essential tremor, alleviating consequences of strokes or elevating human mental capacity.

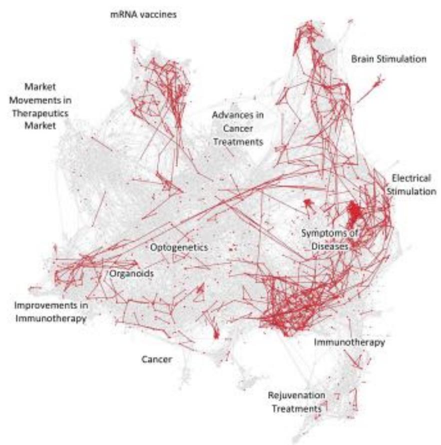
2.1.2 **Neuromodulation delivery systems**

Market reports on biotechnology growth prospects, partnerships and mergers & acquisitions.

The use of BCI/HMI for military applications as a "necessary evil".

2.2.3 **Novel bioengineering approaches**

2.4.3 **Brain-Machine Interfaces**



Negative sentiment is centered around:

Medical conditions and diseases for which there aren't many treatment options available, as well as next-generation treatment possibilities.

2.6 Future Therapeutics

Fear of COVID-19 vaccination and its expedited approval process.

2.6.3 Cell, gene, biomimetic and nucleic acid therapies

Fear of institutions and authorities; this is apparent in conspiracy theories and discussion about the "Great Reset", "Experimental Gene Therapy" and Bill Gates.

2.2.2 Gene therapies and enhancement

Fear of losing mental autonomy through BCI, HMI, changes in brain plasticity and the susceptibility to cyber threats.

2.4.3 Brain-machine interfaces

2.2.3 Novel bioengineering approaches

What do people do?

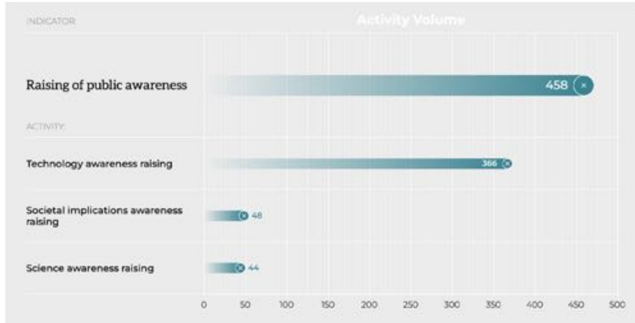
Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected 685 "actions" in the field of Human Augmentation in the first six months of the year. This is the lowest level of activity across our Platforms, which includes Quantum Technologies & Advanced AI, Eco-Regeneration & Geoengineering and Science & Diplomacy. This is understandable, given that emerging topics within Human Augmentation require advanced knowledge in science and technology for civil society actors to act.

The emerging topic of Radical Health Extension saw the most activity, with nearly 40% of monitored actions, followed by Cognitive Enhancement (25%) and Human Applications of Genetic Engineering (18%).

Monitored activity was divided into four indicator categories — raising public awareness, entrepreneurial activities, policy-oriented activities and contributions to science and technology. This data will be updated quarterly on our digital platform. 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 appendix.

Activity was not equally distributed across indicators, with Cognitive Enhancement and Human Applications of Genetic Engineering seeing more entrepreneurial activity than the other emerging topics. This is linked to developments in neurotechnology and applications of CRISPR tools, including next-generation genetic therapies and open-source platforms based on genome-sequencing technology.

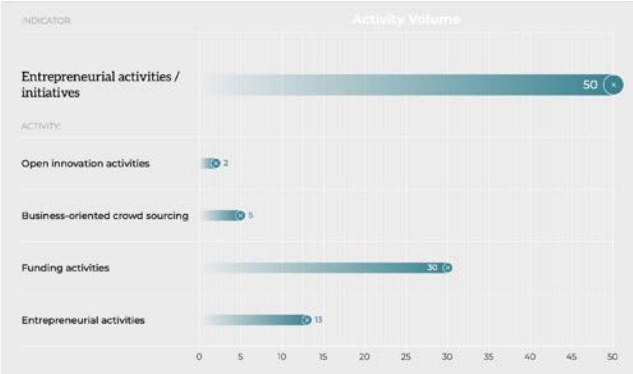
When it comes to volume of actions, technology awareness-raising clearly stands out. The spike in activity in March is linked to the ten-year anniversary of the landmark CRISPR-Cas9 paper from J. Doudna and E. Charpentier. It also coincides with the announcement of a proposal to release genetically modified mosquitoes in California. This has resulted in many awareness-raising activities about the perceived potential and dangers associated with genetic engineering.



The large majority of activities detected are evenly spread between Cognitive Enhancement, Human Applications of Genetic Engineering, Radical Health Extension and Future Therapeutics. Science awareness raising primarily focused on communicating the latest scientific results and on public perception of genetic engineering. In the area of Cognitive Enhancement, the awareness-raising activities centred on the potential of neurotechnologies to restore brain function or to treat different conditions, with a focus on the benefits of brain implants to tackle neuro-degenerative diseases, "bionic eyes" or brain-computer interfaces.

Looking at awareness-raising about the societal implications, the issue of ensuring diversity in genomic research came out strongly as clinical applications began to emerge. This links with discussions at the GESDA summit about 'Negotiating the Boundaries of our Genetic Future'. Advances in neurotechnology or longevity research were framed in a much more positive way.

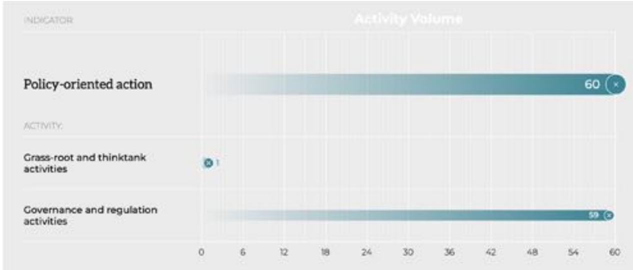
- 2.1 Augmented Reality
- 2.2 Augmented Reality Hardware
- 2.3 Augmented Experiences
- 2.6 AR platforms



Most of the entrepreneurial activities monitored centred around immunotherapy and gene therapies. An interesting development is CROSP — the first open-source software tool for genome-wide design and evaluation of guide RNA (gRNA) sequences for CRISPR/Cas9 experiments. This will accelerate gene-editing research and help democratise the technology. The large amount of small-scale entrepreneurial activities around genetic engineering highlights the potential of the field for investors and innovators alike. This correlates well with the high number of awareness raising activities detected by our monitoring tool.

Radical Health Extension is less present in this indicator, partly because the field is less mature and sees a larger chunk of investments in more fundamental science and larger scale initiatives.

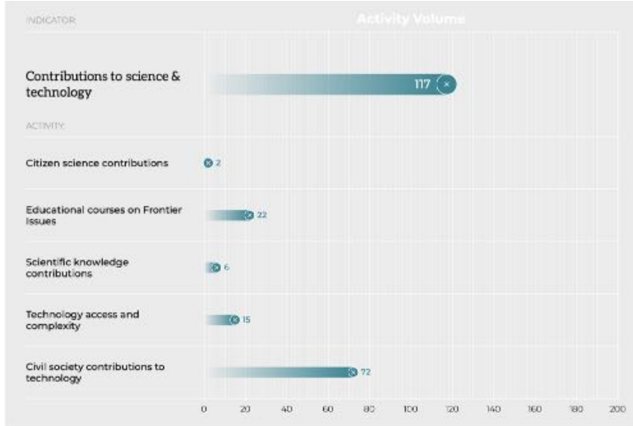
2.6.4 Immunome-based therapies
2.2.2 Gene therapies & enhancement
2.3 Radical Health Extension



Our monitoring tool detected very few activities of civil society movements, grass-root organisations or think tanks. This is surprising as one may expect many activities linked to COVID-19 vaccine conspiracy theories. The only activity of a civil society movement that was detected, was a three-year public campaign to raise public and governmental support for genomic research.

Most of the governance and regulation activities are tied to genetic- and immuno-therapy approvals.

The grass-root and think tank activities focused on the implications of increased human lifespan for society at large and which measures and strategies governance should take.



Contributions of civil society actors to science and technology are centred around the large number of non-academic publications on longevity research, immunotherapies and genetic therapies. This reflects the perceived promise of new therapies, drugs and approaches.

An interesting initiative captured by the tool concern the emergence of DIY tools for gene therapies or CRISPR-based applications, which enable biohacking at increasingly affordable prices. Similarly, initiatives working towards universal access to genetic diagnostics and testing are seen as ways to increase diversity in genomic research, open the door to population-wide data collection and precision medicine, as well as help educate citizens about gene-based therapies.

2.2.1 Genetic diagnostics & prevention

Eco-regeneration & Geoengineering

What do people say?

Analysis of more than 6 million social media posts reveal that the scientific fields related to Eco-Regeneration and Geoengineering, including decarbonisation and ocean stewardship, show a very strong engagement with citizens. Overall, the discussion is predominantly driven by male authors and younger voices, with professional scientists and researchers dominating the work profiles.

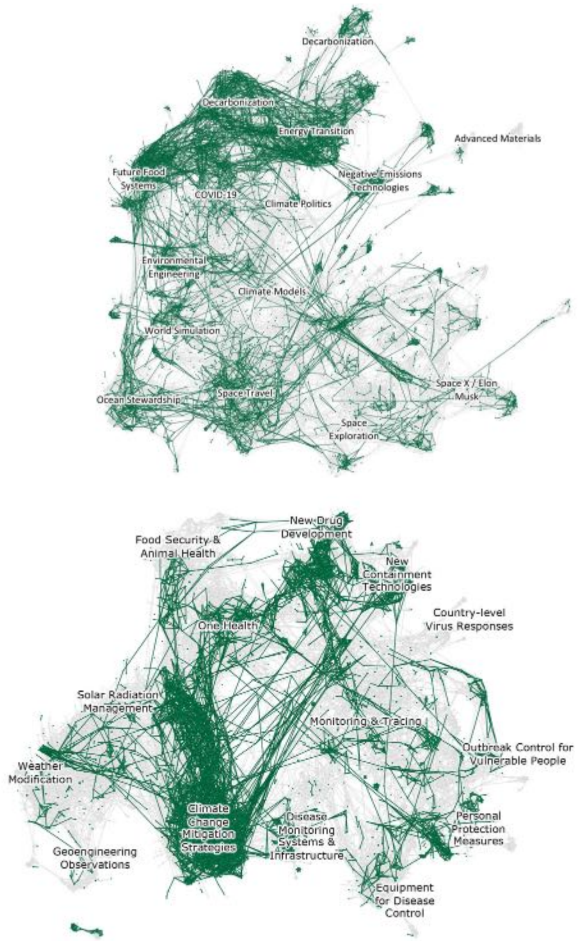
Generally, these topics are discussed by younger, less educated people than the the other three Platforms (Quantum Revolution and Advanced AI, Human Augmentation and Science and Diplomacy), although the new 2022 topics of solar radiation modification and infectious diseases show more of a balance between age groups and academic background.

Concerns vary significantly across regions. In Europe, Asia and South America, the perceived failure of the energy transition dominates discussion, while dangers associated with space travel are strongly discussed in North America. Concerns over future investment levels in oil and gas are more dominant in Africa.

There are demographic variations too: young authors discuss the positive potential of decarbonisation and the energy transition, but don't focus on concrete approaches. Climate change and food systems topics appear more likely to interest individuals with higher education, and they "under-interest" females, both in absolute and in relative terms compared to the general population.

The COVID-19 pandemic has heavily affected discussions on infectious disease, with a perceived lack of transparency reducing confidence in disease control. Conspiracies like chemtrails — the belief that governments are controlling the weather or poisoning the environment, as evidenced by contrails behind planes — strongly bias discussions around solar radiation management on social media. Discussions around solar radiation modification and infectious disease are niche, mainly dominated by experts and sceptics, highlighting a lack of accessibility to these topics. This is the smallest dataset among new topics across scientific Platforms. There is a fear about an improper allocation of funds to future-looking topics at the detriment of investing in topics such as social justice. Across the board, topics revolving around space travel and exploration seem to impress and fascinate the general public.

Within the sentiment analysis clouds below each node represents one article and the linkages between dots show relations between topics in the analysed data.



Positive sentiment is centered around:

Acceleration of climate change policies worldwide to set ambitious carbon-reduction targets and promote climate change mitigation strategies.

3.1 Decarbonisation

Transdisciplinary and collaborative efforts to improve the health of humans, animals and the environment through research.

Use of AI in drug development and testing, including virtual clinical trials, decentralisation and the increased use of digital tools (these were seen as a path to creating a more efficient and cost-effective system).

New detection methodologies and digital technologies that improve patient monitoring and disease surveillance.

3.7.4 Outbreak prevention

Advanced healthcare infrastructure, such as permanent task forces for testing, tracing and other epidemic monitoring measures, expanding into developing regions.

3.7.4 Outbreak prevention

Ocean stewardship, including community-led ocean and beach cleanup initiatives.

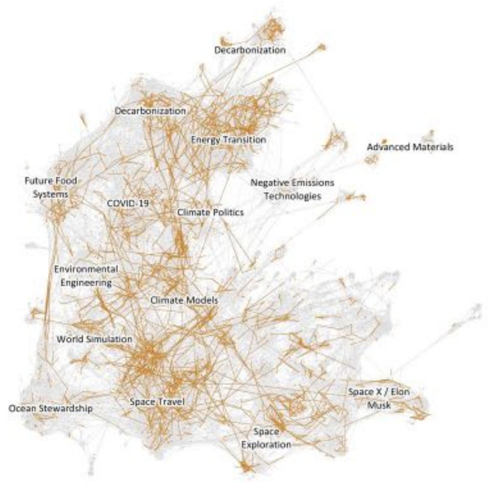
3.5 Ocean Stewardship

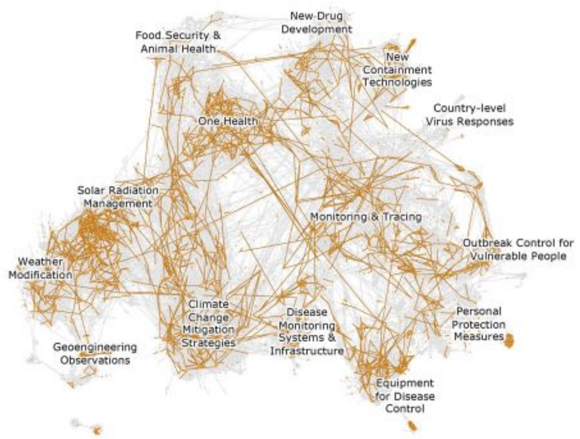
Sustainable food production, including sustainable farming and aquacultures, and reducing consumer food waste.

3.3 Future Food Systems

Decarbonisation advances and clean energy initiatives in the form of policy decisions or private sector pledges and collaborations to cut CO2 emissions.

3.1 Decarbonisation





Neutral/mixed sentiment is centered around:

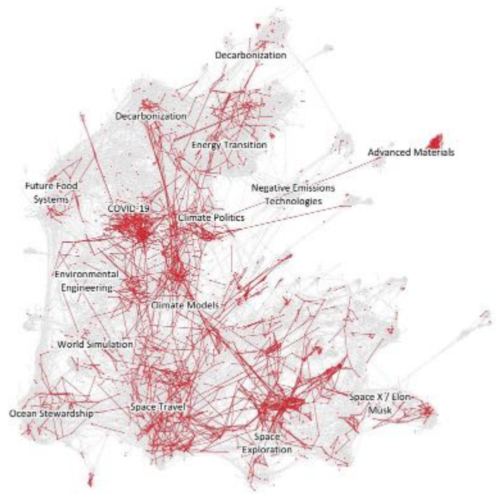
Increased public interest in geoengineering activities driven by new research and funding for geoengineering applications.

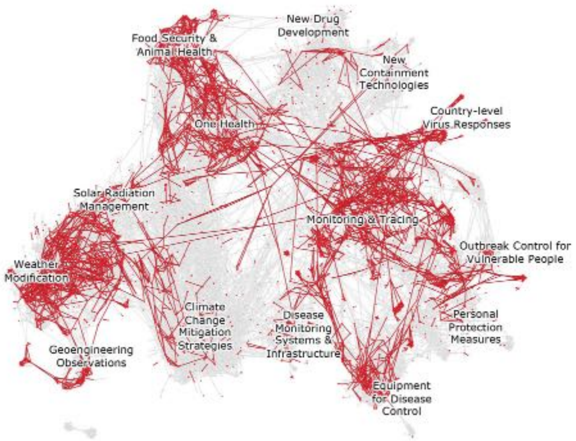
Progress of the energy transition and climate politics, especially regarding the required pace of transition and its predicted effect on businesses (mainly due to the high cost of transitioning).

3.1.2 **Energy Transition**

Space exploration: how it can help us understand our development as a species, as well as recent scientific reports from NASA's Perseverance Rover and the ISS.

3.4 **Space Resources**





Negative sentiment is centered around:

New or improved technologies and infrastructure that can more quickly and effectively detect and track the spread of infection (the discussion is affected by the COVID-19 pandemic and a perceived lack of transparency around disease tracking)

3.7.4 **Outbreak prevention**

The emergence of new, antibiotic resistant zoonoses through inadequate food security and animal health, especially in developing countries (widespread use of antibiotics in livestock is also a subject of concern).

3.7.2 **Zoonotic disease**

Drastic differences in country-level responses, which lead to doubts about the most efficient infection control measures and future preparedness of countries.

3.7.4 **Outbreak prevention**

Outbreak control for vulnerable people: the controversy of protection versus freedom and associated discrimination has incited fears of repetition in future outbreak responses.

3.7.4 **Outbreak prevention**

Measures for disease control and the lack of transparency in decisions.

3.7.4 **Outbreak prevention**

Divides between the public and science on solar radiation modification, with concerns remaining about ethical, health and economic issues.

3.6 **Solar Radiation Modification**

Commercial space travel, and the volume of investment and public subsidies poured into it compared with funding to combat issues of social justice.
The chemtrails conspiracy, suspicions about government tests of geoengineering and the potential risks of geoengineering for human health and climate.

Climate politics and the failure to avert either extreme climate events or the slow degradation of glaciers, ice sheets and ocean currents such as the Gulf Stream.

3.1 **Brain-machine interfaces**

5.3.1 **Managing climate externalities**

What do people do?

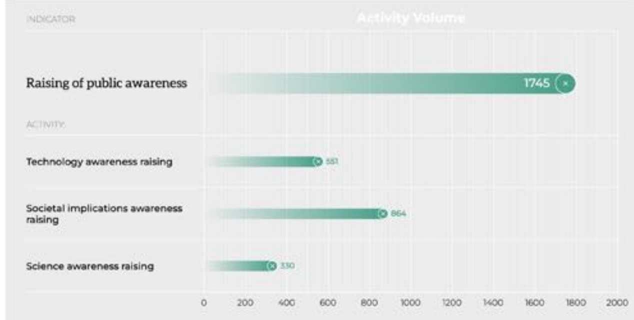
Our monitoring tool — which provides live data on the actions of selected civil society actors (citizens, small groups and NGOs) — detected 5133 “actions” in the field of Eco-Regeneration & Geoengineering in the first six months of the year. Compared with the other Platforms of Quantum Revolution & Advanced AI, Human Augmentation and Science & Diplomacy, Eco-Regeneration & Geoengineering had by far the most activity, representing over 50% of all recorded actions.

The emerging topic of Decarbonisation saw the most engagement, with 84% of all monitored activities. The remaining actions were split between Space Resources, Infectious Diseases and World Simulation.

Diving deeper, many activities surrounding the topic of Decarbonisation dealt with the Energy Transition and improved Energy Storage. For example, civil society actors participated strongly in awareness-raising activities around developments in renewable energy sources such as wind, solar and hydrogen.

Monitored activity was divided into four indicator categories: raising public awareness, entrepreneurial activities, policy-oriented activities and contributions to science and technology. This data will be updated quarterly on our digital platform. 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 appendix.

While most activities fell under raising public awareness, the focus for each scientific emerging topic was slightly different. For example, while the potential of new technologies was highlighted in the area of Decarbonisation, discussions shifted towards more fundamental scientific issues related to space debris in Earth Orbit or remote sensing from space. In the area of Infectious Diseases, awareness-raising focused on outbreak monitoring strategies, governance and regulatory activities linked to Antimicrobial Resistance (AMR) and advances in Vector Control.



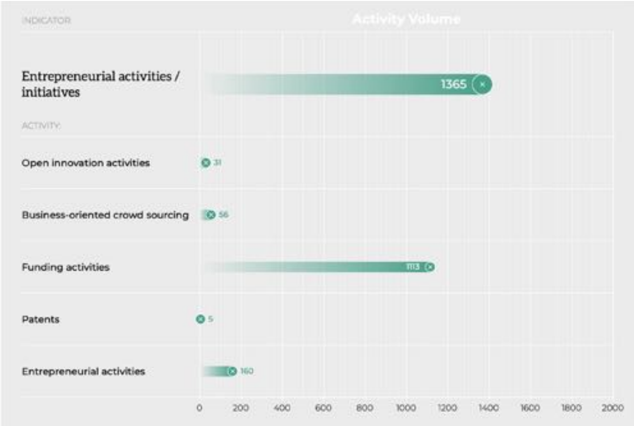
Almost 90% of all technology awareness activities were linked to Decarbonisation, with a focus on renewable energy development, batteries and electricity storage. In contrast, very little activity was detected around carbon capture technologies.

Science awareness-raising activities focused much more on the research enabling space exploitation and exploration, or the interplay between climate change and health.

Looking specifically at World Simulation and digital twins, most discussed focused on how the technology could improve factory management and construction, linked with smart cities approaches.

Finally, awareness-raising activities about societal implications discussed the cost of transitioning to a low-carbon economy, the consequences of climate change and the role new technologies could play in facilitating this transition — including renewable energy investments, negative emission technologies and electric vehicles. On top of this, selected NGOs raised awareness of the increased prevalence of zoonotic diseases.

- 3.1.2 Energy transition
- 3.1.4 Energy storage
- 3.1.1 Negative emission technologies
- 3.4 Space Resources
- 3.7 Infectious Diseases
- 3.2 World Simulation
- 3.7.2 Zoonotic disease



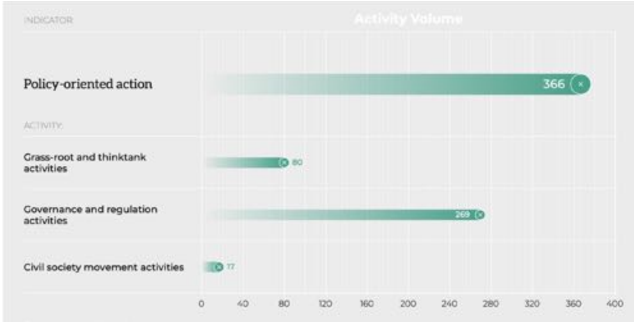
This indicator monitors activities like funding announcements, start-up creations, seed investments or actions that enable access to funding opportunities.

The majority of detected activities were related to funding renewable energy projects or the development of carbon-neutral technologies by regional authorities, cities or incubators. This is happening all across the world, with for example, the announcement of a start-up programme in Africa to finance projects building climate resilience.

Many monitored crowd-sourcing activities were connected to research in space and space exploration, with for example ideation and coding challenges for pupils in UAE or the release of open source projects by Nasa to create space applications.

Finally, in the area of open innovation, our monitoring tool detected several joint research programmes for universal vaccine development. There were also crowd-data ideation challenges around climate and smart city issues, whereby citizens and innovators solve challenges based on open data approaches.

3.1.1 Augmented reality
3.7 AR platforms

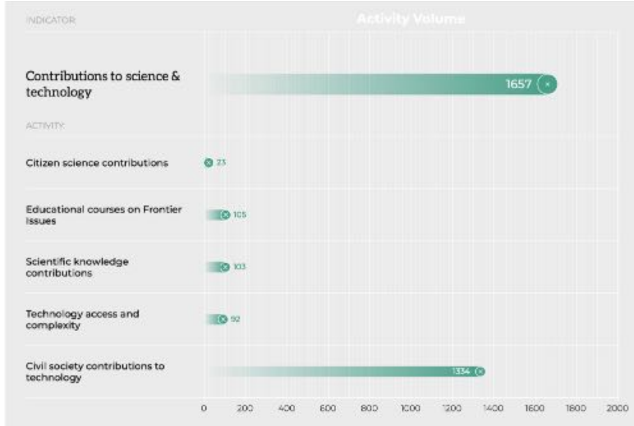


Most of the monitored activities targeted governance and regulatory issues around climate actions. For example, in many different countries, citizen associations brought lawsuits in an effort to make governments accountable for their climate targets.

In the area of Space Resources, policy-oriented action was targeted at making policy makers aware of the need to legislate the exploitation of resources in space, and the need to tackle the space debris issue globally.

Vector control — the release of biologically or genetically modified mosquitoes to reduce infectious disease transmission — is a much debated issue, with some NGO pushing for a complete ban.

3.7.3 Vector control



Almost all activities linked to the production of scientific knowledge were related to climate technologies and decarbonisation. Most studies — by private actors, small governments and research groups — covered what needs to be done to reach climate targets.

Other activities centre around the connection between the health of people, animals and the environment (One Health), AMR research or announcements about the Artemis space programme, which aims to bring humans to the moon.

Our monitoring tool also picked up activities that could support citizen science, such as the creation of an open-source digital representation of Earth systems or an open-source digital twin of a human heart.

3.4.2 The moon
3.2 World Simulation

Science & Diplomacy

What do people say?

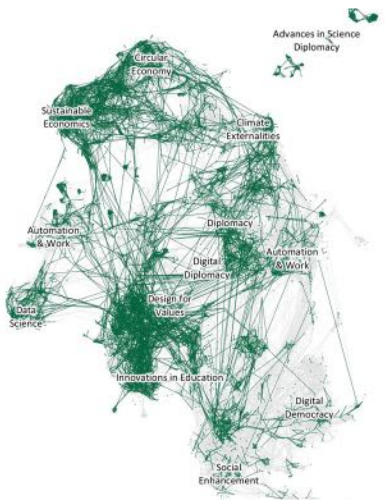
The scientific fields related to Science and Diplomacy, including innovations in education and sustainable economics for this first phase, showed a strong citizen engagement, with more than 3 million analysed posts. The general discussion was strongly focused on issues related to climate change, according to our 2021 analysis. Science has become increasingly politicised and polarised in some areas due to tensions between the US, China and Russia, a situation that has been exacerbated by COVID-19.

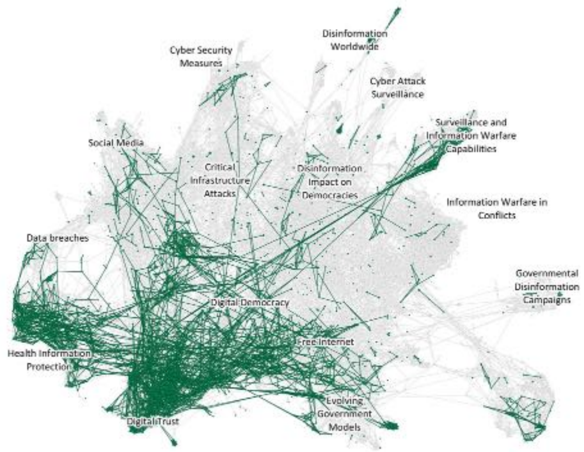
The citizens discussing this area are comparatively gender-balanced, with female voices overrepresented compared to the general Twitter population, particularly in the northern hemisphere. However, young men are dominating discussions around the implications of technology for conflicts and democracy. Younger age groups (<34 years old) are generally underrepresented in developed areas, whereas they appear to be overrepresented in developing countries.There is a large disparity between the perspectives of very young and old authors, with the very young authors focusing on how technology can be used for democratic purposes, while older generations want to preserve existing democratic processes and appraise technology through that lens.

This topic is unusual in that it is also comparatively well-balanced geographically, with Africa, Central and South America and Asia accounting for a third of the posts. The main concerns vary significantly across regions. North America's focus is on security issues with digital democracy; Europe's is on the further polarisation around, and disregard for, the rule of law; Asia's is on climate change and extreme weather events; Latin America's is on economic policy and unemployment; Africa's is on elitism in democracy and party systems.

Multilateralism is discussed positively in Africa, Central and South America, Asia and Australia, but not strongly mentioned in North America and Europe. Overall, there are underlying concerns about the future of democracies, and feelings of anxiety around disinformation and cyberattacks by geopolitical entities. However, there is a gap between the sentiment and topics of discussions on social media and what specialists are reporting.

Within the sentiment analysis clouds below each node represents one article and the linkages between dots show relations between topics in the analysed data.





Positive sentiment is centered around:

Global co-operation of military and researchers and scientists to build up increasingly sophisticated surveillance and cryptologic warfare capabilities.

The rise in importance of digital trust for businesses and governments alike, which encourages new initiatives and tools to foster trust.

4.4.2 **Digital identity and trust**

Advances in science diplomacy, primarily regarding the integration of non-state actors in diplomacy through educational programs like the International Model United Nations.

4.2.2 **Integrating non-State actors**

Charities focusing on providing education to minority groups and those in need.

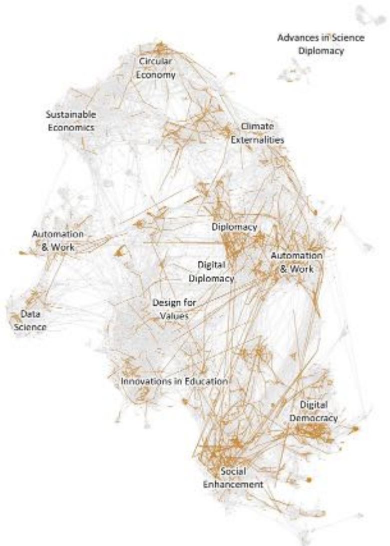
5.1.4 **Design for values**

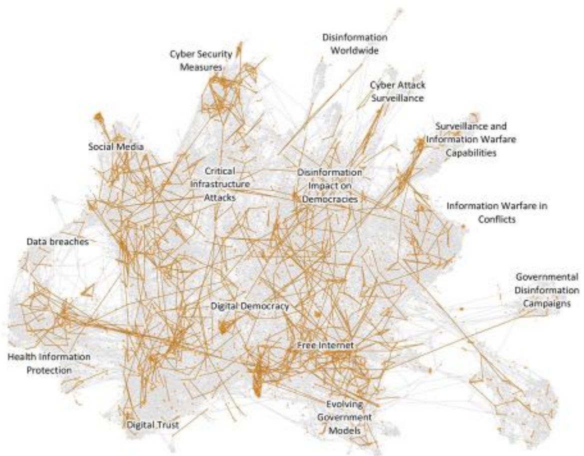
Innovations in education, specifically in digital, decentralised education and encouraging diversity in access as it relates to gender and sexuality.

5.2 **Future of Education**

Sustainable economics, in particular sustainable consumer goods, recyclable materials and plastic-free living.

5.3 **Future Economics, Trade and Globalisation**





Neutral/mixed sentiment is centered around:

Increases in government regulation to prevent disinformation and election meddling, and increased collaboration with private technology companies in response to threats of cyberattacks and disinformation.

4.4 **Democracy-Affirming Technologies**

4.2.2 **Integrating non-state actors**

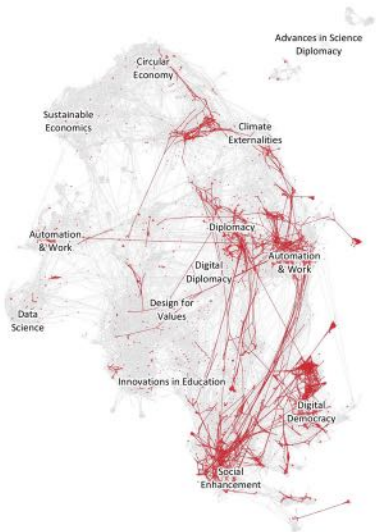
The divisiveness of digital tools and their effects on participatory, digital democracies.

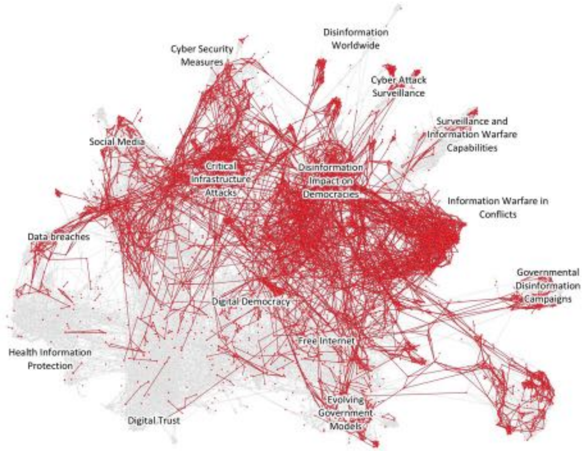
4.4 **Democracy-Affirming Technologies**

Diplomacy, focusing on US-Middle East and US-Russia relationships.

The wider impact of climate change.

5.3.1 **Managing climate externalities**





Negative sentiment is centered around:

The increasing spread of disinformation across news and social media platforms.

The need for increased security measures as evidenced by the rising number of cyber attacks worldwide.

4.3 Digital Technologies and Conflict

Extreme weather events such as forest fires and floods, and slowly degrading ecosystems such as the Amazon and the Arctic permafrost.

5.3 Future Economics, Trade and Globalisation

Employment instability and the fear of losing employment as automation increases (concerns that are being amplified by COVID-19 lay-offs).

5.3.2 Automation and work

Digital democracy, voter safety, validity and e-voting systems — largely driven by the US elections.

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 3449 "actions" in the field of Science & Diplomacy in the first six months of the year. Compared with the other Platforms of Quantum Revolution & Advanced AI, Human Augmentation and Eco-Regeneration & Geoengineering, Science & Diplomacy had the lowest activity. This can be explained by the fact that the emerging topics considered require advanced knowledge in science and technology for civil society actors to act.

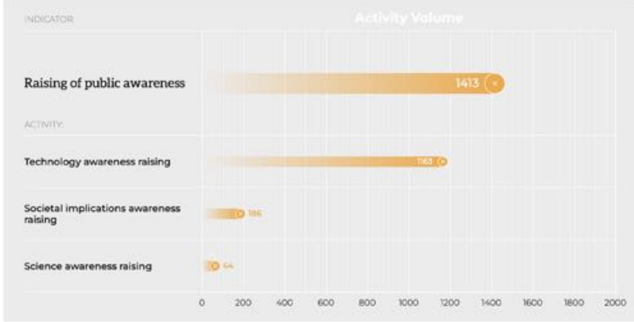
Activities in the areas of Digital Technologies and Conflicts and Democracy-Affirming Technologies contain most of the data, with a particular focus on censorship in cyberspace, the use of blockchain technologies and cyberwarfare.

We also monitored activities around Science-Based Diplomacy. For this emerging topic, the activity focused on game theory and mathematical modelling, as well as data-supported decision making.

In the field of Science Diplomacy, the monitoring tool detected calls from international Arctic-research organisations and Arctic Indigenous peoples' organisations to maintain cooperation in the arctic through science diplomacy.

Monitored activity was divided into four indicator categories: raising public awareness, entrepreneurial activities, policy-oriented activities and contributions to science and technology. This data will be updated quarterly on our digital platform. 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 appendix.

While most of the activities monitored fell under raising awareness of the potential and risks associated with technology, contributions to science were higher in this field than for other Frontier Issues. Those contributions represent research activities done by non-traditional actors. This is linked to the growing activity around blockchain and cryptocurrency technologies, which allow small informal actors to contribute to the field.



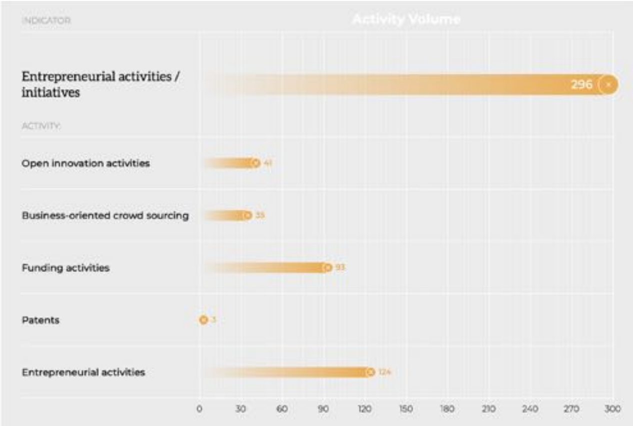
Most awareness-raising activities dealt with the consequences of cyberattacks and data breaches, and what needs to be done to protect cyberinfrastructure. In this case, the stakeholders are local governments, NGOs and small businesses.

Quite a few detected actions drew attention to the consequences of misinformation campaigns, as well as the responsibility of 'big tech' to find the right balance between censorship and tackling misinformation.

On Science-Based Diplomacy, awareness-raising activities focused on the contributions of game theory and data-driven decision making to our understanding of complex global problems such as climate change and conflicts. Those were classified by our tool as awareness-raising activities around fundamental science, in contrast to cyber-related activities, which are more about technology.

Finally, behavioural studies in the area of Economics, linguistics and decision-making were also frequently mentioned.

4.1.2 Energy transition
4.1.1 Energy storage
5.3 Negative emission technologies
4.1.4 Space Resources

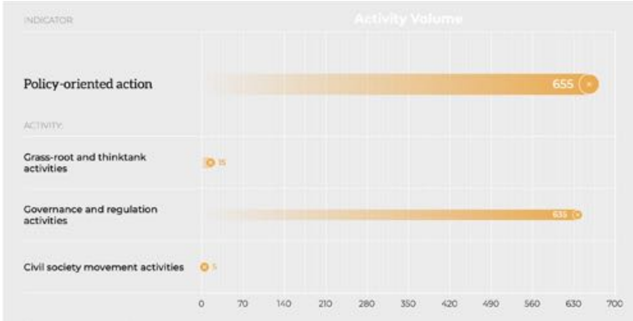


Most entrepreneurial activities were linked to Cybersecurity and blockchain technologies. They concern seed funding activities for early-stage startups across those two areas, both from public incubators and venture capitalists.

Science Diplomacy activities detected under this indicator dealt with data-driven, collaborative decision making and are therefore linked to advances in Collective Intelligence but on a smaller scale and for larger teams.

The tool detected quite a lot of activities aimed at accelerating innovation and entrepreneurship by, for example, launching open source platforms and sandboxes for blockchain applications in virtual worlds or open collaborative platforms for the development of standards to tackle deep-fakes.

- 4.3 Digital Technologies and Conflict
- 4.4.2 Digital identity and trust
- 1.6 Collective Intelligence
- 4.4.1 Verification technologies
- 4.4.2 Digital identity and trust
- 4.4.4 Censorship circumvention and content moderation

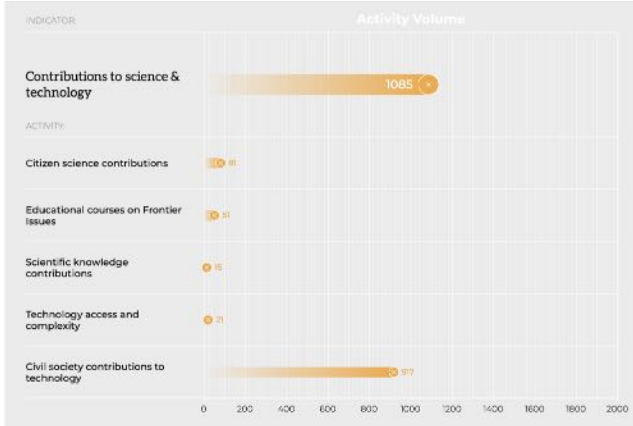


Most policy-focused activity involved civil society actors calling for governance and regulation on misinformation and censorship, as well as protection of personal data in the context of raising data leaks and cyberattacks.

In the area of Science Diplomacy, calls for new frameworks allowing international and interdisciplinary collaborations for ocean stewardship were detected.

Civil society movements drew attention to the consequences of malicious activity in cyberspace, such as misinformation, cyberattacks or cyberbullying on democracy and society.

- 4.4.4 Censorship circumvention and content moderation
- 4.2 Advances in Science Diplomacy



Research and development of blockchain technologies dominates activity, with a particular focus on applications that could enable trusted interactions in digital worlds. These activities are driven by individual entrepreneurs, local governments or small private entities.

Our monitoring tool also picked up significant activity labelled as citizen science. This includes open source intelligence activities, the public release of software allowing open-source cybersecurity or the launch of large public cybersecurity application challenges.
This activity confirms the trend described in 'Non-state actors in conflicts', where small groups of citizens become actors in conflicts by conducting their own cyber-intelligence operations and cyberattacks. Open source tools and access to digital technologies are key enablers for this. Our monitoring tool confirms the large availability of these resources and their use.

- 4.3 Digital Technologies and Conflict

Knowledge Foundations

What do people say?

New to the 2022 radar is the addition of a Knowledge Foundations platform. Its topics, such as Future Economics and the Science of the Origins of Life, raise fundamental questions about the future of the world, society and our place therein. Of these new topics, Future Economics received the most attention on social media and in news and blogs. Interest has grown considerably in the past 5 years, with a surge in discussions during the COVID-19 pandemic. Reducing consumption through a circular economy received globally positive sentiment: it is perceived as an opportunity for emerging economies to leapfrog more established economies.

18-34 year olds are dominating the discussion in these areas, and sentiment towards the topics of Complex Systems Science and Future of Education is more positive than the other Knowledge Foundations of Future Economics and the Science of the Origins of Life and Synthetic Biology.

Citizens are excited about new forms of education and learning opportunities and see them as necessary to stay relevant. Sentiment around future education is particularly positive in Asia, with a focus on how it can enhance skills and employability. This is driven in part by the general public, which points to strong competition in future job markets. However, there is disagreement on the accessibility of new education formats, with some arguing that they are accessible to all, while others criticise unfair disparities in access to digital platforms. There is also growing interest in understanding social development in wider society, which could be driven by current global crises. But discussions on the importance of social sciences are often limited to experts, suggesting a need for moderation between the two groups.

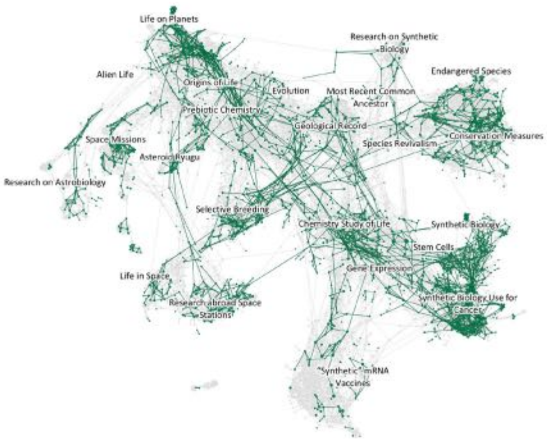
18-34 year-olds are dominating discussions about future economics, with men participating more often than women. Interestingly, rising automation and the implications for some jobs are not always seen as negative: there are discussions on how digitisation could open up new opportunities, while requiring new skills. Interest in future economies, trade and globalisation has grown considerably in the past 5 years, with a surge in interest during the COVID-19 pandemic. The Suez Canal blockage and the zero-COVID policy in China accelerated discussions around supply chain disruptions caused by single points of failure, and there are growing concerns about the stability of the globalised world as new crises occur. Interest in supply chains is higher on news sites and blogs, the circular economy is discussed more on social media.

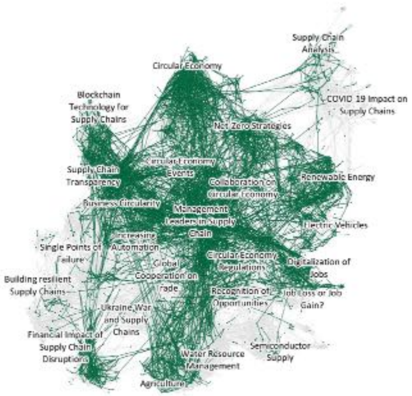
There is rising interest in the decoupling of economies, with support for less interlinked economies. This would increase resilience but could threaten free trade.

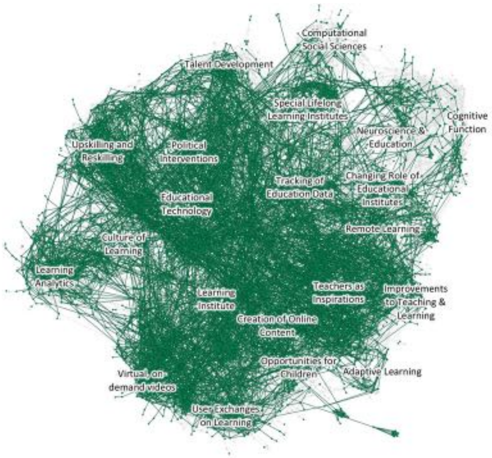
For our new topics, there is a disconnect between discussions on social media versus discussions on news and blogs. Social media discussions carry a stronger negative sentiment and are centred around the origins of life, while news and blogs report more heavily on synthetic biology. Social media discussions are also more influenced by publicity (for example, the publicity surrounding space missions) than by scientific research. Sentiment around the launch of the James Webb telescope is overwhelmingly positive, opening the possibility of using this topic to inform the public about related research.

Unsurprisingly, perhaps, sentiment is generally more positive on professional forums than in the wider public. But it is clear that the term “synthetic” carries a strong negative connotation due to mRNA vaccines against COVID-19: addressing such concerns may help increase public acceptance.

Within the sentiment analysis clouds below each node represents one article and the linkages between dots show relations between topics in the analysed data.







Positive sentiment is centered around:

New technologies for collecting and generating data that will facilitate discoveries in space exploration and provide insights into the origins of life and the potential for discovering extraterrestrial life forms.

● 5.4 The Science of the Origins of Life

Investment in platforms that make it easier for other companies to get involved in synthetic biology.

Foundational advances in synthetic biology, such as development of the first synthetic cells that can divide and multiply, and mimic the behaviour of natural cells.

○ 5.5.2 Synthetic cells

Finding pathways to more resilient supply chains ,and the circular economy, with first circular businesses (fashion, for example), particularly business opportunities and global cooperation.

○ 5.3.4 Sustainable global trade

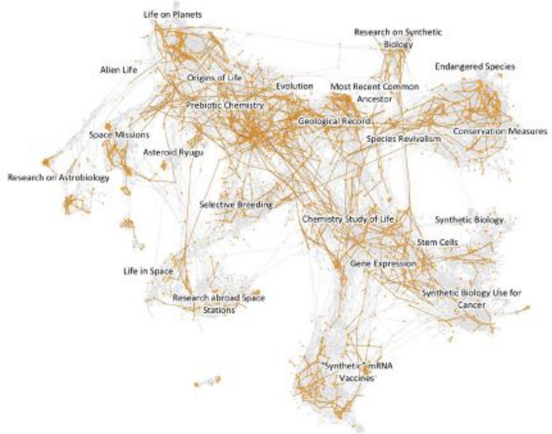
○ 5.3.3 Bootstrapping circular economies

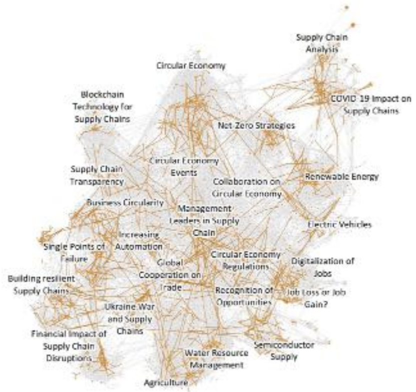
Opportunities to exchange tips about upskilling on social media, new formats to listen to educational topics on-the-go and the increasing ability to track progress.

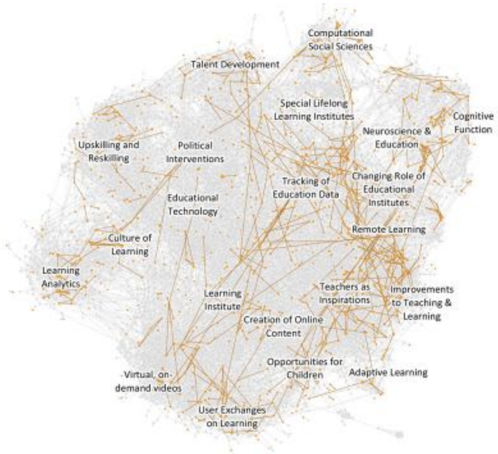
○ 5.2.1 Learning analytics

New technologies that promise to improve teaching outcomes.

New academic research publications and reports on computational social science, such as studies that model the effects of controversial social media topics and study human behaviour on apps.







Neutral/mixed sentiment is centered around:

Single points of failure in supply chains, which have been revealed in recent crises via congestion or shutdown of ports, dependencies on single countries and blockades of trade routes.

○ 5.3.4 **Sustainable global trade**

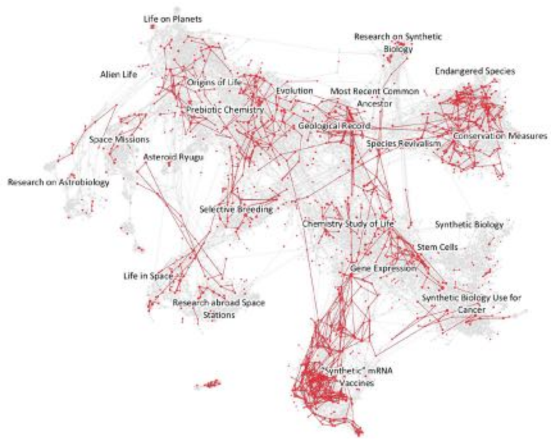
How climate change is affecting farming and what is being done to mitigate its impacts.

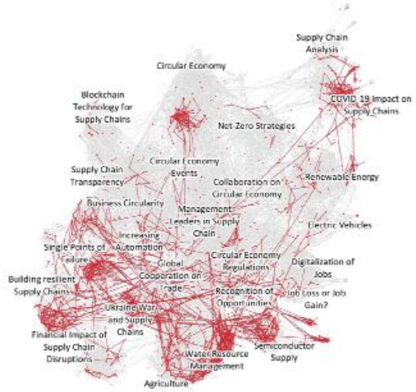
○ 5.3.1 **Managing climate externalities**

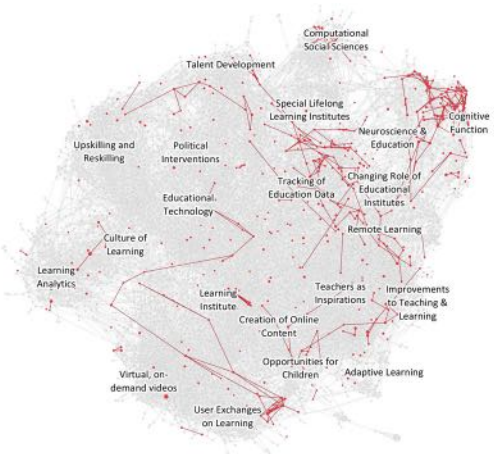
Innovations that are making educational data, including attendance and performance, easier to track: this has triggered conversations about consumer privacy and whether schools have the right to monitor students in this way.

○ 5.2.1 **Learning analytics**

Whether cognitive function and neuroscience are important to education.







Negative sentiment is centered around:

mRNA vaccines, thanks to the long-lasting negative implications of the pandemic on the acceptability of synthetic mRNA technology.

2.6.3 **Cell, gene, biomimetic and nucleic acid therapies**

Water resource management and how climate change is exacerbating the risk of flooding and drought.

5.3.1 **Managing climate externalities**

The financial implications of supply chain disruptions, particularly for the manufacturing industry.

5.3.4 **Sustainable global trade**

Advances in gene editing that could allow scientists to bring back species that have become extinct.

5.4 **The Science of the Origins of Life**

Opportunities

Taking the Pulse of Diplomacy: So...what can we do about it?

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. It is structured in the following two parts:

- two essays by Gérard Escher and Enrico Letta on the role of honest brokering and the costs of non-anticipation.
- a summary of the proceedings of the first GESDA Summit 2021 serving as a basis for the collective solution development process.

Science Anticipation and Diplomacy: Acting as an Honest Broker

Gerard Escher
Senior Advisor to the GESDA Board

Martin Müller
Executive Director Academic Forum, GESDA

GESDA, with its Science Breakthrough Radar, aims to bring science to diplomacy, and to acquaint and alert on the anticipated scientific breakthroughs that will transform our society. Why should we trust science? What is the best path when we move from science to policy?

Scientists are our designated experts for studying the world. And as we trust plumbers to do plumbing, and nurses, nursing — and not vice-versa — we should trust scientists to tell us about the world. This, as Naomi Oreskes says in Why Trust Science (2019) is different from faith.[1] We should still check the references of scientists (as we do for plumbers); that is why the contributors of this Science Breakthrough Radar are all professional researchers. We trust science also because as a community it has developed methods, such as peer review and tenure, to check its claims.

"We have a world of medicines, technologies, and conceptual understandings derived from science, and these have enabled people to do things they have wanted to do. That success does not prove that the theories involved are necessarily true, but it does suggest that scientists are doing something right" (Naomi Oreskes, 2019).

We all are interested in science because it delivers. Still, science is not value-free, and the question stands on how best to translate science breakthroughs from the lab to the peace room; to be, in Otto von Bismarck's words, an "honest broker" of science.

"I do not think of the mediation of peace in such a way that we now play the referee in the case of divergent views and say: this is how it should be, and behind it stands the power of the German Reich, but I think of myself more modestly, …indeed more that of an honest broker who really wants to bring about the deal." Otto von Bismarck (1815-1898, At the Congress of Berlin, 1878)

What is an honest broker?

Science should expand the choices we have as humans and as a society. Honest brokering of scientific results should likewise open and enhance the "solution space" for society and its decision-makers. If the honest broker must engage in decision-making, then it is by clarifying the possibilities and by seeking to expand the scope of choice available to decision-makers by opening "policy alternatives".

Scientists can function as arbiters (Roger Pielke in the Honest Broker, 2007) when the science of a specific problem has a great degree of certainty, and if scientists work within a formal, authoritative committee.[2] A diversity of perspectives, even in this "simple" case, can help to mitigate issue advocacy (stealth or otherwise).

When there is a greater level of scientific uncertainty and an associated wild growth of policy options, scientists will be tempted to take the role of an Issues Advocate, seeking to reduce the number of policy options. *"A straightforward way to think about the key difference between the* Honest Broker of Policy *Alternatives and the* Issue Advocate *is that the latter seeks to reduce the scope of available choice, while the former seeks to expand (or at least clarify) the scope of choice, by placing scientific understandings in the context of a variety of policy options. Such options"*, Pielke argued, may encompass a wide range of interests.

We see GESDA indeed as an *"honest broker of policy alternatives"* that is by anticipating scientific breakthroughs we increase the opportunities for society to act.

Policy-making needs conflicts to be resolved through the political process, which is much better than any of the alternatives (Pielke, 2007).

If we attempt to turn all policymaking into technical exercises without political debate, we fall into technocracy; technical expertise should only be an input to policymaking. On the other hand, if scientific expertise is to function as an honest broker, then its claims must be presented to the public without distortion. *"Scientific knowledge is an essential dimension of culture and progress, it is the most efficient way to understand the world around us, and this knowledge does not belong to the researchers who discover it, it belongs to the society as a whole".*[3] (Thierry Courvoisier & Alex Mauron, 2021). In short, *"Democracy cannot dominate every domain — that would destroy expertise — and expertise cannot dominate every domain — that would destroy democracy"* (Collins et al 2020).[4]

Implications for GESDA

The GESDA Science Breakthrough Radar presents the descriptions of anticipated science and technology advances in the coming two decades. These *"breakthroughs"* have been proposed, described, and reviewed by a community of scientists, with the aim of increasing policy options and action alternatives, in the spirit — described above — of the Honest Broker of Policy Alternatives.

In a highly uncertain context — anticipating the future — brokering science is about enhancing decision-making, not advocating for a specific issue or agenda. The GESDA Radar presents what is possible tomorrow, knowing what is in the science pipeline; the GESDA Radar does not present what is desirable for tomorrow. It is not a substitute for political action but an input for further discussion and action by the relevant communities.

The first ethical duty of an honest broker is to present the best science. It is not to present every opinion expressed by scientists, but to present solid science, which relies on established and solid social processes of science such as peer-review and academic reputation.

Being an honest broker does not require GESDA to be value-neutral. GESDA is not. Our values are these: we trust science — and its anticipated breakthroughs — to be of awe and of concern for decision makers. We think that the challenges of the 21st century can be met if science and technology, can propose and deploy opportunities, within the right institutions or frames for technology, for the good of technology to prevail over the bad, with collective human agency at its heart. We also believe that one of the successful frames for science are the values of multilateralism expressed in the Universal Declaration of Human Rights and the 17 Sustainable Development Goals (SDGs) building the 2030 United Nations Agenda for Sustainable Development.

Finally, honest brokering is also a call for action. Anticipated scientific breakthroughs presented in the Radar (in quantum computing for instance) might convince the multilateral community there is a necessity to act now. GESDA will take part in this *"do tank"* with the absolute determination to let the political decision process proceed. As Robert May said of science in general (but we think it applies to GESDA in particular):

"*The role of the scientist is not to determine which risks are worth taking, or deciding what choices we should take, but the scientist must be involved in indicating what the possible choices, constraints and possibilities are . . . The role of the scientist is not to decide between the possibilities but to determine what the possibilities are."*[5]

Enrico Letta
GESDA Diplomacy Moderator, President of the Jacques Delors Institut, the Secretary of the Italian Democratic Party, former Dean of the School of International Affairs at Sciences Po Paris (PSIA) and former Prime Minister of Italy.

This is an edited extract of his speech at the Public Plenary at the 2021 GESDA Summit.

The costs of non-anticipation: How can we anticipate, accompany and share future science developments?

"It is a great pleasure to be here with you to talk about anticipation, science, diplomacy and Geneva. Thank you GESDA for this invitation.

I have kept two activities in my former and happy life in Paris, for six years. One is the Presidency of the Jacques Delors Institute — I could not do otherwise, not only for the friendship I have for Jacques Delors, but also for the attachment I have to his ideas. The other is to be one of the actors of GESDA, with all of you. This is a brilliant idea, born in Geneva, and I am truly delighted to have been able to participate in the founding moments — moments during which I really had great intellectual pleasure in understanding and learning.

Anticipation, scientific diplomacy, Geneva: these are the three points I will try to elaborate."

Anticipation

The first — the most interesting from my point of view — is anticipation. What does it mean today? Why do we say that anticipation is essential to build the future?

When I entered politics, I was told that, in order to do so, you had to know the past and base your actions upon it. This is true. But when I see everything that has happened in the last few years, I have the impression that knowing the past was not enough to understand the world of today. Consider Brexit; the election of Donald Trump to the White House in the US; the financial crises; the covid-19 pandemic; climate change — or everything else that we are experiencing in our lives and in international relations. Anticipation is essential, because it is the ability to imagine the world of tomorrow. And to do this, we need both the capacity to "use the future to build the present", as GESDA puts it, and the capacity to make the present a present in which ideas for the future are the focus of our activities, in other words: something concrete, something serious.

And when I think of politics, again, although looking back over our shoulders is the easiest thing to do in times of change, it is not what's right. Look at what has happened in the last few years: a rapid and strong globalisation, which has changed our lives. This globalisation has made a lot of people afraid and seek a refuge. This refuge is the old nation-state, and the languages that we already master perfectly.

Populism, in our societies today, is thus above all a simple way of comforting people who are afraid because of the acceleration of globalisation, which brings justified fears. The essential question is: how can we turn these fears into positive energy? When you go into these well-known refuges, you don't try to imagine futures or prepare for the future. This is exactly what has been missing in recent times, as we have instead sought comfort in the past.

Another example is demography. Here again, the past rarely gives us the interesting data that we need for understanding. Anticipation, in this context, requires understanding the fundamental changes that occur in society as a consequence of demographic change. Currently, however, this demographic change and its consequences are struggling to become the focus of concrete political reflection. When I think of my own country, Italy — one of the countries experiencing one of the most violent demographic falls — when I think of what it will be like in 2050, and when we talk about what we should do to avoid this situation, we can easily see the problem but we have no intention of taking the decisions necessary to avoid a disaster. They are political decisions concerning the birth rate and the family, as well as complex and necessary decisions on integration and immigration. For a country like mine, which no longer wants children and which does not want immigrants, it is quite complicated to imagine a future in which this demographic fall will not become an earthquake that will completely change society.

So how can we anticipate? What does it mean to have an elderly population? Is it that neighbourhoods and services are completely focused on the elderly? A society that is not capable of encouraging young people? We have to anticipate this problem of an ageing population because it will happen. We will then live in societies in which the majority of voters will have white hair. And when you are a voter with white hair, you look at things differently, and you vote with a different sense of the future. A 20-year-old votes — if they vote — knowing that they will live another 70 years on average. This is not the case for an elderly voter, obviously. This means that our electorate is totally unbalanced, and will be even more so in the future. For example, there should be parliaments in which there is not only a "pink quota", but also "blue quotas"; that is, assemblies in which it is taken for granted that a percentage of the members of parliament are under 30 years old. But such proposals cause me to be criticised in my country.

I am told, "This is not the priority, there are many other problems." That is true. But this is the problem concerning anticipation: we always tell ourselves that the priorities are elsewhere. In Italian, we call this benaltrismo. And we say to ourselves, "Well, we'll leave that for later." But the aftermath never comes. Or it arrives too soon, and the problems are already there.

The other important aspect of anticipation is the cost of not anticipating. A very simple example is the economic-financial crisis of 2008-2011. In the specific case of the European crisis, the cost of non-anticipation was incredible in terms of human lives and financial resources. Entire countries have fallen; people died by suicide: an economic disaster due to a delayed response to the crisis and non-anticipation. That is not to say that it was necessary to anticipate the fact that the crisis was coming; that would be too much to expect. But the response should have come a year or eighteen months after, not four years after. The "whatever it takes" statement by the Prime Minister of my government — which I support — was made on 26 July 2012; Lehman Brothers had collapsed on 15 September 2008. This is the cost of not anticipating and, above all, of not having understood the speed at which responses were absolutely necessary. Anticipation is essential.

Science diplomacy

My second point is science diplomacy, which is essential. Naturally, GESDA plays an essential role here. It is incredible how far it has come, and how far we have come together, in just two years — two years that have been rather special. This shows that the idea is good, and that we must continue. But what does that mean? How can we bring together diplomacy, international politics and science, especially on the subjects that we have been dealing with recently? Because the pandemic, for instance, has made us understand that we also need political leaders who are really capable today of taking into account both the social sciences and the hard sciences. If you lack one or the other, it is very difficult to find a way to understand what is happening, to anticipate and to take the right decisions.

Another big issue where policy and science have to play a key role is space. We talk about it a lot at GESDA. When we see the private actors and tourists who go into space, we wonder what this world will be like tomorrow. This is an area in which anticipation and the role of politics are absolutely essential, and where Europe plays a fundamental role.

I will also mention the poles: the Arctic and the Antarctic, which are, in my view, the other major areas where anticipation offers the chance for politicians to play an important role. Furthermore, Big Data is obviously a major issue, and there has been a great deal of mistrust about 5G infrastructure, even in recent election campaigns, and in relations between states. How can we ensure that trust becomes a key component in strategic discussions and avoid what happened between China and the USA?

Finally, of course, there is climate change. Many alarms have been sounded by the Intergovernmental Panel on Climate Change (IPCC). But we all know very well that science has played the key role in this area. Because only science is in a position today to say things that politicians cannot say, or that politicians can say only after science has said them. I think that this sixth IPCC report plays a crucial role: the fact that it states so clearly the role of mankind in climate change obviously obliges us to take action and to make sure that we decide to act differently than we have in the past.

Geneva

My third point concerns the City of Geneva.

Geneva is not just a city; it is much more than that. I remember our students at the Paris School of International Affairs (PSIA): Geneva, for them, was something mysterious, important, fundamental for their future. The most interesting thing for them was to come to Geneva, and to do things in Geneva. I haven't seen any agreements reached by Zoom during this recent period. Agreements, or compromises, are reached by looking each other in the eye, by talking side by side, by understanding each other. That is why diplomacy needs locations. Geneva is the best location. And I think that with the launch of this idea — that anticipation is the key to the future — into a world that is changing and is no longer based on the past, Geneva can be even better.

Geneva is therefore the ideal place. The strengthening of multilateralism, of the UN model, of reforms at this level, is crucial. Because we also have to start calculating the real costs of not co-ordinating. It is essential to make people understand that the United Nations — multilateralism — plays an essential role where we find ourselves now. Look at the first few months of the pandemic, before the coordination came. We spent weeks without coordination at the European level, because Europe had no competence, and still has no competence in health.

In the pandemic, the cost of not coordinating has been huge in terms of loss of life. Before I left PSIA, I had proposed to the OECD that it should set up a major multilateral initiative to try to calculate the cost of non-coordination for Europe; Jacques Delors himself had launched this exercise: the “cost of non-Europe”. These are important steps. But the first need is to have a place, a physical place, where we can talk to each other, and work together, sharing this spirit of anticipation and of mutual trust — a trust between people with different backgrounds, people who come from different countries, but people who can meet here and find here the will for a future that holds us together.

The pandemic has played an essential role in this respect, because in the pandemic we have understood that we are all in the same boat. We have understood that an event that happens in a market in a city that we may not even have known about can bring down our economies, and cause a country like mine to have to pay 20 points of public debt in one year. This is the difference between the pre- and post-pandemic worlds.

We have learned about our total interdependence. And this total interdependence means that anticipation today is something that concerns us all. If there is someone in another country with perhaps different political ideas from mine, but who helps me to anticipate what is going to happen in all the areas I have just mentioned, it is obviously in my interest to work with them. That is why this work of scientific diplomacy is so crucial today after the pandemic.

Conclusion

My conclusion is that, in order to achieve this, we must rely on education, which is essential, and utterly central. That’s why it’s good that we are here at the Graduate Institute in Geneva, to discuss this. The question of languages, and their translation, is also crucial. If we do not ensure that all these activities take place in many different languages, we will remain in an elite. Finally, anticipation means being able to convince people that the decisions that need to be taken are essential because, on the basis of the scientific data that we understand, significant events will ensue.

I have put young people at the centre of the political life of my party and my political project, because we are creating a world in which young people are too marginalised. I therefore ask them to be courageous, to dare, and to exploit their capacity to create — not on the basis of what has happened in the past, but on a completely new basis. This is what we need. I have learned recently that what is going to happen has no basis in the past, but will be completely new. What is going to happen in many areas, because of technological or demographic changes, requires us to be creative, and for this we need to develop education. Because of all human activities today, education is probably the most important.

Conference proceedings: 2021 GESDA Summit

The GESDA Summit

The inaugural GESDA Summit took place 7–9 October 2021 in Geneva, at Campus Biotech, where GESDA is headquartered. This hybrid event attracted more than 900 participants, both onsite and online, including 108 speakers from 33 nations. Scientists and academics, diplomats, executives, investors, philanthropists and citizens gathered to participate based on GESDA's vision: *"Use the future to build the present."*

This vision was enhanced by Federal Councillor Ignazio Cassis, 2022 President of the Swiss Confederation, which co-founded GESDA, and head of the Federal Department of Foreign Affairs, in his welcome address: *"There is a growing feeling that a new 'Cold War' is about to be fought over science and technology and the power they confer to the states, who master them. We must, therefore, reflect on how we can adapt, evolve, and respond to the challenges and opportunities of our time. We need to build the global governance of the 21st century which can only succeed if it is far-sighted, evidence-based and equitable. In this spirit, GESDA is designed as a new tool at the service of effective multilateralism, as a resource we wish to offer to the legitimate actors of international governance."*

Sixteen plenary and parallel sessions formed the core of the 2021 GESDA Summit programme – of which the proceedings of 13 sessions are presented in this document, directly linked to the 18 initial emerging topics and 216 breakthrough predictions identified in the 2021 Science Breakthrough Radar. Organised across the five scientific Platforms, they provide the space for all relevant communities — science, diplomacy in the broad sense, the private sector, philanthropy and civil society — to discuss the implications of those advances and identify first concrete and practical actions.

Anticipation to renew multilateralism

The summit made it clear that anticipation in science and diplomacy can help renew multilateralism. As Alondra Nelson, Director of the White House Office of Science and Technology Policy, told the gathering, *"President Joe Biden has described our time as one of great perils and great promises. For those of us in government, to truly be of service, we really have a responsibility to be forthright about both those realities at once. And to be honest both about the risks of innovation and partnership, but also bold in addressing them head-on. And I think that GESDA is a fantastic possibility for working this through. Anticipation is filled, of course, with both enthusiasm and yet unease."* Achim Steiner, Administrator of the United Nations Development Programme and chairman of United Nations Sustainable Development Group, further added that: *"One interesting question to explore is: 'Can we make the transition from where science enabled us to understand the challenge, to how diplomacy can accelerate that capacity to act, notwithstanding different interests and geopolitics?' I think multilateralism is absolutely fundamental to that."*

However, as argued by Sir Peter Gluckman, President of the International Science Council, meeting that target will be possible only under one essential condition: *"One of the things that this debate is highlighting is the need to make sure that all the sciences, in particular social scientists, are part of the discussion right from the start, rather than allowing the technological sciences to run ahead of the social considerations."*

Trust at the core

A first of its kind, the 2021 Geneva Science and Diplomacy Anticipation Summit reached its objective: to create an event as a unique opportunity to bring the most essential scientific issues out of the laboratories and to the attention of world leaders, politicians and diplomats. *"We had invaluable inputs. We had creative and motivating comments and messages. They were full of knowledge and of wisdom. And all with intention to help GESDA to find its way into the future,"* said Peter Brabeck-Letmathe, GESDA Chairman of the Board of Directors, in his Closing Address. *"GESDA can be and should be relevant for all stakeholders. But I also know very well that the relevancy will only last as long as you all have trust in our work. Trust in GESDA as an honest broker which works in a fact-based, transparent and inclusive way. Those are the fundamental conditions at which GESDA can perform its duty as a builder of bridges, between the scientists and the politicians, but also with the involvement of the civil communities from all over the world and in the respect of cultural diversity."*

This section provides a description of the 13 sessions related to the scientific emerging topics discussed in the Science Breakthrough Radar 2021 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 2022 from 12–14 October.
The full summit proceedings, including programmes and speakers is available at: https://gesda.global/summit/.

Conference proceedings: Co-Developing Accessible Advanced AI

There are 56 artificial intelligence (AI) startups worth over $1 billion today. That is a testament to the enormous power of deep learning, which has found transformative applications in everything from finance to healthcare. These approaches require huge amounts of data and computational power, however, which means that advances are increasingly driven by a handful of large companies and governments.

1.1 Advanced Artificial Intelligence

More information

https://radar.gesda.global/opp

Abstract

We are about to enter a “third wave” of AI that will imbue machines with “common sense” and reasoning capabilities, allowing much broader deployment, and increasing the breadth and depth of human-machine interactions. That makes it crucial that these advances are not shaped by narrow interests and that everyone can take part in the development of advanced AI and benefit from its use.

- What will the next generation of AI look like and how should we best prepare for it?
- What priorities should inform the next stage of AI development?
- How will advanced AI be able to address global challenges differently than today’s technology?
- What can we do to avoid “AI nationalism” and ensure broad access to the technology and applications developed on the basis of advanced AI?

Participants

Moderated by:

Amandeep Gill
Envoy on Technology, United Nations former Director I-DAIR project, India

With:

Pushmeet Kohli
Head of Research, AI for Science, DeepMind, India (remotely)

Nanjira Sambuli
Policy Analyst, Advocacy Strategist; Board Member,Digital Impact Alliance, Development Gateway, and The New Humanitarian; Member, GESDA Diplomacy Forum, Kenya

Daren Tang
Director General, World Intellectual Property Organization; Member, GESDA Diplomacy Forum, Singapore

Rüdiger Urbanke
Dean for Computer and Communication Sciences, EPFL; Member, GESDA Academic Forum, Austria

Wendell Wallach
Yale University Interdisciplinary Centre for Bioethics, United States

Ewan Birney
Deputy Director General, EMBL; Director, EMBL-EBI, UK

Takeaway messages

"The rise of AI is moving from data input to context and experience."

"Deep scepticism remains with AI algorithms, data sets and technology, which experts point out is culturally constructed. More regulation may be needed to prevent bias."

"Open source data and data-sharing in a fair and equitable way is essential to create new possibilities and solve scientific and technological problems."

"Science and technology organisations should incorporate people and strategies that reflect diverse sets of interests from the start when developing projects, not as an afterthought."

"Few scientific areas have not been impacted or completely revamped by the "pervasiveness" of advanced AI, and many things can go wrong if improperly used."

"Digital technologies and AI condition access to the world for an ever-larger group of people, making inclusiveness, representativeness and cultural biases ever more important."

"Inclusivity means building a table for everyone to gather around in the first place, not just adding seats."

"More reliance on 21 st century governance --- such as "soft law" that is not always enforceable but can be applied quickly through standards, practices, codes of conduct and insurance --- might be useful."

Conference proceedings:
Opening Quantum for the Benefit of Humanity

In 2019, Google used a computer with 54 quantum bits, or qubits, to perform a calculation in 200 seconds that would have taken the world's most powerful supercomputer 10,000 years to complete. The answers had little practical use, but it marked a major inflection point in the development of quantum technology.

1.2 Opening Quantum for the Benefit of Humanity

More information

https://radar.gesda.global/opp

Abstract

Over the next decade, quantum computers that can turbocharge the search for new materials and drugs will become a reality. So will quantum communication networks with uncrackable encryption and quantum sensors providing ultra-precise measurements in medicine, Earth sciences and positioning systems. The strategic potential of this new quantum infrastructure will require global co-ordination to both ensure and control access to it, so that its opportunities are open to everyone, and its applications are beneficial to all.

- What intractable problems could quantum computers help to solve?
- What is the best way to help policymakers understand quantum technology, so they are better prepared to take advantage of quantum advances and to make sensible and forward looking decisions?
- How can we make sure the benefits of quantum technology applications are open to all?

Participants

Moderated by:

Katia Moskvitch
Communications Lead Europe, IBM Research, UK

With:

Anousheh Ansari
CEO, XPRIZE Foundation; Member, GESDA Diplomacy Forum, USA/Iran

Fabiola Gianotti
Director-General, CERN; Board Member, GESDA, Italy

Nicolas Gisin
Honorary Professor, University of Geneva, Switzerland

Elham Kashefi
Professor of Computer Science; Personal Chair, Quantum Computing, School of Informatics, University of Edinburgh; Director, CNRS, Sorbonne University; Co-Founder, VeriQloud, Iran

Matthias Troyer
Technical Fellow and Corporate Vice President, Microsoft; Member, GESDA Academic Forum, Austria

Peter Knight
Emeritus Professor, Faculty, Natural Sciences, Department of Physics, Imperial College London; Former Defence Scientific Advisory Council, UK Ministry of Defence, UK (remotely)

“Quantum computing is a revolution long in the making: at least 30 years of research by a large fundamental research community. It is a total game-changer with over $22 billion invested worldwide by governments by 2021, prompting international competition fuelled by fear and hype.”

“Not enough young people are being trained to work on quantum, which is creating hiring challenges for all sorts of jobs due to a huge skills gap. Governments with money to hire young talent could put them to work on military and less desirable uses.”

“Quantum computing, though complicated, can be taught earlier than at university: it could be introduced to high school students or even at an earlier age, so kids get an innate sense of it.”

“A hybrid organisation for quantum could guarantee safe access to and use of critical quantum infrastructures for communication and computing.”

“Quantum can change chemistry and material science and help us predict the properties of materials accurately. It could let us design a catalyst for negative carbon fixation for global warming.”

“More collaborative projects and the sort of cooperation that GESDA espouses will be essential, because building a quantum system is complex and there is a need to steer research towards beneficial applications that are not only focused on economic, geopolitical or military advantages.”

“Sharing information and data are important because knowledge and education are capacity-building and empowering tools that can reduce inequities across the world.”

Conference proceedings: Establishing Neuro Rights

Brain implants already enable people with paraplegia to control robotic limbs, restore basic vision and modulate neural activity to treat diseases like Parkinson's. Over the next decade our growing ability to both read and write brain data will transform the treatment of neurodegenerative and psychiatric conditions, but it will also increasingly be used to enhance cognitive function in healthy people.

2.1 Cognitive Enhancement

2.4 Consciousness Augmentation

More information

https://radar.gesda.global/opp

Abstract

This could greatly expand our ability to learn and improve ourselves. But the creation of two-way conduits into people's minds and huge pools of sensitive brain data also raise profound questions about privacy, personal agency, and the integrity of the individual. This might necessitate the establishment of a new bill of neuro rights to ensure that new technology is used properly, and its benefits are available to all.

- What are the implications for society of the development of technology in brain science?
- How can we ensure wide access to neurotechnology and prevent the formation of "cognitive elites"?
- Do we need new neuro rights or a reinterpretation of existing human rights?

Participants

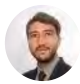
Moderated by:

Nadia Isler
Director and Founder, SDG Lab, Office of the Director General of the UN Office at Geneva, Switzerland

With:

Olaf Blanke
Professor of Neurosciences; Bertarelli Chair, Cognitive Neuroprosthetics; Director, Laboratory of Cognitive Neuroscience, EPFL/Campus Biotech; Professor, Neurology, Department of Neurology, University Hospital of Geneva; Member, GESDA Academic Forum, Switzerland

Lidia Brito
Director, UNESCO's Regional Bureau for Sciences, Latin America, and the Caribbean; Member, GESDA Diplomacy Forum, Mozambique (remotely)



Marcello Lenca
Group Leader, EPFL; Senior Research Fellow, ETHZ, Italy

Judy Illes
Professor of Neurology, University of British Columbia, Canada (remotely)

Jürg Lauber
Permanent Representative of Switzerland to the United Nations and other International Organisations in Geneva; Member, GESDA Diplomacy Forum, Switzerland

Takeaway messages

"Over the last two decades, the driving factors in neuroscience and neurotechnology have been the engineering sciences, computer science and AI that enabled new ways to read brain signals."

"Because of the complexity of the ethical challenges, a one-size-fits-all approach to governance will likely not be effective; a multilateral governance framework will probably offer the best solution."

"It is clear that the involvement of scientists and policymakers is not enough; the voices of citizens also need to be heard because of the profound implications."

"Four levels of governance could be applied towards neurotechnology: self-regulation; ethical guidelines and so-called soft law; binding national regulations; and international human rights law."

"Neuro rights" are the moral and legal rights to protect the human brain. Given the novelties of neurotechnologies, emerging governance frameworks are subject to the same novelties, making it a rapidly and dynamically evolving scenario."

Conference proceedings:
Negotiating the Boundaries of our Genetic Future

The price of sequencing a human genome has fallen from $2.7 billion to $300 in just 20 years. This dramatic improvement in our ability to read DNA is now setting the stage for an even bigger revolution in our ability to write our genetic futures. Over the next decade gene therapies that can tackle the most intractable inherited diseases and cancers will go mainstream.

2.2 Human Applications of Genetic Engineering

More information

https://radar.gesda.global/opp

Abstract

Within 25 years the ability to enhance human capabilities will come within reach, letting us augment sensory capacities and enabling us to thrive in space. That could pose complex biosecurity challenges and raise profound questions about what it means to be human. Given the immense costs of today's experimental gene therapies, work needs to be done to ensure their benefits are shared equitably.

- What are the opportunities and risks posed by our growing mastery over human genetics?
- Where does the line between healing and augmentation lie and who decides what is allowed?
- Genetic capabilities will appear gradually and surreptitiously. How do we ensure their benefits are shared equitably?

Participants

Moderated by:

Jane Metcalfe
Founder, NEO.LIFE; Co-Founder, WIRED magazine, USA

With:

George Church
Professor of Genetics, Harvard Medical School; Professor, Health Sciences and Technology, Harvard and MIT, USA (remotely)

Katherine Littler
Co-Lead, Global Health Ethics & Governance Unit, World Health Organisation, UK

Effy Vayena
Professor of Bioethics, ETHZ; Founder, Health Ethics and Policy Lab, Department of Health Sciences and Technology; Member, GESDA Academic Forum, Greece/ Switzerland (remotely)

Ambroise Wonkam
Professor and Senior Medical Genetics Consultant, Division of Human Genetics, Faculty, Health Sciences, University of Cape Town, Cameroon

“The new Crispr gene-editing tool opened new and questionable frontier uses, showing how science and technology often outpaces our ability to understand their applications.”

“There are differing opinions about when and if a technology (such as gene-editing tools) is ready to be integrated with the public and how that process should be carried out, also in terms of communication.”

“It may be irrelevant to distinguish between a disease treatment and an enhancement, because if one thinks in terms of well-being, the boundaries are blurry. The questions of safety and precision of the interventions are key.”

“There are differing stages all over the globe in terms of governance and oversight, and different starting points for what we think is acceptable. We should be talking about preparedness for genome and emerging technologies in terms of governance.”

The genomes of more than one million individuals have been sequenced but less than 2 per cent are from Africa or recent African descent, raising questions of inclusion and equity. Moreover, the lack of African genetic material might impede our full understanding of basic functions.

“We did not wait for full understanding of all the genes or virology or immunology before vaccinating for smallpox. Similarly, some of the technical hurdles in gene-editing technology lie in the fact that it’s impossible to wait as long as necessary to really know if something will be safe for a person’s lifetime. Occasionally we can reach consensus without full understanding.”

Conference proceedings: Engineering Pathways for Radical Health Extension

By 2050 one in six people worldwide will be over the age of 65. This grey tsunami threatens to put a huge strain on health and economic systems as the burden of age-related illness booms and the proportion of working-age adults shrinks. But breakthroughs in our ability to slow the physical and cognitive decline associated with advanced years are on the horizon.

2.3 Radical Health Extension

More information

https://radar.gesda.global/opp

Abstract

Drugs that target biological pathways that underpin ageing and interventions that turn back cells' "epigenetic clock" could soon extend our healthy years long into old age. This could completely reshape the dynamics of ageing populations and will require fundamental shifts in public health policy, economic planning, and labour relations.

- Where will breakthroughs in radical health extension come from?
- How will societies change as the number of healthy older people grows?
- How can we ensure boosting health span becomes a global priority?

Participants

Moderated by:

Jane Metcalfe
Founder, NEO.LIFE; Co-Founder, WIRED magazine, USA

With:

Samia Hurst
Professor of Ethics, University of Geneva, Switzerland

Brian Kennedy
Distinguished Professor, Department of Biochemistry and Physiology, Yong Loo Lin School of Medicine, National University of Singapore, USA

Guy Ryder
Director-General, International Labour Organization; Member, GESDA Diplomacy Forum, UK

Atsushi Seike
Executive Advisor for Academic Affairs, Professor, Emeritus, Keio University, Japan (remotely)

Takeaway messages

"Ageing research was once a field in which it was not believed that people could alter the ageing process, but now most researchers think it is possible."

"People living longer lives raises fundamental questions about inequality based on demographics, geography, and socioeconomic status."

"Distinguishing between biological and chronological ageing would be helpful, partly because older people can still contribute as workers, investors, teachers, mentors, social and childcare workers. Promoting good health among elderly people is, therefore, crucial."

"New tools (pharmaceutical and natural products, gene therapies, and stem cells treatments) might increase the average lifespan to 120 years; blood biomarkers may determine the biological age of a person."

"Among the chief questions to be addressed are how to organise social protections and care, and to balance retirement ages with the workforce and funding for social safety nets."

"The wider implications raise fundamental questions about how people structure the "biographies" of their lives; new language might be needed that is based on health status, rules, and functions, other than actual age."

Conference proceedings: Accelerating the Active Decarbonization of our Planet

The amount of carbon dioxide in the atmosphere is at its highest level in four million years. If we want to meet our goal of capping global warming at 2°C, urgent action is required to both slash emissions and remove carbon dioxide from the atmosphere.

3.1 Decarbonisation

More information

https://radar.gesda.global/opp

Abstract

Drugs that target biological pathways that underpin ageing and interventions that turn back cells' "epigenetic clock" could soon extend our healthy years long into old age. This could completely reshape the dynamics of ageing populations and will require fundamental shifts in public health policy, economic planning, and labour relations.

- How can we get promising decarbonisation technologies out of the lab that are viable in the marketplace?
- How can we reach an agreement on a global minimum carbon price and how should we set carbon prices?
- How can we ensure that the burden of decarbonisation is shared equitably?

Participants

Moderated by:

Janos Pasztor
Executive Director, Carnegie Climate Governance Initiative C2G, Hungary/Switzerland

With:

Jim Hagemann Snabe
Chairman, Supervisory Board, Siemens AG; Chairman of the Board of Directors, A.P. Møller-Mærsk A/S; Member, GESDA Diplomacy Forum, Denmark (remotely)

Gerald Haug
President, German National Academy of Sciences Leopoldina; Professor for Climate Geology at ETHZ; Director, Climate Geochemistry Department and Scientific Member at the Max Planck Institute; Member, GESDA Academic Forum, Germany

Sergio Mujica
Secretary-General, International Organization for Standardization; Member, GESDA Diplomacy Forum, Chile

Wendy Lee Queen
Tenure Track Assistant Professor, Laboratory of Functional Inorganic Materials, at EPFL, United States

Takeaway messages

"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."

"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."

"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: Utilizing Space Resources for Collective Prosperity

The minerals locked up in the most valuable asteroid in our solar system are worth $15 quintillion, according to estimates from startup Planetary Resources. The number should be taken with a grain of salt, but even if it is off by several orders of magnitude, the sum would still be colossal.

3.4 Space Resources

More information

https://radar.gesda.global/opp

Abstract

The ability to mine these minerals is at least 25 years away and the economic benefits are still uncertain, but their scale demonstrates the enormous opportunities lying beyond Earth's atmosphere. Taking advantage of this abundance is beyond any one country or industry and will require renewed multilateralism to ensure the global commons of space benefits all of humanity. Setting the stage for a new, collaborative approach to using space resources will also have nearer-term impacts as we expand our use of lowEarth orbit and prepare to go to the Moon.

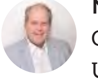
- What is the potential scale of space resources, and will we be able to exploit them?
- Will/Should space resources boost development on Earth or fuel off-world expansion?
- What rights should countries have to own or exploit resources beyond Earth's orbit?

Participants

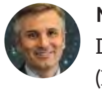
Moderated by:

Adriana Marais
Director, Foundation for Space Development Africa; Member, South African Government Ministerial Task Team on the fourth Industrial Revolution; Faculty, Singularity University and Duke Corporate Education, South Africa

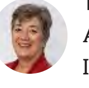
With:



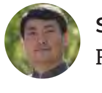
Niklas Hedman
Chief of Committee, Policy and Legal Affairs Section, UNOOSA, Sweden (remotely)



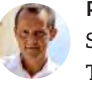
Mathias Link
Director, European Space Resources Innovation Centre (ESRIC); Director, International Affairs and Space Resources, Luxemburg Space Agency, Luxembourg



Tanja Masson-Zwaan
Assistant Professor and Deputy Director, International Institute of Air and Space Law, Leiden University; President Emerita, International Institute of Space Law, The Netherlands (remotely)



Su Meng
Founder, Origin Space Corp., China (remotely)



Patrick Michel
Senior Researcher, CNRS (Observatoire de la Côte d'Azur), Team Leader, TOP (Théories et Observations en Planétologie), France

Takeaway messages

"Interest is widely growing among nations and private companies towards the identification, extraction and use of space resources."

"Companies are willing to take on risks that space agencies prefer to avoid in the space exploration race, but the business model behind that risk-taking has yet to be fully developed."

"In this fast-moving field, a step-by-step system of "adaptive governance" is the best way to approach technological, financial and regulatory issues."

"How to give equitable access to resources and technology, and how to broaden the involvement of developing nations, are important questions without clear answers."

"More knowledge about asteroids is needed that goes beyond Earth observations and can only be gained through space missions. Academic institutions and space agencies are developing such missions."

"In addition to UN discussions about the regulation of space resources, another forum at the international level is needed to encompass private sector-related issues such as extraction safety zones, environmental protection measures and mining priority rights."

"Potential conflicts exist between the use of space resources for Earth or for further space exploration."

Conference proceedings: Advancing Science for Ocean Stewardship

The ocean supports all life on Earth, but we have explored only 80 per cent of it and an estimated 91 per cent of ocean species have yet to be classified. What's more, the ocean is changing at unprecedented rates in the face of climate change, pollution and over-exploitation. Understanding these changes demands a rapid scale-up in ocean monitoring and the collection of valuable data before it disappears.

3.5 Ocean Stewardship

More information

https://radar.gesda.global/opp

Abstract

Innovations in sensors and autonomous vehicles are needed to collect that data; new modelling technology will be needed to make sense of it. The benefits will be a wealth of genetic information with applications in pharmaceuticals and biotech as well as a better understanding of ocean ecosystems, their connectivity, and how we can manage these vast resources in a more equitable and sustainable way.

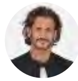
- What do we not know about the ocean that we should know?
- How can we make the best use of the vast amount of genetic data flowing from the oceans?
- How can scientists catch up with the rapidly changing state of the ocean?
- How can we measure the value of the oceans and share those benefits equitably before its resources are irreparably harmed or depleted?

Participants

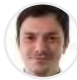
Moderated by:

Kasmira Jefford
Editor-in-Chief, Geneva Solutions, UK

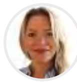
With:



Gerard Barron
CEO & Chairman, The Metals Company, Canada (remotely)



Robert Blasiak
Researcher, Stockholm Resilience Centre, USA (remotely)



Antje Boetius
Director, Alfred Wegener Institute; Marine Biologist; Leader, Helmholtz Association, German Research Centres, Germany (remotely)

Anders Meibom
Professor, EPFL's Laboratory for Biological Geochemistry; Professor ad personam, Institute of Earth Sciences, University of Lausanne, Denmark

Vladimir Ryabinin
Executive Secretary, Intergovernmental Oceanographic Commission (IOC) of UNESCO, Russia

André Hoffmann
Businessman, Environmentalist, Philanthropist; Vice-Chairman, Hoffmann-La Roche, Switzerland

"The ocean and coastal areas cover more than two-thirds of Earth's surface and contain 97 per cent of the planet's water, but 45 per cent of the Earth's surface has no laws to protect marine species and minerals."

"Companies rush to register patents for marine genetic resources of organisms that could have lucrative and beneficial uses for industry and biomedicine."

"Efforts to map the bathymetry of the ocean seafloor are accelerating with international cooperation."

"Demand for minerals for the world's battery-powered transition to electric vehicles and sources of clean energy has led to prospective mining on the ocean seabed that could spare land from mining but damage unknown marine life and release pent-up carbon from the depths."

"Stewardship rests on three pillars: knowledge, care, and agency. That is why stewardship could be at the core of science and diplomacy actions for ocean protection."

"Ocean life goes back about 3.7 billion years, but scientists have described only about 10 per cent of it."

\"The threat of climate change has increased dramatically for the oceans, creating a race to protect marine species and functions."

"A "global charter" may be needed to fulfil one of the UN's 17 Sustainable Development Goals for 2030 that calls for conserving and sustainably using oceans, seas, and marine resources."

Conference proceedings: Learning from COVID-19 to Prepare the Response to the Next Systemic Crisis

More than 200 million people around the world have been infected by COVID-19, and the number of deaths is approaching five million. Almost six billion vaccine doses have been administered. The pandemic has put the principles and practices of multilateralism to their most severe test in decades.

3.7 Infectious Diseases

More information

https://radar.gesda.global/opp

Abstract

Many environmental, economic, and societal factors have contributed to this global health crisis, including a focus on national rather than international solutions. These trends show no signs of slowing and the next pandemic may be just around the corner. This makes it imperative to integrate the lessons of COVID-19 quickly and to start preparing our response to future systemic crises now. Tomorrow's global challenges will be inherently transdisciplinary and transnational in nature. That means it will be crucial to break down traditional silos if we want to improve our ability to anticipate and prepare for these kinds of emergencies.

- What lessons can be learned from the response to COVID-19?
- Where is the next systemic crisis likely to come from?
- What role should be played by the international community, both in Geneva and around the world, in preparing for the next systemic crisis?

Participants

Moderated by:

Elaine Fletcher
Editor-in-Chief, Health Policy Watch, Switzerland/USA

With:

Patrick Aebischer
President Emeritus, EPFL; Vice- Chairman GESDA, Switzerland

Chorh Chuan Tan
Chief Scientist, Ministry of Health, Singapore; Board Member, GESDA, Singapore

Matthias Egger
Professor of Bioethics, ETHZ; Founder, Health Ethics and Policy Lab, Department of Health Sciences and Technology; Board Member GESDA, Switzerland

Jeremy Farrar
Director, Wellcome Trust; Board Member, GESDA, UK

Soumya Swaminathan
Chief Scientist, World Health Organisation (WHO), India

Takeaway messages

“Develop leadership structures and strategies to respond faster and to distribute vaccines more fairly, establishing a bridge between scientists and policymakers that should be permanent, not restricted to moments of crisis.”

“Invest in manufacturing and coordination of research and development; mRNA technology allows for quick prototyping and decentralised manufacturing, which could break through some of the impasses in vaccine inequality. Scientific research on vaccines (and also on anti-viral and anti-microbial agents) needs to be accelerated and put in a holistic frame, notably in a One Health (humans, animals) approach. More emphasis should be put on the links between climate change and the threat of pandemics.”

“Create a worldwide genomic surveillance network to spot new diseases wherever they emerge. Better integration of national data and surveillance are essential tools for fighting a pandemic. The Swiss and GESDA could help set up a Geneva hub of WHO’s Health Emergencies Programme like that in Berlin.”

Conference proceedings: Revitalizing Multilateralism through Anticipatory Science and Diplomacy

The grand challenges facing humanity in the 21st century will be both global and technical. Climate change, unemployment, hunger, and a host of other issues will require experts of all kinds around the world to come together to solve them. Yet today, trust in science is on the decline and multilateralism in some regions appears to be in retreat.

- 4.1 Science-based Diplomacy
- 4.2 Advances in Science Diplomacy

More information

https://radar.gesda.global/opp

Abstract

This highlights the need for a revitalisation of science diplomacy and a major update to the frameworks that underpin it. This will be crucial, not only for tackling the challenges already before us, but also anticipating future technical and policy developments in time to foster multilateral solutions.

- How can we bring current and anticipated scientific breakthroughs to the forefront of policymaking to tackle emerging grand challenges, and how can we train future leaders to be bilingual in both science and diplomacy?
- In future science diplomacy, what would be the most effective roles for people on the local level or those outside of government?
- How can we reinvigorate trust in science among citizens?

Participants

Moderated by:

Marga Gual Soler
Science Diplomat; Founder, SciDipGLOBAL, Spain

With:

Micheline Calmy-Rey
Former President of the Swiss Confederation; Visiting Professor, University of Geneva; Board Member, GESDA, Switzerland

Yves Flückiger
President, swissuniversities; Rector, University of Geneva; President, Campus Biotech Geneva Foundation, Switzerland

Joël Mesot
President, ETHZ; Co-Chair, GESDA Academic Forum, Switzerland

Nikhil Seth
Executive Director, UNITAR, India

Takeaway messages

“Science diplomacy is resurgent but has firm roots with examples in the Red Cross movement, Swiss government and UNESCO that used cutting edge advances to overcome political hurdles.”

“Leading universities such as those in Switzerland can use their educational tools, research, and technologies to help international organisations move forward and keep their relevance.”

“A multidisciplinary approach to science diplomacy can build trust through outreach and inclusiveness, raise science knowledge and awareness, and educate generations of potential future leaders.”

“Together with the revitalisation of science diplomacy, a major update on the frameworks that underpin it is needed. The focus on anticipation should be a key feature of it.”

“Opportunities exist for GESDA, as a public platform, to create two-way dialogues between science communities and international organisations.”

“Switzerland could promote anticipatory science diplomacy through a Security Council seat in 2023 and 2024.”

Conference proceedings: Designing an Economic Compass for Sustainable, Inclusive and Resilient Societies

Economic growth has significantly improved material well-being around the world, reduced poverty and closed the gap between rich and poor nations. At the same time, it has led to growing inequality within nations and over-exploitation of the Earth's resources.

● 5.3 Science-based Diplomacy

More information

https://radar.gesda.global/opp

Abstract

Global economies face several challenges in the future: first, a wave of technological developments fuelled by artificial intelligence (AI) will further test the limits of today's views about labour, capital and employment. Second, climate change creates an urgent necessity to use natural resources more carefully. Third, there are grounds for a move against globalisation and towards more localisation that could undo the benefits of international specialisation. These developments call for a new economic compass to help us chart a course through the policy challenges ahead. This will help anticipate winners and losers of economic shifts ahead of time, design welfare systems fit to purpose, better understand and counter environmental externalities associated with various economic choices and build more resilience into the global economy.

- Which policy interventions have the best chance to guarantee human employment in meaningful jobs and avoid growing inequalities when intelligent machines become more widespread in the future?
- How can we move rapidly towards a regenerative circular economy that limits the impact of our economic actions on the planet while assuring the well-being of all?
- Can we make globalisation more resilient and sustainable without losing the benefits of international specialisation?

Participants

Moderated by:

Richard Baldwin
Professor, Graduate Institute Geneva, Switzerland

Organised by:

Jean-Pierre Danthine
E4S Executive Director, University of Lausanne/IMD/EPFL; Member, GESDA Academic Forum, Switzerland

With:

Philippe Aghion
Professor, College de France, INSEAD and London School of Economics, UK

Ian Goldin
Professor, Oxford University, Senior Fellow at the Oxford Martin School, UK

Katheline Schubert
Professor, Paris School of Economics, France

Takeaway messages

"Our economies are facing big challenges, but the policy solutions are on the table and have to be implemented."

"Climate policies that take into account historical contributions to rising emissions are likely to gain wider acceptance by the public."

"Globalisation is expected to accelerate but can be managed through more international cooperation."

"Automation can be managed without losing potential gains through labour and education policies, such as investing in skills, and good jobs, and by redistributing the gains of automation."

"More research is needed in economics to tackle environmental questions and the circular economy."

Conference proceedings:
Building Digital Models to Navigate the 21st Century's Complex Ecological and Social Systems

Humanity created, captured, copied, and consumed more than 64 trillion gigabytes of data last year. This deluge of information is being used to try to model the world around us in unprecedented detail. That includes complex systems like cities, ecosystems, and the climate.

5.1 Complex Systems Science

3.2 World Simulation

More information

https://radar.gesda.global/opp

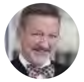
Abstract

Going forward these models will become increasingly intermeshed, creating sprawling socioecological simulations that can provide policymakers with invaluable foresight on the outcomes of economic, environmental and social policies. While those simulations, often referred to as "digital twins", can provide knowledge about the potential evolution of a system, big data and machine learning approaches have so far failed to capture the full complexity of real-world situations and different feedback loops. Finding ways to combine models with different scales and purposes and ensuring that today's biases and prejudices are not baked into them, will require a sustained interdisciplinary effort that includes full engagement among citizens.

- Many initiatives for "digital twins" have been recently launched. To what extent will these initiatives be able to reproduce the complexity of real-world systems?
- Can we combine models of physical reality with those simulating more intangible social phenomena?
- How reliable are today's leading models and how can policy makers use them wisely?
- How can we ensure models used to guide policy are transparent, equitable and explainable?

Participants

Moderated by:

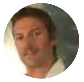


Chris Luebkeman
Leader, Strategic Foresight Hub, Office of the President, ETHZ, USA

With:

Maurice Borgeaud
Head, Department Science Applications and Future Technologies, Directorate, Earth Observation Programmes, European Space Agency, Switzerland

Sean Cleary
Executive Vice-Chair, FutureWorld Foundation; Member, Advisory Board, Carnegie Artificial Intelligence & Equality Initiative; Managing Director, Centre for Advanced Governance; Member, GESDA Diplomacy Forum, South Africa



Neil Davies
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Dirk Helbing
Professor, Computational Social Science, Department of Humanities, Social and Political Sciences; Affiliate, Computer Science Department, ETHZ; Member, GESDA Academic Forum, Germany (remotely)

Mami Mizutori
Special Representative of the United Nations Secretary-General for Disaster Risk Reduction; Head, UNDRR; Member, GESDA Diplomacy Forum, Japan

Philippe Gillet
Chief Science Officer, SICPA; Former Vice President, EPFL, FranceComputer Science Department, ETHZ; Member, GESDA Academic Forum, Germany (remotely)

Takeaway messages

“Digital twins function as experimental landscapes that let scientists analyse risks, support decision-making and foster disaster resilience, which is becoming important to adapt to climate change.”

“There are limitations from being obstructed by biases, randomness, turbulence, chaos theory. It will probably never be possible to produce an exact digital twin of life on Earth, or of our body, or of our health. And we need, therefore, to expect uncertainty.”

“The transition to open science and a full, free and open data policy have spurred many digital twin initiatives and are vital for such models.”

“Models are useful as long as there is a literacy in the communities to translate their results into policies. Otherwise, even the best models will remain useless.”

“It is critical to realise that scientists are not going to be able to model everything, or even be able to draw definitive conclusions.”

“A digital avatar project in French Polynesia, rooted in open science, was aimed at helping local governments better prepare, respond, and build climate resilient communities. Such projects use a collective intelligence infrastructure to possibly spur democratic ecological action.”

“An observatory could be put in place to 1) capture existing initiatives of “digital twins”, 2) include some oversight in the process to increase trust and 3) ensure citizen engagement, through a digital agora.”

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. (UDHR), adopted under the guidance of Eleanor Roosevelt, who chaired the drafting committee, and in the UN's 1966 International Covenant on Economic, Social and Cultural Rights (ICESCR) and other international and regional treaties.

The Philosophical Lens

More information

https://radar.gesda.global/opp

Abstract

It is far from clear, however, exactly what freedoms and responsibilities derive from this established right of all people to "share in scientific advancement and its benefits", as the UN declared, and 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, now might be the time to bring this right back to life. An important first step would be to specify just what exactly is meant by the right to science. Proposals for reviving this right include a collective commitment to open science and inclusivity, new forums for data-sharing and the establishment of a deliberative body to ensure the latest scientific evidence is taken into account in policymaking.

- What freedoms and responsibilities does the "right to science" entail?
- How can the right to science be used to benefit humanity?
- How can we make this a "living human right" that is taken seriously by policymakers, and how can we encourage signatories to the UDHR to renew their commitment to the right to science?

Participants

Moderated by:

Samira Kiani
CEO and Founder, GenexGen; Director, Tomorrow. Life Initiative; Associate Professor, Liver Research Center, Department of Pathology, School of Medicine, University of Pittsburgh; Member, GESDA Academic Forum, USA

With:

Michelle Bachelet
E4S Executive Director, University of Lausanne/IMD/EPFL; Member, GESDA Academic Forum, Switzerland

Yvonne Donders
Head, Department of International and European Public Law; Commissioner, Netherlands Human Rights Institute, University of Amsterdam, The Netherlands

Kamila Markram
Neuroscientist, cofounder and CEO of Frontiers, Germany

Peter Maurer
President, International Committee of the Red Cross; Member, GESDA Diplomacy Forum, Switzerland

Takeaway messages

"Reviving the human right to science is a timely and important initiative. GESDA can serve as an appropriate forum to encourage this conversation."

"The existing international legal framework does not appropriately reflect the economic, cultural and social aspects of today's science enterprise."

"Open and free access to scientific data and publications should be a consequence of this right."

"This human right is violated when low-income countries cannot benefit from scientific breakthroughs (like the COVID-19 vaccines)."

"This right mandates evidence-based policymaking --- having society take advantage of scientific research in order to solve problems."

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 28 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 28 scientific emerging topics described in the 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

radar.gesda.global

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