The GESDA 2021 Science Breakthrough Radar

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

A Letter from the Chairmen

Just 24 months have passed since the Geneva Science and Diplomacy Anticipator, also known as GESDA, began taking shape as something new under the sun: a Swiss Foundation with global reach; a start-up of multilateralism working from Geneva as a public-private partnership in order to anticipate, speed up and broaden the benefits of science and technology for all.

Accelerating the use of the opportunities that advanced scientific explorations bring to the world might seem straightforward.

On the contrary, it is very difficult.

First, success in this endeavour depends on the ability to access, scout and follow year by year what is already cooking in the laboratories. The acceleration of scientific development also raises sensitive issues. And since no moratorium will ever stop the spread of any disruptive technologies or their uses, we have no choice but to embrace them, despite their apparent complexity. In fact, the sooner the better — hence the need to anticipate.

To this end, the 2021 GESDA Science Breakthrough Radar, an annual report and interactive digital platform, is the first edition of a new global indicator of some of the most significant laboratory advances expected within the next five, 10 and 25 years. We have developed it in partnership with the Fondation pour Genève and in collaboration with the Open Science Publisher Frontiers. This 2021 edition is scouting four areas: (1) advanced AI and the global quantum revolution; (2) new science and technology that improves human resilience; (3) ecosystem regeneration and geoengineering; and (4) the growing relevance of global science diplomacy.

• The Radar offers an open access tool to the international community and the world population to help them anticipate and tackle today’s and tomorrow’s challenges as concretely, accurately and quickly as possible.

• The first 2021 edition is based on the collective insights of 543 top-class scholars including 79 in Switzerland where it all started. Another 177 are from other parts of Europe; 162 are from North America; 92 are from Russia, Asia and Oceania; 22 are from Africa and the Middle East; and 11 are from South America.

• Eight seasoned scholars from philosophy, ethics, humanities and the arts kick things off by discussing three fundamental questions about the future of humanity raised by the breakthroughs. We also show how citizens and media around the world currently address these questions and breakthroughs.
Second, accelerating the use of the opportunities offered by these science breakthroughs requires us to organise the complex relationships and interactions between scientists, politicians, entrepreneurs and citizens, whose agendas, mindsets, experiences and responsibilities are all very different, as demonstrated by the current Covid-19 pandemic.

Therefore, the 2021 GESDA Science Breakthrough Radar serves as a trigger for opening the debate on what to do with these science breakthroughs. 16 topics coming out the radar will be discussed at our first annual Geneva Science and Diplomacy Anticipation Summit organised from October 7 to October 9 for hundreds of scientists, policymakers, entrepreneurs, non-governmental organisations and citizens worldwide interested in developing and funding partnerships, projects and initiatives.

We are also opening the same consultation for everybody to join our efforts through our GESDA Digital Interactive Global Sounding Board, the third tool our Foundation is launching in October 2021.

Based on the results of the Summit and the worldwide consultation, the GESDA Foundation will produce a second edition of this Radar and of the Anticipation Summit in August 2022.

By doing so, we fulfill the vision of GESDA’s founders, the Swiss and Geneva governments, which decided to create our not-for-profit foundation to serve as an honest broker of debate and collaboration within the worlds of science and politics, leveraging International Geneva and Switzerland as a neutral and impactful hub of global governance, multilateralism and science diplomacy.

Peter Brabeck-Letmathe
Chairman of the Board of Directors
GESDA

Patrick Aebischer
Vice-Chairman of the Board of Directors
GESDA

Geneva, Switzerland, October 2021
About GESDA

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.

- **1 Vision** Use the future to build the present
- **3 Products** Developed in 24 months and going public on October 7, 2021
- **2 Initiatives**
  - Joint GESDA-XPrize Quantum Contest
  - Anticipatory Science & Diplomacy Capacity Building Initiative in partnership with Asuera Stiftung of Hurden, Schwyz
- **8 Task Forces** with 120 leaders from GESDA’s Academic and Diplomacy Fora engaged in identifying pathways for solutions
- **9 Million Swiss francs** raised from public (3.6) and private (5.4) partners after 2 years of operations
- **2 Founders** The governments of the Swiss Confederation and the Canton of Geneva in collaboration with the City of Geneva
- **1 Swiss and Global Community working together**

GESDA Science Breakthrough Radar

In partnership with Fondation pour Genève

- **3 fundamental questions for tomorrow of interest for society debated by** 8 scholars from philosophy, humanities and the arts
- **4 scientific frontier issues, 24 emerging topics and 216 breakthrough predictions at 5, 10 and 25 years of interest for science**
- **23 global challenges of interest for diplomacy**

Geneva Science and Diplomacy Anticipation Summit

- **16 sessions based on the first edition of the Science Breakthrough Radar** to help address **23 global challenges**
- **1000 onsite and online participants**

GESDA Digital Interactive Global Sounding Board

- **11 million** social media posts analysed to take the pulse of society
- **543 scientists** involved in Switzerland and throughout the world in the first edition of the Science Breakthrough Radar out of 4,000 scientists invited to contribute
Country of host institutions of contributing scholars via surveys, workshops and interviews 543

North America 162
South America 11
Europe (without CH) 177
Switzerland 79
Africa & Middle East 22
Russia, Asia & Oceania 92
Introduction

GESDA’s Structure

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.

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Ambassador Alexandre Fasel  
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An Academic Forum presides over the anticipatory science scouting, chaired by Joël Mesot (President of ETHZ) and Martin Vetterli (President of EPFL):

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President, ETHZ

Martin Vetterli  
President, EPFL

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Sir Peter Gluckman
President-elect, International Science Council (ISC), Chair of the Advisory Board to the International Network for Government Science Advice (INGSA), former Chief Science Officer to the Prime Minister of New Zealand – Auckland/New Zealand

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An Impact Fund currently under development, will seed-fund the implementation of those solutions.

An Executive Team in charge of the operationalisation of the CESDA 2020-2022 Roadmap and providing support to the above-mentioned organs, under the lead of Secretary General Stéphane Decoutère.

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Science and technology are moving forward very rapidly, at a rate which is faster, and with stronger and cumulative consequences for humanity, society and the planet, than ever before. These developments put us at the centre of a dilemma. Some of today’s biggest global challenges, as for example ultimately the origins of anthropogenic climate change or indeed the covid-19 pandemic, are linked to the progressive and cumulative development of technologies. At the same time, science and technological advancements are central to tackling those challenges and provide new opportunities for people in the world. A careful balance between avoiding missed opportunities and creating existential risks need to be found.

With this objective in mind, GESDA has developed its Science Breakthrough Radar as a neutral, science- and expert-based platform. In that sense, the Radar is neither predicting the future nor projecting a compass for a desirable society. It is simply scouting what is already happening in the laboratories in Switzerland and throughout the world, and mapping, as a best guess by experts, the possible advances and breakthroughs in a broad range of scientific areas within a 5, 10 and 25 year time horizon.

The anticipated science and technology breakthroughs described in this report are not happening in a vacuum. They a part of broader societal and political contexts. They are discussed and debated by citizens worldwide as they deal with fundamental aspects of what is means to be human, our relation to each other and to the planet. The GESDA Science Breakthrough Radar is intended to help initiate an interaction with people from all horizons and backgrounds by listening to what is being said on scientific emerging topics. It also opens up a space where conversations about science trends and their impact can happen without implying that they are being endorsed.
This provides the opportunity to genuinely and rigorously look at potential policy options and future initiatives. The Radar thus is serving as an initial tool which has the goal of creating a joint language and starting the broader societal and political debate around these emerging topics in relation to fundamental and existential questions. This will ultimately lead to identifying collective pathways for action.

As will be shown in this report — and further extended in future editions — it is equally important to consider cutting-edge thinking and to anticipate developments in social science and the humanities. Charting issues such as future social innovations and social structures, advances in international relations theory or innovation in economic thought alongside more “technological” breakthroughs, will create a comprehensive vision of a future and provide the information needed to anticipate and design positive solutions for humankind.

The present inaugural rolling yearly mapping of the science trends represents the views of a part of the Swiss and global science community. Our intention is to turn it into a continuous effort about how science might evolve and which additional emerging topics the Radar should consider.

It is a live document, not a closed list. It will be continuously 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

The GESDA 2021 Science Breakthrough Radar provides a unique description of breakthroughs at 5, 10 and 25 years, which may impact, people, society and the planet.

A new tool for multilateralism, informing discussions and concerted action
- Giving a neutral overview on the science trends.
- Sharing this knowledge as an honest broker with diplomats, philanthropists, entrepreneurs and the general public in order to maximise the chances of a positive use for the benefit of all.

Eye-opening reflections on the impacts of future scientific discoveries for people, society and the planet
- Initial contributions on the implications for international affairs, global challenges, and the SDGs.
- A synthesis of what society thinks about the examined fields of research.
- 8 philosophers and ethicists assessing how these science breakthroughs will and are already reshaping the way we see ourselves as human beings, the way we relate to each other as a society and the way we care for our environment.
- 16 topics proposed for discussion in a new Geneva Science Diplomacy Anticipation Summit.

One single point of entry to catch-up with the unprecedented pace of science and technology
- A carefully vetted overview of what 543 Swiss and World researchers expect to be the most significant science breakthroughs in 5, 10, 25 years.
- An interactive digital interface to easily visualise the value of anticipation in those domains.
- The ability to deep-dive and confront opinions thanks to comprehensive references to other key publications and media articles.

An interactive rolling instrument for multilateral collaboration and action
- Updated yearly.
- Continuously enriched through extended interactions worldwide.

The full set of topics and related research areas can be found in the trends explorer, via the link below.

radar.gesda.global/tr0
Introduction

The GESDA Science Breakthrough Radar is made up of 18 scientific emerging topics and related sub-fields, across four broad frontier areas. These are collated below for quick access into the report.

Through the contributions of more than 500 scientists across the globe, 216 breakthroughs over 18 scientific emerging topics have been identified and are presented through an easy-to-read visualisation. This list is extended by a series of invited contributions by leading scientists on topics that will be addressed in future editions.

The radar presents what scientists are working on, how they see their fields evolving and which developments will be important to consider. It is a neutral and fact-based presentation of some of the scientific advances that will impact humanity, with GESDA acting as an honest broker between disciplines, communities and world views.

The GESDA Science Breakthrough Radar is the result of a strategic partnership with the Fondation pour Genève and a close collaboration with open science publisher Frontiers. It is designed to become, in the coming years, an exclusive decision and action support tool for multilateralism that assesses the dynamics of future scientific advances at 5, 10 and 25 years over the three fundamental questions and the four initial scientific frontier issues identified by GESDA in its 2020-2022 Roadmap.

The three questions deal with essential dimensions of what makes us humans, the way our society evolves and our relation to the environment. They are formulated as follows:

1. **Who are we?** 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?** Which deployment of technology can help reduce inequality and foster inclusive development and well-being?
3. **How can we assure humanity’s well-being while also sustaining the health of our planet?** How can we supply the world population with the necessary food and energy, and still regenerate our planet?

The initial scientific frontier issues define four broad areas that have been taken up as starting points, and for which this report presents the science breakthroughs. Those frontier issues are:

1. Quantum Revolution & Advanced Artificial Intelligence
2. Human Augmentation
3. Eco-Regeneration & Geo-Engineering
4. Science and Diplomacy

This inaugural edition of the Science Breakthrough Radar extends science anticipation by also considering current Debates in society in relation to the themes above and global societal challenges such as the Sustainable Development Goals of the UN 2030 Agenda and geo-political considerations. It contains:

- A **Debates** chapter examining why the topics addressed by GESDA matter. This provides a synthesis of the debates in society on the current challenges facing humanity in relation to the themes addressed by GESDA.
- A **Trends** chapter presenting 216 potential breakthroughs at 5, 10 and 25 years. This shows what is cooking in the labs.
- An **Opportunities** chapter answering the question “What can we do with it?” This gives an insight into the global challenges, geopolitical issues and societal implications linked to these scientific breakthroughs.
The GESDA Science Breakthrough Radar - a look at the anticipation potential of key emerging topics

All 18 scientific topics considered will see major developments in the coming 25 years. These will reshape how human beings think about themselves, relate to each other and their society, and interact with the environment, our planet and its resources.

The topics are each divided into four sub-fields, for which each leading scientist provides a description of the current-state-of-the-art and list the most important breakthroughs according to our timescale. The global scientific community involved (543 scientists from 53 countries and 4,000 consulted) provided a value of the “anticipation potential” of each emerging topic and related sub-fields, by assessing:

1. the estimated time to maturity of underlying breakthroughs;
2. their potential transformational effects;
3. the degree of awareness among stakeholders;
4. the potential impact on the three fundamental questions on people, society and planet.

When combined in the anticipation potential, these four dimensions provide an overall vision of the relative importance in terms of anticipation, as perceived by the scientific community.

A Rolling Report - Initiating the consultation with the global community

Science and technology are moving very fast. New fields of research emerge constantly and new knowledge forces us to update the anticipated trends. The GESDA Science Breakthrough Radar deals with this in three ways.

First, it provides a series of invited contributions from leading scientists on topics of high anticipation potential that need to be developed in future editions. These essays deal with a wide variety of salient topics, such as the importance of seeking life’s origins (Didier Queloz), the potential of geo-engineering (Janos Pastor), the sustainable use of global resources (Ioan Negrutiu), the benefits of developing the skills to think about the future (Riel Miller) and the evolving nature of conflicts through digitalisation (Mriyam Dunn Cavelty, Camino Kavanagh and Anja Kaspersen).

Second, every emerging topic contains a link to curated key resources from the GESDA Best Reads. These provide key publications and media articles on the latest trends in a specific area, reflecting the most up-to-date knowledge on an issue.

Third, the release of the Science Breakthrough Radar launches a continuous interaction with the global scientific community in order to discuss, refine and expand the anticipated breakthroughs.

So what? - Opportunities from science anticipation for diplomacy and society

Finally, the opportunities chapter brings in reflections from Swiss Federal Councillor Ignazio Cassis and the Chairman of the GESDA Diplomacy Forum Michael Møller on geopolitical issues and the transition to a new multilateralism (the Pulse of Diplomacy). These reflections are completed by a discussion on the societal and political implications of science anticipation, and how to avoid missed opportunities and existential risks related to the science breakthroughs presented here.

We also present selected examples of how international organisations already engage in science anticipation as part of their mission. The section includes example from the World International Patent Organisation (WIPO), the United Nations Development Programme (UNDP), the Sustainable Development Goals Lab (SDG Lab) and the International Committee of the Red Cross (ICRC).

Taken together, Debates, Trends and Opportunities provides the basis to start creating a shared language to discuss and address without delay the emerging opportunities and challenges of the 21st century.
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The building of the 2021 GESDA Science Breakthrough Radar was possible thanks to the engagement of a large number of institutions, networks and individuals. This enabled the development of a product of sufficient breadth and depth to become a useful tool for multilateralism.

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- The Members of the Scientific Advisory Board:
  - Sir Peter David Gluckman
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    Representative of the Fondation pour Genève
  - Prof. Marie-Laure Salles
    Director of the Graduate Institute of International and Development Studies

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The 543 members of the global scientific community that contributed via survey, workshops and interviews.

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Why does it matter?

Humanity is facing global challenges, putting people and the planet under stress. At the same time, the world is experiencing breakthroughs in science and technological discoveries, such as advanced AI, genome editing, or synthetic biology, that expand human knowledge at an unprecedented pace. This will reshape the way human beings think about themselves, relate to each other and society and interact with the environment, our planet and its resources.

Considering this, the vision of GESDA — to use the future to build the present — raises a series of essential questions about the future of humanity and the main challenges of the 21st century:

- **Who are we, as humans?** What does it mean to be human in the era of robots, gene editing and augmented reality?
- **How can we all live together?** Which technology deployments can help reduce inequality and foster inclusive development and well-being?
- **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?

This has been recognised by GESDA since its formation and is part of its initial roadmap 2020-2022. Answering those questions requires continuous interactions with key thinkers from philosophy, the humanities and the arts, as well as two-way engagements with the broader public.

This section deals with these three fundamental questions. It is an initial assessment of debates around those issues as seen by scholars from philosophy, the humanities and the arts brought together by GESDA to form the embryo of a philosophical compass that will be put in place in the months to come;

citizens expressing themselves on social networks via an AI-powered social media and news analysis tool, understood as a ‘Pulse of Society’.

The range of issues considered for taking this pulse includes the three questions about the future of humanity as well as the four scientific frontier issues of “Advanced AI and Quantum Revolution”, “Human Augmentation”, “Eco-Regeneration and Geo-Engineering” and “Science and Diplomacy”. It provides a real-time snapshot on the topics driving the discussions on social networks and the current global sentiment about perceived trends.

The Debates section is designed as an input to the upcoming exchanges on the development of potential initiatives as well as to the identification of new emerging scientific topics to be included in the next edition of the GESDA Science Breakthrough Radar. The ambition is to extend it into a truly interactive digital tool in order not only to listen to what the media and the citizens are saying on a given issue, but also to engage in a dialogue with the relevant global communities. This is a pre-condition for Anticipatory Science and Diplomacy to effectively contribute to a new and inclusive form of multilateralism: it must listen to as well as interact with a broad and diverse range of representatives from all relevant communities, be they scientists, diplomats, policy makers, executives, entrepreneurs, philanthropists, artists, journalists, community leaders or citizens.
Debates

Debate 1:
The Philosophical Compass – Three Questions for Tomorrow

Use the future to build the present

The vision of GESDA — to use the future to build the present — and the anticipation of scientific breakthroughs at five, ten and 25 years raise a series of essential questions, ultimately for an improved human experience of life, and on a healthy planet. Answering those questions will allow to set our compass in the right direction as we move from anticipation to translation into initiatives in the concrete world.

This demands more than a single debate; it requires continuous interactions with key thinkers from philosophy, history, anthropology, sociology and related disciplines, as well as an engagement with the broader public.

During the past year, GESDA has consulted global leading scientists in their field about which scientific advances in the coming 5, 10 and 25 years will have a strong impact on people, society and the planet. This anticipatory mapping has involved more than 400 scientists over twenty topics, including social and human sciences, as the trend section of the report will show.

While the anticipatory mapping provides a vision about what scientists think about future advances in their disciplines, the broader meaning of those developments and their implications for the fundamental questions facing humanity, which are part of GESDA Roadmap 2020–2022, have not yet been elaborated.

The meaning of what makes us human, how we live together, and our relation to the planet are at the core of GESDA.

Using the future to build the present in a way that benefits humanity calls on our ability to respond to these three questions. As GESDA moves from science anticipation into concrete solutions for the benefits of humankind, addressing the fundamental and existential questions of ‘using the future to build the present’ becomes critical.

Akin to a “philosophical compass”, these notions will equip GESDA with the tools to guide its actions towards positive outcomes. GESDA initiated a first dialogue in July 2021 on the three questions with a series of key thinkers. We provide below some impressions of the discussions as quotes, which will be enriched as we progress.

Monique Canto-Sperber
République des Savoirs, Former Director of the École Normale Supérieure

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Theological Anthropology, Vrije Universiteit Amsterdam

John Dryzek
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Mark Hunyadi
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John R. McNeill
Professor for Environmental History, Georgetown University

Eric Salobir
President OPTIC Network, Roman Catholic priest and a member of the Order of the Preachers

Wendell Wallach
Yale University Interdisciplinary Centre for Bioethics, Senior Advisor at The Hastings Center and Carnegie-Uehiro Senior Fellow at the Carnegie Council for Ethics in International Affairs
1. Who are we?

New scientific discoveries are radically changing the nature of how we perceive ourselves as human beings. Advanced synthetic biology and gene-editing techniques have the potential to modify the biological fabric of our bodies. Advances in cognitive neurosciences, brain-machine interfaces and neural technologies may provide access to our inner thoughts in the near future and allow others to steer our behaviours. The power of quantum technologies and advanced artificial intelligence might provide new understanding of conscience and the origins of life.

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

Mark Hunyadi
Professor for Moral, Social and Political Philosophy,
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“Homo technicus”. There is one thing that is extraordinarily striking under the effect of technological development, namely that until very recently, philosophy was obsessed, one can say, by the question of distinction between man and animal.

Each philosopher has his own contribution: for Rousseau, for example, it is freedom that distinguishes; for Heidegger, the fact of having what he calls a world. And under the effect of developments in artificial intelligence, robotics too, the question really arises of the distinction between man and machine, a kind of displacement of the question. In general, I find our scientists much too fascinated by the power of machines, and insufficiently surprised by human intelligence, in particular where it is most immediately visible, that is in children. I find that we are reasoning the other way around, that is to say that we are fascinated by this computational capacity of machines. Everyone can see that the machine does things that the human mind cannot do. Suddenly, that gives a kind of extraordinary privilege to this function, let’s say of calculation or computation, but we are not surprised by the questions of a child, by the way a child apprehends the world. To all these new algorithms we give millions of images to distinguish a cat from a dog. But what fascinates me is that once you show a cat to a child, not only does it recognise other cats and distinguishes it from dogs, but it even recognises the symbolic forms of a cat, for example Gelluck’s cat. I think that if we retuned our astonishment a bit we would get another image, maybe humbler on the side of artificial intelligence and more admiration of human intelligence. [Everyone] is fascinated by computing power. And when we tell [the scientists] but look at the child like he can not only tell, but summarise a story — [they reply] yes, but artificial intelligence will be able to do it. I don’t think so at all.

The summary of a story is not a question of calculating words, or of identifying the number of occurrences of words. It is a question of being able to give a meaning to a narrative sequence of events, and that is something totally different. I think that we are in the false paradigm with the paradigm of calculation. Questions of meaning are so important for childhood. These questions of meaning are extraordinarily important to humans in general and they are simply not reducible to calculation. A crane — this is a somewhat brutal parallel of course — lifts weights that a human body can never lift. This does not mean that we find it intelligent. In the same way, basically, this extraordinary computing power that machines have, that does not make them intelligent for all that. From a more ethical point of view, what I fear for the future of humanity, since it is a bit your question and it is mine too, is that by dint of constantly valuing calculation, what will count [in the end] is calculation, neglecting questions of meaning. My fear is that little by little, we will come to eliminate the human being himself, his dispositions and his aptitudes, precisely the search for meaning, imagination, spontaneous creativity.
If what matters is what you can count, then everything you cannot count will gradually be devalued. When you make machines, when you make a world of machines and algorithms, you don’t just make machines, you make the humanity that goes with them. We robotise humanity, and it becomes basically a kind of partner of machines as you have to go through machines all the time. And that is something completely new in the history of technology, that is to say in the history of mankind. [...] Human beings have always been technical animals, but there is something quite new happening right now before our eyes. The great thinkers of technology like Marx or Hannah Arendt, described the tools as being an intermediary between me and nature. Something that prolongs my body. A little later with people like Jacques Ellul, for example, we think of technique as a system. For Leroi-Gourhan, paleontologist, it was an environment. [...] But today, we are still in something else. This means that now, it is technology via digital technology, that allows us, in general, to have access to the world. The digital becomes the obligatory mediation. Not just an intermediary who helps us. It becomes compulsory mediation. Tendentially, — let’s not exaggerate — it means that we are all the time obeying machines. We are in a real dependence on machines; it implies a very asymmetrical dependence, since these machines are programmed by someone. It gives the designers of these machines quite exorbitant power over how we can access the world. As I usually say: Obeying machines makes us obedient machines.

Monique Canto-Sperber
République des Savoirs, Former Director of the École Normale Supérieure

The perspective of an augmented human being. Here are some issues to think about in relation to the prospect of a cognitively augmented human being: would such an augmentation only amplify already formed capacities or could it give these capacities from the start without the need to acquire them? In this second case, the question of the consequences for the definition of what is a human being are quite different.

Let us take the example of learning, the necessary acquisition process of knowledge and skills. If knowledge and skills were immediately available, without any learning, the following issues would need to be further explored:

- **Learning is a process of self-transformation.** Which is necessary for the human body to adapt to its environment. If this process no longer existed, what would be the consequences?
- **Learning implies repetition and therefore an experience of duration** which has an impact on the functioning of the brain (exercise of patience, learning of the temporal dimension, familiarisation with the time required to complete a project). In this way, it opens up a range of other related competences: would the disappearance of learning lead to the weakening of these competences?

- **Learning responds to a desire and an effort.** In other words, it enables the mobilisation of a set of motivational dispositions that allow the individual to orientate himself towards the world and to act to transform it. If there were no more learning, what would be left of these dispositions?

This simple example about the learning process, formulated without any moral considerations (it is not a question of knowing whether a augmented human would be better or worse), shows what is at stake. Augmented humans could represent a considerable gain for humanity, but there is the risk that this augmentation goes hand in hand with the attenuation, if not the disappearance, of a set of cognitive or motivational capacities which play a major role in the interactions of a human being with the world and with his kind

The same reflections could be made about our capacity for imagination, or about emotions. Current research in cognitive psychology tends to show that this capacity plays a significant role in the process of knowledge, discovery, and innovation. But these emotions are also linked to desire and dissatisfaction, including about knowledge: would the immediate accessibility to knowledge through cognitive augmentation allowed to free the imagination and innovation resources of human beings? Or would exempting human beings from the experience of dissatisfaction, trial and error and progress deprive them of the cognitive resources necessary for innovation?
There are all kinds of technologies being predicted, all kinds of areas being worked on. We don’t know when breakthroughs will be made in these various realms of research or in what order. And as these breakthroughs are made, we don’t know how they will synergistically interact. Therefore, it’s very hard to anticipate exactly what the near and longer-term challenges are going to be. This places us in a difficult position in the science policy dialogue about how to shape technological development through our actions in the present. The philosophical and institutional structures that we put in place must ensure that our policies are well thought out, that we are prepared for unanticipated events, and that we have at least the right values or the right approaches for factoring in ethical considerations. Those ethical considerations must acknowledge the benefits of the various innovations, but also lend a cursory eye to the undesired societal impacts and risks of allowing certain technologies to move forward.

On the philosophical front, there are ontological, epistemological, and of course meta-ethical and metaphysical considerations that come into this play. For example, is the machine/human distinction really helpful or not? We have been using machines as an imperfect mirror to understand what it means to be human and the ways we are similar to or truly differ from those artificial entities we create — whether these are intelligent machines, whether they integrate biological and human material, or whether they are enhanced humans. Are the ontological categories we have helpful, or do we need to be thinking in new ontological categories? What should be the rights of artificial entities, whether intelligent machines or enhanced humans? What’s the ontological status of ecosystems or of the planetary environment? What kind of say do, or should, they have in the decisions we make? What is the ontological and legal status of animals, particularly those that seem to show cognitive faculties? And I don’t just mean great apes, but also species whose cognitive capabilities differ from or evolved differently from ours. There’s a whole vast realm of cognitive capabilities that nature has created and from which we can learn. That all needs to be factored into how we forge a pathway forward.

Then there are the epistemological questions. What counts as knowledge? Is there a prevailing scientific narrative and scientific framings that at times runs roughshod over other forms of knowledge? And if so, as I believe there is, what are these other forms of knowledge and understanding and how can they be elucidated?

We are in the midst of what Jürgen Habermas referred to as a delegitimisation crisis where the public loses faith in its governments and its institutions to solve their problems. Self-driving cars provide an apt metaphor for the Information Age — technology is moving into the driver’s seat as a primary determinant of human history. [...]

I’m pro science, but I’m also someone who is perhaps best known for underscoring the dangers of various technologies whose goals, risks, and tradeoffs have not been considered comprehensively. With these words, I hope to underscore the vastness of the subject matter and the fact that even people like myself who have been submerged in it in the most transdisciplinary of ways, only have an inkling of what’s going on or what all needs to be addressed. [...]

This complexity points to one very simple fact — the notion of intelligence as being the property of any entity, either artificial or a human, misses the reality that intelligence is collective and participatory.
Eric Salobir
President OPTIC Network, Roman Catholic priest and a member of the Order of the Preachers

The human person is defined by interactions with others. Where I think it is interesting, it is precisely that the great strength of our species has been this capacity to renew itself and to transform itself through genetic evolution, through the mixing of genes. As we can see, it is not by chance that, in the end, the prohibition of incest is not just a psychological prohibition of access to origins. It is also a prohibition which has a biological dimension.

We are ourselves and we only flourish as ourselves with the other. I need the genes of the other to perpetuate myself. I need the difference. It also actually means that human beings develop in interaction with others. The work of the Canadian Charles Taylor on the doubles speaks to this: “The two sources of the self” or the two sources of our identity. This means that there is a part of my identity that comes from me. There is also a part of my identity that comes to me from the other. From the moment that technology blocks or transforms the relation with the other, it will transform me. There will be a mediation of this technology on the constitution of my identity through the other, which, suddenly, will transform me.

The difficulty that I see when I speak about the emergence of a human person, is that it is not only that we are enriched by discussions with others, but also because it is the confrontation with the other that moves me and allows me to transcend myself.

This will not happen with a machine that is deliberately not made to transform the individual, which therefore risks remaining raw.

Also, consider the very far-off scenario of the possibility of interacting with an AI that would have a form of self-consciousness or a form of intelligence (or the illusion of intelligence) to a point where the AI system becomes a part of your life at the same level as a relationship with a human person. After a while, the problem with AI is that, by definition, as it is made to meet our individual needs, these interactions can become interactions that are exclusive to everything else. And here too, we are in a scenario where we could gradually see a human being find fulfillment in their digital twin or their digital clone. Look at yourself in this kind of mirror. A kind of self-fascination for two, but which, in the end, can be a rather complex relationship. In Japan, there is a term for it that, pathologically, those who no longer live only in technology or go out no longer. It could become a pretty common lifestyle model, but one that, in my opinion, does not allow the complete emergence of the person, and will not result in completely structured humans.

Human agency and free will. In this context, for me, the question is what it is to be human in the age of artificial intelligence? The question I am asking myself is: is this transformation which is underway and for which we do not yet have a great readability — is this a transformation that will bring more sense to human life? Or will it lead to a form of dehumanisation?

But I think the key elements are those around human agency, the capacity for action and free will. It is interesting to think that a certain number of digital technologies, are made to make our lives easier. You no longer choose the temperature in your car, you no longer choose the pieces of music you would like to listen to, or your playlist. We have more and more machines that handles all of this for you. As we get rid of all these little choices that poison our daily lives, do we liberate ourselves to ask ourselves the big questions? Or, on the contrary, because we do not need to make small decisions on a daily basis anymore, do we risk, at some point, reducing our capacity for free will? I would make an analogy. We know that people who use their GPS extensively can gradually lose their sense of orientation. After a while, when they lose access to the machine, they aren’t really able to orient themselves anymore. And so, their perception of their position in space, of their relation to space, is changed. There is an almost phenomenological dimension in the relationship we have to the space around us, which is evolving quite simply because we are more used to moving around than having to orient ourselves. We are guided and do not have to ask questions. As we go from point A to point B, we are taken from point A to point B. Is the same thing going to happen with our capacity for action and our capacity for decision? Or does this facilitation, on the contrary, free our minds for the most important topics?
2. How are we going to live together?

New advances will not only modify our perception of ourselves but our relationship to others. Research on ageing might extend the lifespan of people and raise new questions about equitable access to science or the intergenerational contract of current societies. Advanced AI might lead to further automatisation and fundamentally change the nature of labour and political participation. Advanced biology combined with quantum computing might provide solutions to poor health or hunger. Well thought out deployment of technology can help reduce inequality and foster inclusive development and well-being. Which deployment of technology can help reduce inequality and foster inclusive development and well-being?

A second example (about augmented human being) relates to interactions with others. The need of the other is fed by the inability to be self-sufficient. Human beings become aware of their interdependence very early on, precisely because there are things they do not know and cannot do. An increase in human capabilities that would give rise to a certain form of omnipotence in all areas would lead to ignoring the need for the other. Without this basic need, the political community loses its raison d’être. And when it loses its raison d’être, so does the raison d’être of the modes of regulation that are laws and norms. Such a state of affairs could lead to a permanent state of war, which only an extremely authoritarian power would be able to pacify in some way from the outside, as a form of Leviathan. On the other hand, it is also possible to imagine that an augmented human being would have extremely developed emotional capacities and an increased ability to identify with others.

A last question is whether human augmentation would lead to the equalisation of all. It is a question that is seldomly asked, but which is absolutely fundamental. If there were systems of amplification and augmentation (of the human) of this importance, which would affect the cognitive processes themselves, human capacities would tend to become equal for all individuals. We have never been in this kind of society.
“A gloomy vision of the future of humans”. Will there be an awareness of humanity to take back control? With the grip of digital, everything is done to prevent this awareness. This is what worries me. The digital works on a principle that I call libidinal, it works on the pleasure and the satisfactions it provides, in leisure and also in professional life. It’s everywhere, it’s intuitive, it’s fast and efficient. This libidinal principle fragments us into individuals, into profiles. This goes against the grain of any collective or political awareness. The degree of satisfaction that digital technology brings is so high that it actually prevents any criticism. If we look at great societal changes historically, they were made when people were suffering. (I’m simplifying): people said stop, we’re going to beat the regime or start a revolution. But [here] now no one is suffering. It happens again thanks to our own pleasure, by our passive adhesion. But the situation is catastrophic, but not hopeless. Why? Because I see an increasing awareness, through my teaching for instance.

There’s already a world between my freshmen ten years ago, and my freshmen now: they’re a lot more aware of what Facebook is doing to them, how it works. I also think that across the world, there are a lot of initiatives, very local, but they are done to reappropriate things, to turn digital technologies a bit, in a way that is a little more collective, creative, free, etc. There is individual awareness around the world, and actions of reappropriation, in a way. What gives me hope is that the awareness is there. Actions do exist. I think what these two layers lack is a third floor, an institutional floor. What is missing is a kind of UN of technologies. I do not clearly have the solution. But we can take an example from bioethics. In the 1980s, when we saw that genetic engineering was going to take on an exorbitant power, we quickly created institutions in all countries. I am not desperate, but as Gramsci said “I am a pessimist of intelligence, but an optimist of will.”
"Which technologies can reduce inequality?

My answer to that is: simple technologies that are easy to operate and to maintain. One of the democratising technologies that historians are familiar with are iron tools and iron weapons, three thousand years ago. Some people say that today’s cell phones and social media have a democratising effect. That may be, although I think it’s too soon to say with respect to communications technologies. I think there is a long-term historical pattern whereby new technologies upon introduction do have a democratising effect; however, over time, and it may be decades, maybe centuries, that democratising effect is replaced by a centralisation of power. States learn how to use new communications technologies to empower themselves over citizens. I think you can see this in the history of writing, the history of printing, the history of early electronic communications technologies such as radio. And I would not be surprised if we see this in the history of social media.

I do think with respect to international relations, new energy technologies are going to change things fundamentally, not that I can predict exactly how, but so much of the distribution of wealth and power in the international system in the last two hundred years has been connected to the fossil fuel energy system, that a reduction in the centrality of fossil fuels.

How can we assure mankind’s well-being with the sustainable health of our planet? Well, the first answer is we can’t. It’s beyond our power. The way I approach this question, however, is to think about particular challenges: one is nuclear war, a second is pandemics, and the third is climate destabilisation, in no particular order of importance or urgency. Nuclear war while it used to be a preoccupation of the chattering classes, has grown less interesting to most. I think that’s unfortunate. We’ve been quite lucky since nineteen forty-five. I think that’s an unjustly neglected aspect of our health and well-being on the planet.

Pandemics are not neglected. In the last 17 months, we’ve begun at last to pay attention to this particular risk to health and well-being on the planet. Covid-19 is actually a blessing in deep, deep, disguise. I say this because the SARS-COV-2 virus is not nearly as lethal as many other equally or even more transmissible viruses. The covid-19 pandemic has alerted us to the risk of lethal and highly transmissible viruses without exposing us to the maximum effect. And it is therefore like a societal vaccination. I would predict that for a generation we will have better preparation and better surveillance against the next emerging pathogens. If we’re successful, however, complacency will return after a generation or two. Last, on climate destabilisation: the way I understand this problem is to think of three broad paths to climate stabilisation. The first of these would be a radical reduction in the use of energy and in certain materials that contribute to greenhouse gas accumulation; this seems a very unlikely path to me. The second path is a radical decarbonisation of the energy system so that fossil fuels account for a much smaller proportion of energy use. This would have to be combined with carbon sequestration on a grand scale. This, to me, seems the most desirable path. The third path is geoengineering to mask the effects of greenhouse gas loading. This frightens me terribly because the history of technology tells us that it’s very hard to do only one thing at a time, and we cannot know the full range of effects of planetary scale tinkering of the sort that the proposals for geoengineering entail. I hope that the second path will prevail rather than the third.
Marius Dorobantu
Theological Anthropology,
Vrije Universiteit Amsterdam

My background is in theological anthropology, and it is reflected in how I see the challenges posed by AI technologies, in general, and the possibility of Artificial Super-Intelligence, in particular. What I notice is that most of the discussion takes place around the all-important questions of how to ensure that AI will not malfunction or inadvertently increase inequality, discrimination, or authoritarianism. These questions are hugely relevant and urgent. But an argument can be made that these are, in fact, the easy questions posed by AI. They don’t have easy answers, but at least everyone can more or less agree upon the desirable outcome.

Here are two questions that are, in my opinion, more difficult. They both deal with the more optimistic scenario, where we actually succeed in doing AI ‘right.’ Firstly, if we were somehow able to solve the alignment problem and instill in AI exactly the kind of goals and values that we wish, what would these be? Should, for example, humility be prioritised over courage? This is a topic where philosophy and religion, with their rich traditions of reflecting on such questions, could be of real help in our attempt to understand what we really value.

Secondly, what if advanced AI could relieve us of some of our most pressing issues? Given absolute power and freedom, it could govern the world more efficiently than we do, and it could, for example, potentially mitigate climate change and global poverty. Such a scenario seems desirable and, to some, even morally imperative. However, we might also sense that there is something intuitively wrong about completely delegating our decisions to AI, as benevolent as it might be. Why is an utopian world — where AI does all the work on our behalf and we become free to enjoy the cosiness of a pet’s life — so inherently repugnant? Such questions may become more urgent in the near future. To be prepared, we need to accompany current scientific and technological efforts with serious moral, philosophical and spiritual reflections. Everyone agrees that AI should be for the good of humanity, but understanding what good means is just as important as learning how to endow AI with the right kind of values and goals.

Eric Salobir
President OPTIC Network, Roman Catholic priest and a member of the Order of the Preachers

Technologies of today allow us to reflect on the future.
The two questions about what it means to be human and how to live together in the age of new technologies are complementary, and partially overlap. To answer these, we can start from a reflection centred on technologies that already exist. And then evolve towards new technologies such as brain-machine interfaces or the simulation of consciousness by AI. We can push the reflection towards things that are quite forward-looking like fusion or the connection of brains. And, in fact, we see that the questions that arise are ultimately the same. That is what is interesting. Ultimately, even if we don’t have all the data to think about things that are very prospective, we can reflect on existential questions by relying on the data we have from technologies that are already mature now. If we identify the right vectors and good intellectual trajectories, we can almost reverse-engineer thoughts of the impact those advances may have. This reverse-engineering will allow us to identify first elements of answers for future technologies whose contours are still very imprecise.
3. How can we assure mankind’s well-being with the sustainable health of our planet Earth?

Climate emergency, rising population and increased resource needs threaten the balance of our planet. New fundamental scientific advances and future technologies could provide new ways to ensure a sustainable, responsible and inclusive development for all. This requires a new understanding at the edge and the convergence of formal, natural and human sciences. How can we supply the world population the necessary food and energy and regenerate our planet?

Narratives enable us to create orientation and meaning in a highly complex or even chaotic world. Reconstructing narratives is therefore useful and important to understand why different people see the world in different terms, why they look at different causal relationships, and why they come to different conclusions about feasible and desirable futures. [...] We can distinguish between five narratives of the Anthropocene: the disaster narrative, the court narrative, the narrative of the great transformation, the biotechnological narrative and the interdependence narrative of nature-culture.

The disaster narrative has an apocalyptic logic. Humankind is seen as a planetary killer, concerned only with its own short-term survival. It is a story of nature’s decline and collapse caused by mankind. According to Elizabeth Kolbert’s book, the sixth mass extinction (including our own species) is a central feature of the Anthropocene. We have also the metaphor of a sick planet. The narrative has an urging and a warning function. Concerning the topic of food and energy, it poses that we are facing increasing conflicts over control of food and energy resources, even food and energy wars. “The court narrative” is questioning guilt and responsibility. It’s plot follows the pattern of ‘who has done it?’ We have villains and victims.

Some speak about the ‘eurocene’ or a ‘technocene’ with the main polluters in the OECD and BRIC countries. And some others speak even of a ‘capitalocene’ to name the capital markets as the main culprits.

The narrative of the Great Transformation assumes that a rescue from climate crisis is still possible if we collaborate inter- and transnationally. So, it has a hypothetical happy end. It features a ‘responsible stewardship’ of the Earth systems. First, it calls for mitigation, thus reducing the causes of ecological destruction, and secondly for a reasonable adaptation. Schellnhuber from the PIK takes up the discourse of ecological modernisation with the idea of a continued economic growth, including fair burden sharing, so potential victims are avoided. A responsible and a sustainable society needs, many people say, a radical cultural change with a circular economy and different ways of consumption. [...] Here, we have the metaphor of the world gardener or the earth gardener. And the villains are the people who are unwilling to contribute to the course of this transformation.

In the biotechnological narrative the heroes are the inventors, technologists, and venture capitalists. So, we have different features. For example, the geoengineering or solar geoengineering. Some people say, we cannot cope with climate crisis without any climate engineering in the coming times. But we also see the problem of unintended consequences. We also have the discussions on the Green Revolution 2.0, technologically intensified seeds and crops, which causes new inequalities.
The nineteen people who have formed the eco modernist manifesto speak of a great Anthropocene, with solar energy, with nuclear energy and with intensive farming and so on. The villains are the people who still cling to romantic concepts of nature and all the people who are proponents of the precautionary principle.

“The interdependence narrative of nature-culture

The anthropos, the we, are seen as a part of networks of distributed actors that also include animals, plants, microorganisms and fungi. Proponents of this narrative speak of multispecies entanglements and multispecies justice. They problematise the long-established juxtaposition of nature and culture. And they also question the ‘we’ as a homogeneous or universal entity and assume multiple fractions of humanity. The interdependence narrative puts at the centre the mutual relationship between humans and other species. Its recognition of the contribution of other species to human well-being and civilisation leads to a responsibility of humans for other species. This has potentially far-reaching consequences for the use and treatment of animals and maybe also plants and food systems. From the perspective of an interspecies ethics and multispecies justice, the reduction of farm animals to bio-reactors for protein generation becomes unjustifiable.

John Dryzek
Professor at the Centre for Deliberative Democracy and Global Governance, University of Canberra.

“Politics of the Anthropocene” How can we ensure the well-being of humankind, the sustainable future of our planet? My thoughts are published in my co-authored book The Politics of the Anthropocene (2020). The basic point of the book is that dominant institutions, including states, markets and international organisations, developed under relatively benign Holocene conditions in which the influence of a potentially unstable earth system was simply not recognised. The Holocene is the epoch preceding the Anthropocene, the last eleven thousand years or so of unusual stability in the earth system. My colleague Will Steffen likes to say that the Holocene represents the only state of the Earth system we know for sure that can support human civilisation. The problem is the dominant institutions developed under the Holocene are not fit for purpose in the Anthropocene. The institutions that developed in the Holocene have a tendency toward pathological path dependencies, which makes them very resistant to change. That’s why we’re stuck with fossil fuels: these institutions generate forms of feedback which reinforce their own necessity, but largely ignore the condition of the earth system.

The opposite of that kind of pathological path dependency is reflexivity, which is the ability of a structure, process or set of ideas to change itself in light of reflection on its performance; the capacity to be something different rather than just to do different things. So, it’s much more fundamental than adaptiveness for example. Ecological reflexivity in particular recognises the active influence of the earth system itself, as no longer a passive backdrop against which humanity and its institutions operate. Our institutions developed forms of feedback which systematically ignore feedback from ecological systems. Ecological reflexivity also involves recognising non-human entities, be they local ecosystems or the Earth system itself, as active players, not as things that we just operate on but things that are active, capable of causing surprises. This is where the Anthropocene narrative comes in: ecological reflexivity also involves looking ahead. It requires foresight, anticipation of potentially catastrophic state shifts in the system and acting to prevent that. That’s really demanding. And that’s something which current institutions are really bad at. Democracies, for example, can sometimes respond pretty effectively to crises, but they’re very, very bad at anticipating crises. So, what to do? We need to start from where we are now, rather than just postulate the sort of models which might exist sometime in the future, and look at how current institutions, practises and structures might be reformed.
We find some encouraging hints: the global governance of climate change, for example, has transformed over time. And it does show just a little hint of reflexivity, a recognition that the system was not working. The Paris agreement, for example, which after several decades of negotiations which got nowhere, involves a shift to hybrid multilateralism, a combination of top-down and bottom-up processes, as well as the orchestration of the role of non-governmental actors. We can also think of trying to produce a deliberative collective intelligence that is much more than the sum of its parts. My co-author Richard Norgaard analysed the Millennium Ecosystem Assessment and looked at the role of deliberation across different forms of scientific expertise. This kind of vernacular language, which integrated different kinds of expertise, also provides an opening for meaningful citizen participation, which could help construct a reflexive, deliberative science. It is also possible to rethink justice in order to recognise influences across space and time much more than do our current dominant conceptions of justice, moving toward what we call planetary justice, which also involves thinking more explicitly about justice towards future generations.
Debates

Debate 2:
The Pulse of Society – on Three Questions for Tomorrow

As the current pandemic has made clear, science and diplomacy are not happening in a vacuum. Debates about scientific advances, future breakthroughs and their impact are taking place around the globe, at all levels of society. Taking the pulse of society is an attempt to listen what citizens are saying, their hopes and fears, their feelings about future scientific developments, and how these attitudes shape their vision of the future of humanity.

Building on a dataset of roughly 11 million social media posts as well as over 6 million news articles and blogs, we present here the outcomes of an AI powered social media analysis about global conversations on the main topics of interest in the Breakthrough Radar. This encompasses the three fundamental questions for tomorrow that were presented in the previous section in the philosophical compass:

1. Overview of the Analysis
2. Who are we?
3. How are we going to live together?
4. How can we assure humanity’s well-being while also sustaining the health of our planet?

The analysis, carried out using AI-based research and trend sensing tool Deep View, combines human intuition with machine objectivity enabling robust strategic decision-making. It has been guided by the aim to distinguish the core differences between regions, demographics and topics in order to be able to identify the fields which ask for a broader societal debate. For more information on the analysis and the tool, please refer to the methodology section in the annex.

Taken together, the Pulse of Society, the Pulse of Science and the Pulse of Diplomacy provides the basis to start creating a shared language to discuss and address the emerging opportunities and challenges of the 21st century.
Overview of the Analysis

Existential debates about the future of humanity and the main challenges of the 21st century do not only take place in academia or diplomatic circles. They happen also amongst citizens that are concerned, show hope or are ambivalent about how advances in science and technology influence and sometimes redefine our views on human nature, our relationships with each other, and with the planet.

The section below provides an overview on the discussions taking place on social media on issues related to the questions for tomorrow introduced above. Through the Deep View AI-powered social media analysis tool, we describe the underlying concepts and narratives that drive conversations on issues related to the three fundamental questions. These narratives can be analysed separately for different groups with different geographical, generational, cultural, educational or gender backgrounds. The sentiment analysis also allows estimation of whether the different groups position themselves positively or negatively with respect to a specific narrative.

The three questions for tomorrow, as formulated above, were used to poll the system and structure the analysis. They all include in their formulations a reference to advanced science and technology. As will be shown in the analysis, most of the narratives therefore have a strong link to the anticipated technological advancements presented in the Trends section of the Science Breakthrough Radar.

This social media analysis, which has been guided by the aim of providing an objective and constructive discussion basis, is a first step. Although it has some limitations and contains inherent biases, it provides a unique picture of how debates about essential questions facing humanity are taking place in wide parts of society, and complements the reflections of philosophers and scholars from social sciences, humanities and the arts on the same questions.

These questions deserve to be debated in broader groups and fed into fundamental discussions about science anticipation and our future.

The section presents the insights across each section sequentially. A description of the methodology is presented in the appendix.

Who are we?

What does it mean to be human at the age of robots, gene editing and augmented reality?

The distinctive meaning of our human nature evolves constantly, influenced by the images we see around us in popular media, the books that we read, and our knowledge about new scientific insights: our anticipation of science and technology play a big part in the formation of this ever-changing picture.

The following eight narratives were derived from the analysis relating to the first question of what it means to be human during the age of robots, gene editing and augmented reality. The broad and essentially philosophical question of ‘who we are’ is thus seen through the lens of the anticipated science advancements. The analysis of social media shows that people are particularly aware of some fundamental challenges — new social and economic divides and changing self-perception, for example — that contribute to redefining our human nature in relation to potential science and technology advances, but are ambivalent with respect to the concepts that underpin the narrative.
Recurring narratives and sentiment analysis

1. Converging society
   - Society will grow closer together as a whole and there will be significantly less discrimination between groups. Technology is clearly the enabler for this development. The view towards technology is positive.
   - The core emotion related to this narrative is hope, with analysis resulting into 62% positive and 10% negative sentiments.

2. A new social border
   - The social divide between augmented and non-augmented humans will increase. Humans will start to become brutal with machines as they learn that always co-operating with machines allow oneself to pursue selfish needs.
   - The core emotions related to this narrative are fear and frustration, with analysis resulting into 6% positive and 34% negative sentiments.

3. Fear of high-impact technologies
   - Humanity and nature may be in danger as a whole due to the negative impact of these technologies.
   - The core emotions related to this narrative are alarmism and suspicion, with analysis resulting into 5% positive and 35% negative sentiments.

4. Cyborgs: the next step of evolution
   - The current human species will eventually be replaced by the next big step of evolution, augmented humans. Class conflict between augmented and non-augmented humans will develop.
   - The core emotions related to this narrative are confidence and curiosity, with analysis resulting into 45% positive and 7% negative sentiments.

5. Our self-image
   - The integration of technology into human lives will increase and social structures might change. Not only may machines play a crucial part in traditional social constructs such as families and school classes, they may even reach a certain parity with humans and some humans might develop emotions, friendships and other affections toward machines.
   - The core emotion related to this narrative is alarmism, with analysis resulting into 42% positive and 13% negative sentiments.

6. Intelligent machines
   - Machines will develop themselves and develop their own understanding towards humans, society, nature and other technologies.
   - The core emotions related to this narrative are fear and suspicion, with analysis resulting into 32% positive and 10% negative sentiments.

7. Productivity above all else
   - Humans will concentrate on creative roles and will use machines to perform unwanted tasks. Increases in productivity will also result in an increase of sustainability. There is a possibility of increased human dependence on machines.
   - The core emotions related to this narrative are pleasure and thrill, with analysis resulting into 65% positive and 6% negative sentiments.

8. Technology Acceptance
   - Humanity will fully embrace and accept the role that technology plays in their lives. Those not willing to accept this technological diffusion will find it increasingly hard to integrate with the rest of society.
   - The core emotions related to this narrative are indecisiveness and delight, with analysis resulting into 61% positive and 7% negative sentiments.
**Gender**

- Women are slightly more negative, with 38% compared to 33% negative opinion among men. Both name genome editing and AI as the most important effects. With regard to AI, men emphasise more recent developments, while women tend to talk more about superintelligence.
- The third narrative is used by 30% more men than women, with the latter rating it more positively. Women often make a connection to increased productivity and emphasize the need to adapt education in this area. Men are more likely to discuss how to respond to superintelligence once it arrives.
- Technology-enabled work/living and technology acceptance are communicated relatively more frequently by women than by men. Men speak less emotionally but still positively about the narrative.
- In the analysed sample, there is a clear prevalence of men. With 31% positive and 19% negative posts, men answer this question less optimistically than women (41%/14%).

**Background (STEM professions and artistic professions)**

- The fourth narrative is relatively often conveyed by authors with creative backgrounds, less so by authors with STEM backgrounds. The former focus on the humanities legacy, while the latter emphasise the pioneering aspect of innovation.
- The fifth narrative is used relatively often by authors with a creative background. They explain that in the age of AI, it is necessary to redefine what is human and what is machine. For example, it may become normal to have emotions and friendships with machines.
- Intelligent machines are discussed by authors with STEM background with 26% negative sentiment compared to 16% of authors with creative backgrounds. The former often evaluate current advances, while the latter try to understand the implications of a machine becoming aware.

**Continent**

- **African Authors** use the first narrative (increased societal cohesion) most frequently, followed by Asian and European Authors. Yet, this narrative was the least frequent narrative to be used among most continents.
- **A new social border**, which can in large parts be seen as a critical view on the development of society, is notably least used among Asian authors, as opposed to techn-enabled working and living.
- The third narrative (fear of high-impact technologies) occurs frequently in North America, Europe and South America. Europeans view it most negatively (44%), followed by South America (34%) and North America (33%). Asia and Africa use the narrative less frequently, with Asia seeing the issue less emotionally (24% negative).
- The seventh narrative (productivity above all else) is by far the most used among Asian authors. They also view it clearly more positive (74% positive vs. 62% others combined) and more emotionally (21% vs. 31% neutrals) than others, focusing on benefits of cutting-edge technology.
How are we going to live together?

Which deployment of technology can help reduce inequality and foster inclusive development and well-being?

Advances in science and technology are having a major impact on how our societies work and how we interact with each other. This is nothing new and a wealth of academic literature and popular books discuss how the acceleration of scientific knowledge and the deployment of new technologies globally has contributed to redefining social interactions and norms, their effect on inequality and how they contributed to development and well-being. The social media analysis on the “how we are going to live together” question shows, unsurprisingly, that debates about the relation between science and technology and society are driven mainly by narratives around economic equality, access to the benefits of technology and global governance issues. On the one hand, the data sample analysed show some degree of concern about the transformative effect of some technologies. On the other hand, there was optimism that advanced science could contribute to reduce some of the challenges faced by our societies.

Recurring narratives and sentiment analysis

1. Development of economic inequality
   - Automation will lead to a transformation of labour markets. A lack of regulation will lead to increased inequality, and inequality directly impacts the human condition.
   - The core emotions related to this narrative are scepticism and fear with analysis resulting into 46% positive and 5% negative sentiments.

2. Access to technology is a crucial factor
   - New technologies provide little advantage if they are not widely accessible for everyone. They may even prove disadvantageous if the ensuing inequality becomes too strong. Delivering these infrastructures is a complex task that requires multilateral collaboration.
   - The core emotions related to this narrative are anger and optimism with analysis resulting into 64% positive and 3% negative sentiments.

3. Technology alters social norms
   - New technologies will precipitate strong changes in the way humans interact with each other. Current social norms will be replaced by data analytics. Preserving human individuality will be critical.
   - The core emotions related to this narrative are fear and anticipation with analysis resulting into 12% positive and 11% negative sentiments.

4. Governments catalyse the benefits of technology
   - The purpose of governments is to ensure the protection, stability and smooth progression of the social, economic and physical environment. To achieve this, government officials need to have a full understanding of how new technologies will impact the world.
   - The core emotions related to this narrative are confidence and hope with analysis resulting into 90% positive and 1% negative sentiments.

5. Degree of education divides society
   - Education is a safeguard against the spread of inequalities. Although its effects can only be measured in the long term — a fact that often makes education a lower priority for governments — education remains the most commonly accepted means by which a person or a group of people can increase their wellbeing.
   - The core emotion related to this narrative are sadness and hope with analysis resulting into 51% positive and 6% negative sentiments.

6. Availability of technology opens up societal gaps
   - While technology permeates all aspects of lives, its benefits are more acute in some fields. This means that those fields are more prone to promoting inequality than others, as technologies naturally follow an adoption arc that makes it simpler for more resourceful individuals to access them quicker.
   - The core emotions related to this narrative are regret and anger with analysis resulting into 30% positive and 9% negative sentiments.

7. Open discussion and global agreements
   - Promoting open debate about how to integrate technologies into our society is another safeguard (along with education) against the spread of inequality resulting from the adoption of such technologies. Ergo, failure to engage in open debate will most likely increase inequality.
   - The core emotions related to this narrative are hope and confidence with analysis resulting into 37% positive and 23% negative sentiments.
Gender
- The effects of technology on social norms are discussed by 35% more men than women. While they are predominantly discussed neutrally (82% on average), women tend to express themselves more positively than men (16% compared to 5.5%).
- The fourth narrative (the role of government) is viewed very positively by both genders (89% positive), with female authors using it 13% more often than male authors. Within the narrative, women mention the circular economy most often (35% of contributions), while men focus more on the controlled energy transition and the role of fossil fuels.
- The impact of education is mentioned least frequently and by 16% more women than men. The opinion of female authors is often a mix of positive and negative arguments, e.g. citing climate change, and education as a means to bring it to society’s attention.

Background (STEM professions and artistic professions)
- The narratives are evenly distributed, with both groups focusing on society and politics. Apart from that, authors with STEM backgrounds focus more on food systems and energy, and authors with creative backgrounds focus more on the development of biological ecosystems.
- Both groups approach the third narrative from different angles. Authors with creative backgrounds evaluate the impact of AI on social norms from an ethical perspective, asking whether AI will continue to be human-centric or develop consciousness itself, while STEM authors tend to evaluate the human-like capabilities of today’s AI.
- Multiple aspects of ethical technology converge in this narrative. Both sides see the problematic nature of policy-making. STEM authors emphasise the systemic bias in the process, while authors with creative backgrounds see a problematic lack of communication between science and policymakers.

Continent
- Philosophy, general politics, and culture are addressed most by North American authors (16%). Emissions play the largest role among authors from Oceania (12%). Most contributions directly related to climate action are from Asian authors (7%), although the topic resonates in many posts.
- Access to technology is defined differently in different continents. Authors from the U.S. and EU mean enterprise-level digitisation. In Africa and South America, authors often mean just access to the internet. Asian authors see it as a tool for networking and creating standards, e.g. between smart cities.
- Opinions differ on what benefits are: African authors often refer to revenues from natural resources. European authors call for a shift in values from valuation to the well-being of citizens. Asian authors in particular rely on governments to lead society to a sustainable future.
- Asian authors centre on the content of education itself, which must adapt to the changing world. European and North American authors focus on the accessibility of higher education. African authors see quality education as the key to overcoming poverty and emphasise its importance in the early years. Notably, they value education most positively (55% versus 44% of the other authors).

DEMOGRAPHIC DIFFERENTIATION
How can we assure humanity’s well-being while also sustaining the health of our planet

How can we assure humanity’s well-being while also sustaining the health of our planet? How can we supply the world population with the necessary food and energy, and still regenerate our planet?

The effects of climate change on the health of our planet and our way of life are central concerns in social media discussions. The recurring narratives and the results of the overall sentiment analysis of these discussions are negative, compared with those about the future of humanity. However, the social media analysis shows that perceptions about responsibility and the contributions of technology and adaption of the human behaviour as a response to the climate challenges differ across continents and groups.

Recurring narratives and sentiment analysis

1. Universal acceptance of responsibility
   - Global collaboration and proportional contributions by institutions and individuals will be critical. Each sector will play its own role in achieving sustainable growth, and failure of one sector will most likely make overall success impossible.
   - The core emotions related to this narrative are hope and doubt, with analysis resulting into 28% positive and 10% negative sentiments.

2. Sustainable food production systems
   - Food production is a key element in the fight for a sustainable future. Achieving sustainable food production will require a mix of technological innovation and adaptation of human behaviour.
   - The core emotions related to this narrative are fear and frustration, with analysis resulting into 6% positive and 34% negative sentiments.

3. Adoption of circular economic principles
   - Boosting productivity, or the ability to produce the largest amount of goods with the smallest amount of effort, is not the only option. Using produced goods more efficiently and minimising waste will also contribute to global sustainability efforts.
   - The core emotions related to this narrative are enthusiasm and anticipation, with analysis resulting into 38% positive and 7% negative sentiments.

4. Avoiding global catastrophes
   - Global catastrophes provide a daunting sign of our political and economic shortcomings but also serve as a strong motivator for humans to alter their behaviour.
   - The core emotions related to this narrative are anger and sadness, with analysis resulting into 11% positive and 28% negative sentiments.

5. Population Control
   - As global populations continue to increase — predominantly in lower-income countries — ensuring the equal development and economic prosperity of these countries will become more important in our mission to preserve Earth’s health. Facilitating equitable access to resources and infrastructure for all nations regardless of income will help control populations and balance the scales.
   - The core emotions related to this narrative are anger and confidence, with analysis resulting into 22% positive and 17% negative sentiments.

5. Achieving Global Economic Decoupling
   - The ultimate goal of technological efforts in the sustainability space is the decoupling of economy and environment. Achieving this will most likely also require an adaptation of human behaviour.
   - The core emotions related to this narrative are anticipation and optimism with analysis resulting into 40% positive and 9% negative sentiments.
Gender

- Females are more dominant in the narratives about universal acceptance of responsibility and sustainable food production systems, the latter of which also contains posts on sustainable consumption patterns. This confirms our previous research highlighting female concern over human behaviour, where their male counterparts are more concentrated on technological solutions.

- Concerning the narrative around avoiding global catastrophes, females are more optimistic, highlighting the effect such events have on our collective conscience and our link with nature. Males more frequently highlight their apocalypse element.

- On the population control narrative, females more frequently highlight the role that global inequality — both in terms of personal income and national wealth — plays in uncontrollable population booms.

Background (STEM professions and artistic professions)

- The narrative around universal acceptance of responsibility is equally strong among both education groups, implying that there at least seems to be consensus around the need for such acceptance, even if it does not actually occur.

- In the narrative on avoiding global catastrophes, authors with a more creative professional background are more present, in terms of social media posts. This could be linked to the fact that discussions around global catastrophes tend to be framed in more emotional terms in order to remind the general public (outside the scientific community) of the growing impact of climate change.

- The narrative about achieving global economic decoupling appears slightly stronger in social media posts by authors with a STEM background, suggesting possibly that this narrative is still on the cusp of entering discussions in broader society.

Continent

- The narratives surrounding the question of humanity's and the planet's well-being are more broadly discussed in Europe and North America. This is partly due to biases in the data sets but may also reflect that this is not the main debated issue on social media in other parts of the world.

- The narrative surrounding universal acceptance of responsibility is more broadly discussed across Asia. The difference with Europe and North America is striking, and could be linked to different values about the role and relationships of the individual towards society.

- The discussions in South America and Africa focus more strongly on potential adaptation and responses to the effects of climate change, highlighted in the narratives about sustainable food production systems, circular economic principles and achieving global economic decoupling. This contrast with the higher prevalence of the narratives about avoiding global catastrophes, where authors from North America and Europe more strongly drive the global discussion.
Debates

Debate 3:
The Pulse of Society – on Frontier Issues

Science and diplomacy are not happening in a vacuum, as the current pandemic has again made clear. Debates around scientific advances, future breakthroughs and their impact are taking place around the globe at all levels of society. Taking the pulse of society is an attempt to listen what citizens are saying, what they are fearing and hoping for, their inclination to future scientific developments and how this shapes their vision of the future of humanity.

Building on a dataset of roughly 11 million social media posts as well as over 6 million news articles and blogs, we present here the outcomes of an AI-powered social media analysis about global conversations on the main topics of interest in the Breakthrough Radar. This encompasses the four Scientific Frontier Issues presented in the Breakthrough Radar:

1. Overview of the Analysis
2. Quantum Revolution & Advanced AI
3. Human Augmentation
4. Eco-Regeneration & Geo-Engineering
5. Science & Diplomacy

The analysis has been guided by the aim to distinguish the core differences between regions, demographics and topics in order to be able to identify the fields that require a broader societal debate. The AI-based research and trend sensing tool Deep View combines human intuition with machine objectivity enabling robust strategic decision-making. For more information on the analysis and the tool, please refer to the methodology section in the annex.

Taken together, the Pulse of Society, the Pulse of Science and the Pulse of Diplomacy provides the basis to start creating a shared language to discuss and address the emerging opportunities and challenges of the 21st century.

Looking at the bigger picture, Science & Diplomacy is of heightened attention for citizens with high social engagement across the board. Science, the diplomatic community and citizens are aligned on climate change as THE core issue, while co-operation in health sciences seem to lack public interest, even in times of COVID-19 and vaccines diplomacy. Additionally, the trend towards a more positive and intensified discussion on the issues around multilateralism and science diplomacy in Asia (and to a certain extend Africa and Latin America) in comparison with Europe and North America is interesting to observe.

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Global Shaper World Economic Forum, Curator, Global Shapers Zurich Hub
Overview of the Analysis

This section provides an overview and detailed analysis about how the scientific topics of relevance are discussed in social media, how they relate to each other and which groups are driving the discussion.

Executive Overview across the analysis

Overall, the analysis shows a bias towards items posted by mostly male citizens from Northern America and Europe in the age range of 55-64. Even though posts in all letter-based languages have been included, Twitter, Tumblr, and Instagram as the main sources of the analysis still have a very dominant English language bias and thus drive the above-mentioned demographic concentration. However, the refined analysis reveals differences between demographic groups and geographical locations for the scientific topics, and can be summarised as follows.
Quantum Revolution & Advanced AI

The scientific fields related to Advanced Artificial Intelligence (AI) and Quantum Revolution (Advanced Artificial Intelligence, Quantum Technologies, Brain-inspired Computing, and Biological Computing) show a moderate engagement with citizens. Relative to the other three frontier issues, the analysed scientific topics have the strongest bias towards higher education and male participation, and show the highest rates of negative or neutral sentiments.

The effects of climate change on the health of our planet and our way of life are central concerns in social media discussions. The recurring narratives and the results of the overall sentiment analysis of these discussions are negative, compared with those about the future of humanity. However, the social media analysis shows that perceptions about responsibility and the contributions of technology and adaption of the human behaviour as a response to the climate challenges differ across continents and groups.

Key Facts and Insights

- Authorship is mostly male, academic and North America based. Hype topics like Quantum Computing or Quantum Cryptography tend to be from male authors, social implications topics tend to be from female authors.

- The age group dominating the conversation varies across continents, with older age groups more active in North America and Europe and younger people in Latin America, Africa and Asia.

- Younger authors discuss the topic more emotionally. Sentiments are generally positive across regions and demographics with the highest rates in Latin America and Africa.

- Computing power and AI will change the way we work, but sentiment varies across demographics. The young and educated see benefits and ask for rethinking productivity. Others are more critical.

- Innovations in quantum physics dominate the discussion on a macro level (>80% volume). Unlike biocomputing, for example, there is a strong emphasis on general-purpose applications and societal implications.

- AI is penetrating various areas of life, such as law enforcement, and military applications. Strong ethical concerns are expressed in social media, regulatory measures are hardly noticed.

- “Hey, it’s not quantum physics!” — but what really is it? As people search for understandable answers, they fall for conspiracy theories.
Positive sentiment is centred around:

- Interest in Science: Many posts ask the community for information or promote an open discussion on pros and cons of technological advances.

- Quantum Revolution: Emerging applications of quantum technology are seen positively and are expected to change the world sustainably.

- Quantum-Safe Cryptography: Quantum cryptography is believed among the closest to realisation. Increased security is believed desirable.

Neutral/mixed sentiment is centred around:

- Industry Disruption (Quantum): Quantum computing is expected to solve expensive problems, but many question an eventual breakthrough.

- Quantum Supremacy: Following the theoretical justification, companies achieving supremacy are cheered, but also criticised for premature results.

- Human Superiority to today’s AI: Some expect AI to never be able to fully replace human work, while others await replacing cumbersome work.

Negative sentiment is centred around:

- Difficulty of Subject (Quantum): Quantum physics is often referred to as ultimately hard to understand: ‘It’s not quantum physics!’.

- Emerging Cyberthreats: Quantum computing may break encryption as it is practiced today. Discussions highlight future issues and necessity to act.

- Quantum breaking Blockchain: As encryption plays a central role in cryptocurrencies, their prevalence in the age of quantum computing is disputed.

It appears clear from the analysis, that the quantum revolution more strongly drives the discussion compared to advanced AI and related fields. This can be explained with the relative strong hype around Quantum and the fact, that the AI discussion is strongly focused on current forms of Artificial Intelligence but not the next generations of it.
Human Augmentation

The discussions around the scientific fields related to Human Augmentation (Cognitive Enhancement, Human Applications of Genetic Engineering, Radical Health Extension and Consciousness Augmentation) were picked up very differently across continents. Relative to the other three frontier issues, the analysed scientific topics have the strongest bias towards North America, older age groups and positive sentiments.

Key Facts and Insights

- The discussion is strongly focused around age groups 55-64 in North America and Europe; younger groups dominate in Africa, Latin America and Asia.
- Human Augmentation is seen primarily positively with the strongest scepticism in Europe and around mRNA vaccines.
- The discussion taking place in younger groups is more fragmented and neutral/negative (especially in Europe and North America) than that in the older age groups.
- Interest in the age group below 34 years is focused on the promises of Brain-Computer-Interfaces (BCIs) and Human-Machine-Interfaces (HMIs) as a way to “augment” individuals.
- While the concerns in North America and Europe are mainly focused on the risks around the mRNA vaccines (experimental gene therapies), the concerns in Africa are focused on social inequality and conflict due to human augmentation, cyber threats to the body in Latin America and high costs of gene therapies in Asia.

Cloud and sentiment analysis

Each node representing one article and the linkages between dots show relations between topics in the analysed data.
Positive sentiment is centred around:
- Promise and reported success of the use of gene-based treatments for a multitude of diseases and conditions
- Promise and prospect of using HMI in business processes and consumer products (e.g. customer service, production facilities)
- Prospect of using BCI in a number of use-cases in both human augmentation and life prolongation
- First successes in clearing legal/ethical hurdles with regards to the technologies in selected geographies (e.g. China, Chile)

Neutral/mixed sentiment is centred around:
- Use of BCI/HMI for military applications as a ‘necessary evil’
- Market reports on biotechnology growth prospects, partnerships and mergers & acquisitions

Negative sentiment is centred around:
- Fear of losing mental autonomy through BCI and HMI: bringing changes in brain plasticity and the proneness to cyber threats
- Fear of institutions and authorities as mirrored in and conspiracy theories and the lively discussion about the ‘Great Reset’, ‘Experimental Gene Therapy’ and Bill Gates
- Fear of the COVID-19 Vaccination and the expedited approval process thereof. As the insights show, the covid-19 pandemic, mRNA vaccines and announcements around Brain-Computer Interfaces strongly drove the discussions and were the main drivers for the strong regional and demographic differentiation.
Eco-Regeneration and Geo-Engineering

The scientific fields related to Eco-Regeneration and Geo-Engineering (Decarbonisation, World Simulation, Future Food Systems, Space Resources, and Ocean Stewardship) showed the strongest engagement with citizens with more than 6 million analysed posts. Relative to the other three frontier issues, the analysed scientific topics have the strongest bias towards Europe, younger age groups and lower education.

Key Facts and Insights

- The discussion is predominantly male-driven with an over-representation in the age groups <18 years and >55 years. Scientists and researchers dominate the professions most present in the sample.
- Young authors discuss the positive potential of decarbonisation and the energy transition but they do not discuss concrete approaches. Combining their energy with older authors’ knowledge may be key.
- Climate change and food systems topics appear more likely to interest individuals with higher education, and “under-interest” females, both in absolute and in relative terms compared to the general population.
- Scientists/Experts and citizens are equally interested in both climate models and earth observation topics.
- Society appears to fear an improper allocation of funds to future-looking topics at the detriment of investing in social justice. Highlighting future topics with perceived social value (e.g. future food systems) may help.

Cloud and sentiment analysis

Each node representing one article and the linkages between dots show relations between topics in the analysed data.
Positive sentiment is centred around:
- Decarbonisation advances and clean energy initiatives in the form of policy decisions or private sector pledges and collaborations on cutting CO₂-emissions with the goal of achieving carbon neutrality
- Future Food Systems primarily regarding the sustainable production of food (e.g. sustainable farming, aquacultures) and the reduction of consumer food waste
- Ocean Stewardship, driven by an admiration of the ocean and its biodiversity as well as community-led ocean/beach cleanup initiatives

Neutral/mixed sentiment is centred around:
- Space Exploration and its purpose in the broader discussion around our development as a species, as well as recent scientific reports from NASA’s Perseverance Rover and the ISS
- Reports on progress and policies in 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)

Negative sentiment is centred around:
- Climate Politics and the failure to avert extreme climate events (e.g. floods and wildfires) as well as the slow degradation of glaciers, ice sheets and ocean currents (e.g. Gulf Stream)
- Commercial Space Travel, and the volume of investment and public subsidies poured into it vis-à-vis lacking funds to combat issues of social justice

As the insights show, the covid-19 pandemic, mRNA vaccines and announcements around Brain-Computer Interfaces strongly drove the discussions and were the main drivers for the strong regional and demographic differentiation.
Science & Diplomacy

The scientific fields related to Science and Diplomacy (Complex Systems for Social Enhancement, Scientification of Diplomacy, Innovations in Education, Sustainable Economics, and Collaborative Science Diplomacy) showed a strong engagement with citizens with more than 3 million analysed posts. Relative to the other three frontier issues, the analysed scientific topics have the strongest bias towards Africa, Asia and Latin America and female participation.

Key Facts and Insights

- The discussion is comparatively gender-balanced (female are overrepresented in comparison to the Twitter general population) with an overweight in the age group <34 years. Public servants dominate the professions most present in the sample.
- This topic is also comparatively well balanced region-wise, with Africa, Latin America and Asia accounting for a third of the posts’ volume.
- Female discussions focus more strongly on supporting and maintaining justice for others whereas males focus more on the self and the fear of losing one’s identity.
- Younger age groups (<34) are underrepresented in developed areas, whereas they appear to be overrepresented in developing countries.
- The general discussion for all stakeholders is strongly focused on climate change and its mitigation as well as its impact on employment.
- Science has become increasingly politicised and polarised in blocs due to US-CN/RUS tensions, exacerbated by COVID-19, becoming a source of geopolitical tension.
- Trust in science has declined prominently in the developed world, which is echoed in the increasing dominance of reactionary governments.
- Multilateralism is discussed positively in Africa, Latin America, Asia and Australia but not strongly mentioned in North America and Europe.
- UAE, KSA as well as Pakistan and India are entering the scene through increased investment and collaboration in science and education.

Cloud and sentiment analysis

Each node representing one article and the linkages between dots show relations between topics in the analysed data.

- The main concerns vary significantly across regions with North America focusing on security issues with digital democracy, Europe on the further polarisation and disregard for the rule of law, Asia on climate change and extreme weather events, Latin America on economic policy and unemployment and Africa on elitism in democracy and party systems.
Positive sentiment is centred around:

• Sustainable Economics, specifically around sustainable consumer goods (e.g. fashion, cosmetics) as well as recyclable materials, plastic-free living

• Innovations in Education, specifically in digital, decentralised education as well as the gender diversity in education (e.g. female, LGBTQ+ education)

• Design for Values with regard to charity systems focusing on providing education to minority groups and those in need

• Advances in Science Diplomacy, primarily regarding the integration of non-state actors in diplomacy through educational programs such as International Model United Nations.

Neutral/mixed sentiment is centred around:

• Climate Externalities through a number of reports on nature protection projects

• Diplomacy, focusing on US-Middle East and US-Russia relationship

Negative sentiment is centred around:

• Digital Democracy, voting safety, validity and E-Voting Systems as well as general authority are being discussed negatively, driven by the US elections

• Automation & Work in the form of employment instability, fear of losing employment, amplified by COVID-19 lay-offs

• Climate Externalities such as extreme weather events (e.g. Forest Fires, Floods) and slowly dissipating ecosystems (e.g. Amazon, Permafrost)

Looking at the bigger picture, Science & Diplomacy is of heightened attention for citizens with high social engagement across the board. Science, the diplomatic community and citizens are aligned on climate change as THE core issue, while co-operation in health sciences seem to lack public interest, even in times of COVID-19 and vaccines diplomacy. Additionally, the trend towards a more positive and intensified discussion on the issues around multilateralism and science diplomacy in Asia (and to a certain extend Africa and Latin America) in comparison with Europe and North America is interesting to observe.
Trends
What’s cooking in the labs

The 2021 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 major 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 three existential questions described in the GESDA roadmap and introduced in the Debates section.

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 18 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 four scientific frontier issues:

1. Quantum Revolution & Advanced AI
2. Human Augmentation
3. Eco-Regeneration & Geo-Engineering
4. Science & Diplomacy

More than 500 scientists from 53 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 216 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 7 emerging topics that areas 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.

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.
Taking the Pulse of Science

The Science Breakthrough Radar

We cannot predict the future, but we can try to anticipate it. Although we don't know exactly how the future will unfold, we can explore the forms it might take because these forms originate in research that is already being done, conversations that are already taking place and solutions that are already being devised today. By taking the pulse of science, and by sharing it with the global multilateral community, we hope to accelerate the positive outcomes of the scientific breakthroughs that we need to address today's biggest and most intractable challenges.

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 of GESDA’s four initial 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 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 GESDAs vision: use the future to build the present.

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

radar.gesda.global/apm
Trends

Taking the Pulse of Science
Analysing the Anticipation Potential

All 18 scientific emerging topics displayed in the Science Breakthrough Radar will see major developments in the coming 5, 10 and 25 years. These developments will have consequences for the factors that make us human, for how we are going to live together and for the sustainability of our planet. The Anticipation Potential is a response to this, providing a glimpse of the relative importance of anticipating developments in a field according to the criteria described in the previous section and as assessed by the global scientific community.

The 5, 10 and 25 year time horizons serve as anchor points at which potential breakthroughs in a field have been assessed by the scholars involved in the consultations.

Examples of key results
As examples, we list below anticipation potential descriptions for selected fields displayed on the radar. Dedicated pages in the trend section provide further descriptions of main developments in the field and present expected breakthroughs at 5, 10 and 25 years.

Quantum Revolution & Advanced Artificial Intelligence
Quantum Technologies
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. In contrast, the role of foundational effects of quantum in biology has received little attention so far and developments in this sub-field remain at the level of fundamental science. Major breakthroughs in this area are not expected before two decades, with potential applications expected at 25 years, making it hard to assess their disruptive potential. Nonetheless, this uncertainty and the field’s low visibility suggests it is one worth paying more attention to.
Human Augmentation

Human Applications of Genetic Engineering

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 in the 5–10 years timeframe. However, interspecies chimera and the use of genetic enhancement are not expected to go mainstream for another 20 years and have so far received far less focus. This suggests that this second wave requires considerably more attention to map out their potential ramifications. One significant challenge is that the line between therapies and enhancement is blurred, suggesting some forms of enhancement may be closer than currently expected.

Eco-Regeneration & Geo-Engineering

Ocean Stewardship

The oceans cover more than 70 per cent of the Earth’s surface so it is unsurprising that efforts to protect and exploit their resources scored joint highest for environmental impact alongside decarbonisation. Although deep sea mining was assessed as having the highest transformational effect, low awareness of the need to harness the oceans’ biochemistry and the highly-interdisciplinary challenge posed by efforts to repair the ocean mean these topics were judged to require greater attention. The average time to maturity is estimated at 10–15 years. This perhaps reflects the fact that a failure to protect critical marine resources could cause enormous negative disruption for the three billion people who rely on the oceans for their livelihoods. This is the emerging topic with the highest anticipation potential in the current list.

Science & Diplomacy

Science-based Diplomacy

The idea of applying computational and mathematical approaches to diplomacy and negotiation 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 10–15 years, and all four were judged to require considerable interdisciplinary convergence to achieve significant breakthroughs. While the low awareness may be due to the fact that computational diplomacy is currently only being discussed by a small community, when it goes mainstream the field could have profound impacts on international relations suggesting there is considerable need for anticipatory planning.

The Anticipation Potentials and the effects in our analysis described above provide a snapshot of how a specific field is perceived by the scientific community. The Science Breakthrough Radar provides a rolling analysis of those trends, and the assessment will be continuously updated as science progresses and new knowledge and insights come in. The following section provides the opportunity to dig deeper, to engage in the discussion and consult key resources from the GESDA Best Reads as well as the fundamental reports.
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.
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 —, as 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.

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

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 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 and artistic creation.\(^4\) This rapid and impressive 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 highly heterogeneous sources, and long-term memory and the inclusion of context.

Rüdiger Urbanke
Rüdiger Urbanke, Professor for Communication and Information Theory, EPFL
**Survey Observations:**

Rapid progress in the development and adoption of AI has already spurred many efforts to chart the trajectory of this transformative technology. Transparent AI is one topic that has received considerable focus and combined with its low disruptiveness and relatively short path to maturity the need for anticipation here is lower. Unconventional approaches to AI on the other hand have so far flown under the radar, suggesting more work is needed to understand their potential implications. And while artificial general intelligence has already received substantial attention, it has huge disruptive potential and faces a long and uncertain development path, which respondents predict will take more than 25 years.

**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.

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.

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. Other roadmaps focus on the opportunities and expert systems of integrating AI in government, society and industry from European and Chinese perspectives.

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**Anticipation Potential**

**Emerging Topic:**

**Sub-Fields:**

- Advanced Artificial Intelligence
- Common-Sense AI
- Transparent Algorithms
- Unconventional approaches to AI
- Artificial General Intelligence

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**Selection of GESDA Best Reads and Key Reports:**

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
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.

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. 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).

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.
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. 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.

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.
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. 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.

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.
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.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.
Quantum Technologies

1.2

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
Distinguished Scientist Microsoft
SURVEY OBSERVATIONS:

Few emerging disciplines 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. In contrast, the role of quantum effects in biology has 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.

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**SURVEY OBSERVATIONS:**

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
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 100 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.\(^\text{5,6}\)

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.\(^\text{7}\)

### 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.\(^\text{8}\)

### 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.
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 operate with several dozen “quantum bits” (qubits); in 2019, a Google quantum computer with 53 qubits took only a few minutes to perform complex calculations that would take days on the most powerful classical computers. Although this demonstration had no practical use, 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. 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.
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.\(^1\) 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)\(^2\), 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 distinguish 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.
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. 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.

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.

5-year horizon:
Quantum biology becomes established
Fundamental research continues to investigate quantum effects in biology, which becomes an established field of study. 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 and medication. 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.
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
ICL Professor of Computer Engineering at The University of Manchester
Perhaps the most recent roadmap for the field is the multi-institution “2021 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

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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 cases in a wide range of areas. Tempering this though, 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.
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. 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. 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.
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.41 Different hardware configurations seem to provide different capabilities. Intel’s Loihi is highly configurable for specialised applications40, 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.
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.

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.

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.
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.\textsuperscript{14}

It is important for the field to begin demonstrations of its potential for fast, low power processing.\textsuperscript{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.
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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**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.

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**Anticipation Potential**

**EMERGING TOPIC:** Biological Computing

| SUB-FIELDS: | 
|---|---|
| Bio-architectures | 
| Bio-computational Logic and Strategies | 
| Bio-computing Applications | 
| Novel Bio-computing Paradigms | 


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**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’ gives a historical view of the subject, plus the authors’ vision for its future.

‘Pathways to cellular supremacy in biocomputing’, 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’ and ‘Principles of genetic circuit design’.

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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. 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.

**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.
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.

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. The communication pathways that exist between biological cells allow for new forms of distributed computation. 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.
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. It is likely that significant medical applications will eventually be found, 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.
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. 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. 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.
What is life? Scientists have puzzled over this question for centuries, but the discovery of planets outside our solar system means that it has taken on new importance in recent years.
We detected the first exoplanet in 1995. Since then, the existence of more than 4,000 others has been confirmed, and considerable effort is now going into determining whether any of them can support life. Other researchers are looking closer to home as well, probing Mars and, more recently, Venus for signs of ancient or extant extraterrestrial organisms.

This search for life beyond our planet raises fundamental questions about our place in the universe and what exactly it means to be alive. Finding the answers requires us to tackle three interlocking challenges: understanding the matter from which life is made; understanding how life first came into existence; finally understanding life’s most complex configuration — consciousness.

If we can make progress here, it will do more than answer the question of whether we are alone in the cosmos. It will also transform our understanding of ourselves and our planet. Such self-knowledge could greatly increase our capacity to shape the world we live in, and will be crucial for charting the future of life on Earth and further afield.

We have already come a long way on the first of these challenges. While many mysteries remain, the fields of molecular biology and organic chemistry have given us unprecedented insight into how matter supports the functions of life, and creates the inner workings of the cells all organisms are built from.

But while this knowledge has dramatically improved our ability to read and write in the language of life, we still have few ideas about how it started from first principles. At some point in the distant past, simple chemical reactions quite literally took on a life of their own, but how and why remains unclear.

We do know some of the key ingredients. The first organisms must have had a protective barrier to separate chemical reactions integral to their existence from those occurring in the wider environment. The right chemistry also needed to be encapsulated inside this barrier to ensure the organism could thrive and proliferate. This must have included catalytic elements that can harness energy from the environment to power the reactions necessary to sustain a living entity. A system for encoding and replicating the instructions for this internal chemistry would also have been crucial.

We understand how today’s cells solve these problems, using processes like the Krebs cycle to release energy stored in nutrients and catalytic processes to make components to sustain life with DNA and RNA controlling the duplication mechanism. But modern organisms are the product of millions of years of evolution and the chemistry of early life on Earth must have been much simpler. The challenge facing us is something like having to reverse engineer the Wright brother’s first airplane using only the schematics for the Space Shuttle.

This is where the hunt for life on other planets could serve us well. While we can dream of finding life on Mars, the prospect of discovering some early chemistry that predates the first cell and sheds light on the journey towards life’s existence is just as exciting.
As we take our search beyond our solar system, we will also be forced to confront more foundational questions. For instance, is there a specific set of conditions and chemical precursors that creates an optimal pathway for achieving life? Or are the organisms found on Earth just one of life's many possible configurations and could it also arise out of entirely different chemistries and utterly alien environments?

While we have a long way to go in solving these riddles, our growing command of the foundational matter of life and our increasing ability to probe other worlds is putting them within reach. Such a fundamental understanding of the origins of life could have profound implications for medicine and could even open up the possibility of building new life from scratch.

The prospect of such God-like abilities is both exciting and frightening, and makes the final question concerning consciousness all the more important.

Modern society is built on thousands of years of accumulated knowledge and scientific discovery, but humans remain a product of their evolution and are driven as much by ancient animal urges as by rationality. Understanding how this tension governs our behaviour and how our consciousness is tied to our biology will be crucial to predicting where this knowledge will take us.

Here the challenge seems much more daunting. Our understanding of the human brain is still rudimentary and, despite the name, artificial intelligence is a long way from helping us recreate true intelligence — let alone consciousness. It is not even clear whether we have a brain that is capable of truly understanding itself. Much like our inability to grasp what came before the Big Bang, consciousness may be a mystery we can never solve.

However, that doesn’t mean we shouldn’t try. Efforts to deconstruct and reverse-engineer the brain will be critical, but we should also make use of the powerful and largely unused tool of social media. The data collected by these services could help us unravel the psychology of an entire species and we should ensure it is accessible to scientists seeking to make sense of consciousness.

Across all three of these challenges, there is also a need to think about life differently. Rather than taking the traditional biological approach of simply trying to understand the function, we need to approach these problems more like mathematicians or physicists and deconstruct them in order to capture their essence. This will require an overhaul to the way we do science and the way we educate scientists. Essentially, we need a massive boost to interdisciplinary collaboration. This will require more flexibility and creativity from scientists themselves and far greater support from funding agencies and educators to foster this kind of research. But the reward — a fundamental understanding of our place in the universe — is surely worth the investment.

Didier Queloz
Professor of Astronomy, Cambridge University and ETH Zurich; 2019 Nobel Prize for Physics
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, neurotechnology 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 be 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.

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 transform us as humans, our society and the planet.
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
**SURVEY OBSERVATIONS:**

Few technologies have such potential to drastically reshape our societies as cognitive enhancement. This is reflected in the consistently high impact scores found across the four topics investigated by respondents. There is also considerable overlap between the key tools and bringing them to fruition will require advances in a wide range of scientific fields that are likely to lead to breakthroughs in other domains as well. Brain monitoring technology is much closer to maturity and is likely to have a less transformative impact than the other three approaches. But memory enhancing nootropics should be a particular focus as, despite the lack of attention they have received so far, they could be highly disruptive.

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**Selection of key resources:**

**The 2019 ‘Neurotechnologies for Human Cognitive Augmentation: Current State of the Art and Future Prospects’ provides a useful overview of the field.**

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

**Significant progress in reading and interpreting brain signals was described in Nature in 2021. In 2019, the UK’s Royal Society published a perspective on neural interfaces.**

**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](http://radar.gesda.global/r2-1)
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. 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).

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.

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 that is currently hindered by national ethical and privacy laws, 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.
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). tDCS has been shown to enhance certain cognitive functions, such as episodic memory in older adults. Non-invasive technologies and focused ultrasound (FUS) could make it possible to remove unwanted memories. Invasive techniques for neuromodulation include optogenetics and deep brain stimulation, 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.
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. This approach has been used to decode primary visual cortical activity and reconstruct movie scenes as they are being viewed in real-time, and to decode the content of dreams based on pre-recorded visual cortical activity patterns. 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, 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.
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. 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. 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 capacity. Or we may find areas to target for memory suppression, or even implantation.

5-year horizon: The basic science of memory becomes better understood

Fornix data in 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.
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 an international outcry. He was sentenced to prison and the incident thrust the capabilities of CRISPR, only discovered 6 years earlier, onto the world stage.

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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School of Medicine
## 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 less than eight years. Interspecies chimera and the use of genetic enhancement on the other hand are not expected to go mainstream for another 21 years and have so far received far less focus. This suggests this second wave requires considerably more attention to map out their potential ramifications. One significant challenge is that the line between therapies and enhancement is blurry, suggesting some forms of enhancement may be closer than currently expected.

## Selection of GESDA Best Reads and Key Reports:

### Human Applications of Genetic Engineering

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<thead>
<tr>
<th>Sub-Fields</th>
<th>Anticipation Potential</th>
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<tr>
<td>Genetic Diagnostics</td>
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<td>Gene Therapies</td>
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<td>Genetic Enhancement</td>
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In 2017, Weisberg et al surveyed a large and diverse cohort of Americans about their attitudes to genetically modifying human germplines; the results make fascinating reading. 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.

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.”

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[radar.gesda.global/r2-2](http://radar.gesda.global/r2-2)
Gene-based Diagnostics and 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. 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. 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 include CRISPR-based methods are used to detect a variety of targets, including cancer, inherited 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.
CRISPR-Cas9, though not even a decade old, 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. 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. 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.

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 germline 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. Germline editing (transmissible to the next generation) is made possible thanks to increased safety levels. 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.
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. For the time being, 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.\footnote{5}

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.\footnote{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.
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.
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
In 2013, López-Otín et al published “The Hallmarks of Aging,” which detailed better ways to identify the progression of the aging process at the molecular level, including cell senescence.  

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. 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. 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.

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 broad impact across society. Diagnostics and assistive technologies are likely to have more modest effects in the near future. Efforts to slow and even reverse ageing are considerably further off — 12 and 23 years respectively — but have the potential to be highly transformative and will require significant planning to manage their effects.

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
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. Different tissues in the same body can age at vastly different rates as well, which may depend on genetic or environmental factors. To create better measures of age, new strategies are investigating age-related variations in blood markers, DNA methylation states, or patterns of locomotor activity and these may explain differences in longevity. AI technologies are being developed to combine many such factors. 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.
The emerging research consensus is that ageing is driven by several different interacting processes. 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, but the question 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 dysregulation of metabolism, 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.
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.

Another approach is senolytics, a class of drugs that selectively clear senescent cells. 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. Perhaps start metformin at 50, while gene therapy is carried out in the womb to prevent other processes of 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.

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[^16^]: Restricted diets have been shown to extend healthspan and potentially reduce the rates of age-related diseases.
[^17^]: Stem cell therapy has been used to repair damage from age-related diseases such as osteoarthritis.
[^18^]: Gene editing techniques have been used to correct mutations associated with progeria, extending lifespan in mice.
[^19^]: Gene editing has been used to double the lifespan of mice, demonstrating the potential of such therapies.
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.

Giulio Tononi  
Professor and Director of the Wisconsin Institute for Sleep and Consciousness
In 2019, Michel et al published "Opportunities and Challenges for a Maturing Science of Consciousness", which closely examined the field's potential.\(^1\)

Efforts to augment human consciousness were assessed to have some of lowest requirements for anticipatory planning. There is already decent awareness of the main tools and respondents judged their potential for transformative impact to be fairly low. Interestingly, nootropics, which were highlighted as a topic to watch in cognitive enhancement, was rated as most in need of anticipation here as well. Part of the reason for the low scores may be that the impact of this field will be felt primarily at the level of the individual rather than society at large. There is also still a lot of work required to define what exactly is meant by consciousness.

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
The 20th century saw a measurable and significant increase in the average human intellect. 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. 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 and memory retention 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.
24.2 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 and EEG reactivity, such as the Perturbational Complexity Index (PCI), to reliably tell whether someone is in a vegetative state or a (more reversible) minimally conscious state. Therapeutic neuromodulation (precisely targeted noninvasive technology like tDCS) has successfully brought minimally conscious patients back. 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. 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.

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.

Work is underway to determine whether machines and animals have consciousness, and most recently to understand whether organoids and other synthetic biological organisms are capable of developing a kind of consciousness.

The GESDA 2021 Science Breakthrough Radar
Brain-machine interfaces can help to augment human consciousness in three different ways. 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.
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 of 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. Some researchers have used wearables or implants to give themselves magnetic senses or the ability to feel sound.

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.
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.

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.
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. 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. Possible pathways to decarbonisation solutions are presented further down in the report.

Wendy Queen
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Gerald Haug
President of the German Academy of Sciences, Leopoldina and Professor for Climate Geochemistry, ETHZ

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Wendy Queen
Assistant Professor and Director of the Laboratory for Functional Inorganic Materials, EPFL Valais Wallis
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, geo-engineering efforts are at least two decades away and have received little focus so far suggesting there is a greater need for foresight in this area.

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; the International Renewable Energy Agency has looked at innovations in energy storage and the future of solar photovoltaic systems. Finally, there is the National Academy of Sciences, Engineering and Medicine's 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda'.

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 CO₂ 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. In fact, there is already so much CO₂ 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. 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 CO₂ directly from the atmosphere using chemical interactions, a process called direct air capture (DAC). In this case, the CO₂ would be extracted from air and subsequently sequestered underground for long term storage. 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 CO₂ market that might further incentivise the adoption of NETs.

5-year horizon: The development of a CO₂ market

With the anticipated reduction of the price of carbon capture for selected NETs to below $100 per tonne of CO₂, the global CO₂ 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 CO₂, 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 CO₂ from the air is commercially viable

By combining solar energy and various CO₂ 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 CO₂ capture and utilisation begins

Breakthroughs in DAC and conversion technologies now allow large industrial scale applications where CO₂ is captured from air and converted into synthetic fuels and other value-added chemicals.
Due to factors such as a growing global population, the demand for power is expected to rise by 50 per cent before 2050. 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\textsubscript{2}, that is “mined from the air”. In short, solar energy can be used to produce synthetic hydrocarbons from captured CO\textsubscript{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. 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.

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. 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.

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\textsubscript{2} emissions.
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. 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. 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 conversion of CO$_2$ into synthetic fuels as well as many other decarbonisation technologies.

### 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 CO₂ 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.
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 becoming 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 of the University of California’s Gump South Pacific Research Station on Moorea (French Polynesia)
SURVEY OBSERVATIONS:

Digital models are already becoming an increasingly popular tool among both scientists and policymakers. Despite their growing popularity though, respondents felt that none of the main modelling technologies are likely to reach maturity in the near-term with timelines ranging from 10-14 years. Despite similar levels of anticipatory need across the four key domains, digital cities stood out for having the highest potential for disruption and pervasiveness. That points to an expectation that smart city technologies and the use of simulation in urban management will become ubiquitous in the coming years.

Anticipation Potential

EMERGING TOPIC: Digital Models

SUB-FIELDS:

World Simulation

Physical Models

Ecological Models

Socio-economic Models

Digital Cities

HIGHEST ANTICIPATION POTENTIAL

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”.

More recently, work by the IDEA Consortium and Enders and Hoßbach 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
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. 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-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.

### 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. 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. 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.

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.
By 2050, nearly 70 per cent of the world’s anticipated 10 billion people will live in urban areas. 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.
Integration and 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.

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

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

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

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

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

Ralph Graichen
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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 top of 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 synthetic biology, due largely to low awareness of its potential and the long road to the technology’s maturity. It’s also important to recognise that breakthroughs in synthetic biology will have profound effects on all other aspects of future food systems.

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

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”.

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
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), 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. 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.

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. 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.

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, 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. 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.
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.\(^{14}\)
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. 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.

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. 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.
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. 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. As low-Earth orbits become more crowded, orbital management and the removal of debris will become a major ongoing focus of attention.

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, 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. Last year, 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.

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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’s likely to be two decades before we see significant breakthroughs in anything but deep space observation. This is down to the cost and complexity of space flight 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 high variability in awareness, with human presence in space receiving considerable attention while space-based power remains largely neglected, pushing up its anticipatory need.

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

The US National Academies surveyed space science priorities in its “Planetary Science and Astrobiology Decadal Survey 2023-2032”.2 NASA has considerable investment in human spaceflight with its Artemis programme expected to return humans on the moon within the next few years.3

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 2021.4 The United Nations Office of Outer Space Affairs explored the nature of space-related commerce in its “Space Economy Initiative 2020 Outcome Report”.5

SELECTION OF GESDA BEST READS AND KEY REPORTS:

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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\textsuperscript{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.\textsuperscript{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.\textsuperscript{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\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{19} A progressive increase of orbiting object numbers occurs, with collisions becoming the primary debris source,\textsuperscript{20} accelerating the Kessler effect,\textsuperscript{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.
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, too, plans to put the first woman and the next man on the moon in 2024, however the latest report of the Office of the NASA Inspector-General (August 2021) indicate potential delays. 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.

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. 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, 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. 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. Environmental, social and governance factors, along with depletion in terms of diminishing economic returns, 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, raising the possibility of irreversible alteration of the Moon’s environment and tighter restrictions for lunar missions.
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. Today, a modern computer chip employs more than 60 different elements. 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.

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. A rare-earth-metal mine has almost comparable set-up costs of around $1 billion. 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. 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. 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. Mitigating potentially devastating hazards: An asteroid impact is the most widely accepted theory for the mass extinction at the end of the Mesozoic Era. 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.

5-year horizon:

Solar System sampling missions arrive home
Successful sample-return missions from the asteroid 101955 Bennu (NASA’s OSIRIS-Red) 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, there’s an increase in the number of organisations involved in local characterisation of asteroids, either by flyby or contact.

25-year horizon:

Planetary protection becomes important
The Planetary Protection Policy 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.
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,53 while China has recently announced plans to put
humans on Mars by 2034.54

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.
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, 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.

Robert Blasiak
Researcher, Stockholm Resilience Centre
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. It has also been used as the basis for a scientific review paper.

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

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

The oceans cover more than 70 per cent of the Earth’s surface so it’s unsurprising that efforts to protect and exploit their resources scored joint highest for environmental impact alongside decarbonisation. Although deep sea mining was assessed as having the highest disruptive potential, low awareness of the need to harness the oceans biochemistry and the highly-interdisciplinary challenge posed by efforts to repair the ocean mean these topics were judged to require greater attention. This perhaps reflects the fact that a failure to protect critical marine resources could cause enormous negative disruption for the three billion people who rely on the oceans for their livelihoods.
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.
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.
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. 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 CO₂ equivalent by 2050. 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.

Corals must be another focus. The combination of warming oceans and CO₂-fuelled acidification of the waters has meant half of the world’s reefs have already been lost. Although this is a hugely troubling statistic, scientists are engaged in a wide range of conservation efforts worldwide, with some grounds for optimism.

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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.

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.

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.
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, 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.

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.
Even to an audience that has grown numb to climate warnings, a working group report published in August as part of the IPCC’s latest assessment report (AR6) was alarming. The threat of catastrophic impacts felt grimly familiar, but what hit hardest was the rapidly dwindling time left to avoid them, and the woeful, continued shortfall — even after so much discussion and effort — of the world’s emergency response.
Following a year of headline-grabbing floods, fires and storms, there is no more room for scepticism. The UN Secretary General called it “code red for humanity”. Linda Mearns, an IPCC co-author, of the US National Center for Atmospheric Research memorably was quoted: there is “nowhere to run, nowhere to hide.”

The fiendish conundrum facing societies around the world is how to rapidly wean themselves off fossil fuels whilst avoiding too much pain or disruption. As governments do the maths on net zero emissions by 2050, realisation is growing as to how challenging this will be, and how difficult it is to bring everyone along. And that is only the first half of the challenge: then comes the task of cleaning up excess carbon dioxide already in the atmosphere.

That is why an additional pillar of action is rapidly rising up the agenda: large-scale carbon dioxide removal (CDR). The IPCC’s report outlines two scenarios in which humanity has a theoretical chance of limiting warming to either 1.5 or 2°C, and thereby not overshooting the temperature goals of the Paris Agreement. Both scenarios require removing billions of tons of carbon dioxide directly from the atmosphere and storing it in perpetuity.

This idea, until recently, was often dismissed as a distraction. There remain also concerns of “moral hazard” in that CDR could be used by some to avoid cutting emissions. But society is coming to realise that it needs every tool in the toolbox. It is not a question of either emissions cuts or removals, but how to ensure both can work in concert. Not considering and planning for the carbon dioxide removal needed is considered by some as overoptimistic or magical thinking — another side of moral hazard.

But large-scale removal of carbon dioxide from the atmosphere is not easy. All approaches have limits — related to scaling, permanence, maturity, monitoring and costs — and there is no silver bullet. Nature-based approaches give rise to land use and water issues, and can be fragile. As shown by this year’s forest wildfires. Technology-based approaches are immature and expensive, and there is insufficient political and therefore market support for their development.

In practice, even with substantial mitigation efforts, including a combination of emissions cuts on all gases and CDR, it’s far from certain the world will achieve net zero in the next 20-30 years — let alone achieve the required net removal thereafter.

Yet not limiting temperature rise to 1.5 or 2°C will lead to massive global suffering and the breaching of multiple planetary boundaries and potentially global tipping points, with devastating consequences for all humanity.

Faced with this stark situation, it may be time to start thinking about the unthinkable.

Solar radiation modification (SRM) is a theoretical set of approaches that seek to limit warming by deflecting more sunlight back into space. They would not be a substitute for cutting greenhouse gas emissions and removing excess carbon dioxide from the atmosphere, but could potentially help reduce climate impacts and avert tipping points while the essential work of decarbonisation is completed.

The IPCC cites several ideas: surface albedo enhancement, cirrus cloud thinning, marine cloud brightening, and — most controversially — stratospheric aerosol injection (SAI), which would “inject highly reflective aerosols such as sulphates into the lower stratosphere … resulting in a planetary cooling.”
But these techniques are uncertain and bring new risks. The IPCC says it is "conceptually possible for optimally designed SRM strategies to achieve multiple climate policy goals", but notes that there is limited understanding of their effects, and that the direct and indirect effects of deployment would not be equal globally.

A sudden and sustained cessation of SRM, the IPCC adds, would drive a rapid increase in global temperature, endangering biodiversity, weakening carbon sinks, increasing precipitation and changing water cycles. At the same time, the IPCC says a gradual phase-out of SRM with concurrent emission reductions could reduce that termination shock. Could the world create governance robust enough to safeguard against such risks? Could countries find consensus on how and at what level deployment should take place?

The IPCC will address the potential risks, the ethics, the public perceptions of SRM, and other governance issues as part of its second and third working group reports in 2022. But it’s already clear that SRM creates an unusually big and complicated governance challenge, which needs to be addressed.

SRM opponents believe the risks — known and unknown — as well as the governance challenges are simply too high to explore it any further. Furthermore, they believe that SRM would create a moral hazard by deterring other efforts to address the cause of the climate crisis via mitigation, by reducing emissions and removing excess carbon from the atmosphere.

But others see risks in pinning humanity’s hopes on current strategies alone and not exploring whether or not SRM could help avoid the impacts of overshooting temperature goals beyond what is possible through adaptation and resilience measures. They think the time has now come to learn more.

Addressing the causes of climate change is the priority. But should the world not also examine what potential insurance strategies might or might not exist? Should we not explore how to develop them, or how to prepare new possibilities if current implementation strategies prove insufficient?

If we decide to do so, addressing the moral hazard issue through effective governance will be crucial. We would need to build governance structures to avoid any deterrence of mitigation. But we also need to avoid falling into the trap of false optimism in other existing and emerging approaches, and to be prepared for unexpected developments.
The situation is certainly tricky: not building systems to learn more about and better understand the feasibility and viability of SRM is a decision in itself, and increasingly a risky one. It could deny future generations an option to reduce the impacts of soaring temperatures if SRM is found to be viable and the potential risks it poses are found to be acceptable compared to the benefit of reducing climate impacts. It could also increase the risk of ungoverned SRM deployment in the future. What governance would then be required? If we decide to duck this debate, are we accepting those risks?

The reality is that we don’t know enough about the risks, benefits and governance challenges and opportunities to take decisions about SRM today, including whether to reject them.

Understanding more about the availability, feasibility and use of SRM — or indeed the implications of a decision not to use it — could also have important ramifications for other important decisions relating to resilience and adaptation. We need to learn more. Building a global information platform could be a crucial first step to creating more inclusive and responsible discussions. But these things take time, something we are fast running out of. Finding broad-based agreement on the best way forward needs to start now.

One thing we already know: decisions and actions on SRM governance need to be global — including any decision not to use it. If the world went ahead with SRM, and in particular stratospheric aerosol injection, it would be the most global endeavour undertaken by humanity.

In practice, the United Nations is the only organisation where governments can address this issue with the rigour it demands. Ideally, governments would put different parts of the SRM governance challenge on the agenda of various UN bodies — including reviewing the potential risks and benefits, how the use or not of SRM may impact the sustainable development goals and what may come after their expiration in 2030, and make available transparent information on who is doing what in this area worldwide.

We need to face the sobering reality: there are no risk-free pathways ahead. The best we can hope for is to lessen those risks through better understanding and better preparation. In that light, to defer debate about SRM looks increasingly irresponsible.

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Janos Pasztor is Executive Director of the Carnegie Climate Governance Initiative (C2G), and would like to thank his colleagues, in particular Cynthia Scharf, Nick Harrison, Kai-Uwe Schmidt and Mark Turner for their contributions to this article.
Nature's goods and services are the ultimate foundation — the resource — of life and health, and we humans are strongly interested in preserving health. And yet, while the availability of resources drives our individual and collective decision-making, we have allowed our public and private resources to be managed in an unsustainable way.
Resources, including the human resource, are the matrix of economic and political power systems, of history’s ups and downs, and they have great geopolitical sensitivity. They are the substance and driver of economic models and institutions, the “nutrients of the social ecosystem”. But resource overexploitation and strong economic stratification are structurally enshrined in social relations and mentalities. They can end up in societal collapse, as has happened throughout history. Today, critical state shifts in our resources are expected around 2030. Our resources are in trouble today because we have wrongly framed the issues: the short-term view has prevailed. This situation has arisen because of three interrelated problems. The first is that social and ecological issues have been considered as separate items. The second is that we have never quantified the value of the benefits that ecosystem capital delivers to human well-being. As a result, that capital has been allowed to slowly and continuously depreciate, leading to societal harm that is accelerated by cumulative tipping points and compound risks.

Our third problem is that we did not use normative ideas of resource and opportunity distribution to build equity, equality and justice into the social foundations of our society. As a result, public policies are failing to fairly distribute resources and meet people’s needs. Resources are vital for health, but coupled resources and health issues have not been the focus of grand agendas in the last decades. For example, the explicit interconnectedness between resources and health deserves particular attention when designing and implementing the SDC agenda (the social contract) and the maintenance of life support functions of the biosphere (the overshoot process). We estimate that 75 per cent of the 17 goals have resources and health at their core that inherently makes them the metrics, support, and vector of equitable and sustainable development in social, economic, political, cultural, and environmental terms. (See also UNEP). This is not surprising: individually and collectively, the 7.5 billion humans are concerned on a daily basis with accessing resources to sustain their health and be able to do so in the future.

According to the WHO’s 1946 definition, health “is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity.” Health is a notion that resonates strongly with us today. The strength of this resonance stems from the capacity of the word to encompass a range of meanings and contexts. There is the universal value that we place on bodily health, but there is also a metaphorical meaning: we all want to live in a healthy society. There is the actionable, factual, scientific evidence-based policy dimension of public health that plays out in the lives of individuals and societies; a socially just and environmentally responsible society ought to consider that ‘Health is a precondition, outcome, and indicator of a sustainable society, and should be adopted as a universal value and shared social and political objective for all.” And there is also the health state of ecosystems. In other words, the health of nature, society and people is inseparable, and can be termed “planetary health.”
Integrating our approach to health with our approach to global resources helps address the dilemma we face, because this acknowledges the interconnection between social and ecological systems. The main question then is: how can accessible resources be allocated in ways that reconcile the basic needs of populations with maintaining the life-support functions of the ecosystems those populations are part of?

To address this question, we developed a Resource-Planetary Health Toolbox (RPHT), built on the alliance of natural sciences, legal and social studies, and data and complex system science (see also Ostrom). The objective is to articulate the nature-human relationship on universal and indivisible human rights and duties, to which resource-sobriety and inclusive health are cultural driving factors. That culture is based on technological and environmental literacy. The approach is systemic and preventative, and challenges the discarding of social and ecological factors that obliterates sustainability and justice today.

Through this approach we are reframing human agency with the temporality and limits of natural cycles and functions. We anticipate that RPHT is the most straightforward and non-prescriptive science-informed instrument to prompt the emergence of a virtuous dynamics of policy design for the public good.

We translated the Resource-Planetary Health strategy into research priorities, considering how those priority areas will look in the near and more distant future. Food systems and security are one such priority: the state of the underlying strategic resource base (land, water, biomass) can be a unifying proxy for developing political, economic, and diplomatic frameworks for the commons, circular economy, and indicative planning. More broadly, the toolbox can operate as a stress test in all areas of human life and activities; RPHT then becomes a compass of society’s preparedness to undertake radical change. That change implies a profound transformation in ways of thinking, institutions, practices, science and technology, policies and diplomacy, lifestyles and education.

In summary, while resources and health are considered separately, it will be difficult to resolve grand challenges such as poverty, equity and democracy, global pollution and biodiversity erosion, and climate change. But the state of our readiness to enact change can be assessed by a dedicated toolbox. This tells us that if resource justice and inclusive health are considered together — all resources, along with the health of the biosphere, societies, and people — we can meet the necessary and sufficient conditions for a peaceful future.

ACKNOWLEDGEMENTS
The work is based on the project “Resource stewardship and justice — taking the long view and a science-policy agenda for the next decade”, with the contribution of Ioan Negrutiu, Gérard Escher, Ole Peter Ottersen, Jason D Whittington, Philippe Gillet, and Nils C Stenseth.
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, the study of Complex Systems for Social Enhancement has taken off: our ability to gather and process data on massive scales 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.

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 the Scientification of 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.

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 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.
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, 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.
Complex Systems for Social Enhancement

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 and opportunities, while putting humans, their values, and a democratic, participatory governance approach in the centre. It should also allow us to embrace desirable emergent behaviour such as coordination, cooperation, co-evolution, and collective intelligence.

Dirk Helbing
Professor of Computational Social Science, ETHZ
**SURVEY OBSERVATIONS:**

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".  

The increasing digitalisation 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 though. Most of the required technical capabilities already exist and the challenge will be more about increasing the scale of what we are already doing. 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.

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**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".  

Dirk Helbing reviews the problems and challenges associated with complex social systems in "Globally networked risks and how to respond".  

Reinhart and Rogoff study the networked links between financial crashes and debt crises.  

In "Values for the Future," 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/r4-1](http://radar.gesda.global/r4-1)
Social science explores the relationships among individuals within societies and the forces that influence them. For this reason, it has close relationships with network science. However, the networks at play are multifold and complex. They include social, cultural and institutional networks that encompass activities playing out not only between individuals, but also at local, regional and global scales.

In recent years, increasingly powerful computational models have allowed researchers to capture many properties of these networks and to study the transitions from one type of collective behaviour to another. This has led to the emergence of the new discipline of computational social science, which aims to develop better social theories, gather more meaningful datasets in an ever-growing range of experiments and to create increasingly useful models. These models have already given us a better understanding of a wide range of phenomena, such as pedestrian and traffic flows, social inequality and the spread of diseases. 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: Outcome testing guides social interventions
Computational models of complex techno-socio-economic-environmental systems that simulate networks and interactions become progressively more capable. These models lead to a number of innovative approaches to manage complex dynamical systems that prove the power of the suggested approach, e.g. to improve sustainability and resilience, or to prevent or mitigate the spread and impact of diseases.
One of the challenges for democracy is to engage the widest range of people in its practice and activity. Digital tools offer powerful new ways to do this by offering alternative means for citizens to debate and discuss, to communicate, to find solutions, to allocate resources and, ultimately, to govern. This creates the potential for dramatic changes in democracy, making it more representative, more efficient and more capable. That said, challenges will remain. Much effort will be needed to engage the broadest range of citizenry so that no groups are disenfranchised, particularly the elderly and technologically disadvantaged. Furthermore, digital tools also open the way for malicious actors to subvert democracy and to undermine society; securing public confidence will require a transparent design and operation of a robust, reliable and trustable, sufficiently participatory framework.

**5-year horizon:**
Digital tools become commonplace 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 combine 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 their success of actions taken.
4.1.3 Collective Intelligence

Technology that enhances collective behaviour clearly has an important role to play in bringing people together, in supporting their collective behaviour and in bringing it to fruition, which is why so much work is being done on collaborative tools. However, collective behaviour does not always produce the intended or best results. Groupthink and herding behaviour can push groups towards dangerously wrong-headed actions and amplify negative trends, such as racism, unhealthy behaviours and online hate. Computer modelling provides a way to study how collective intelligence emerges (and why it sometimes doesn’t). 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.
4.1.4 Design for Values

The design-for-values movement is based on the idea that technology can promote certain values and discourage others. Desirable values include, for example, equality between men and women, healthy living, personal safety, sustainable living, environmental responsibility and valuing democracy. The hope is that, with this approach, positive conversations about such values would be amplified on a suitably designed social media platform, for example, while fake news and cyber-bullying would be promoted and amplified.

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.

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.

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.
4.2 Science-based Diplomacy

The "Scientification of Diplomacy" is based on computational social sciences, mathematics, optimisation theory or behavioural research and covers different emerging fields of research, such as computational diplomacy and negotiation engineering.

Computational Diplomacy for one, is concerned with our emerging ability to map the landscape of international relations, to gather and analyse data on unprecedented scales and to simulate potential outcomes. This has transformational potential for diplomatic activity. For instance, efforts have already begun to plot the networks of influence between actors on an international scale and to use artificial intelligence to mine the large databases of texts relating to historical negotiations. As such, Computational Diplomacy is revealing not only the complexity of modern international relations but the potential knock-on effects of future actions. It also allows actors to better understand the history of negotiations, how changes in language reveal movements in position and to reduce uncertainty in formulating plans.

Negotiation Engineering, on the other hand, is a solution-oriented approach to negotiation problems that uses quantitative methods in a heuristic way to find an adequate solution. In doing so, it particularly draws on the decomposition and the formalisation of the problem(s) at hand and the heuristic application of mathematical methods, such as game theory and mathematical optimisation. This way, it can de-emotionalise negotiation problems and allow for resolutions of more complex real-world issues.

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

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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 12–15 years and all four were judged to require considerable interdisciplinary convergence 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.

An overview of Negotiation Engineering is given in “Negotiation Engineering: Why Quantitative Thinking Can Also be Useful in Negotiations”.

“Computational trust and reputation models for open multi-agent systems: a review” 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/r4-2
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, 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.
As mentioned in the introduction, 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. 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. 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, such as interpersonal conflicts. 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.
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. 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.

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.

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. 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.
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.  

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." 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.
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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In recent years there have been numerous efforts to track the potential of technology and other tools to transform teaching and learning. 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 decade, which suggests the window for anticipation is already narrowing. The one possible outlier is educational sensing, which is expected to reach maturity last and currently has relatively low awareness. Given the potential privacy issues raised by widespread surveillance in the classroom this is likely to require more work than the other topics to map out the potential ramifications and to find solutions to any problems uncovered.

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

¹ ‘Innovation in education: what works, what doesn’t, and what to do about it?’ focuses 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:

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The GESDA 2021 Science Breakthrough Radar
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.

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. 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.

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.
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.

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. When focussed on learners, digital tools combined with machine learning algorithms, can provide a range of insights. They can, for example, differentiate students who are struggling from those who are just avoiding effort. 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.
4.3.3 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 workplace12, seek up-skill 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.
Although investigations of neuroscience as applied to learning have yet to deliver significant tangible breakthroughs in educational philosophy or practice, there are reasons to continue efforts to understand how the brain functions when learning. 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 and pharmaceutical interventions 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.
Sustainable 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. 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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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. The potential impact of the approaches investigated here on both the planet and society were judged to be among the highest of any assessed by the expert panel. However, the considerable attention these ideas have already received from both researchers and policymakers combined with the short timescales over which they are expected to be implemented significantly reduced the need for anticipation. Nonetheless, their potentially transformational effects on society suggests it would be unwise to disregard them.

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

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.

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radar.gesda.global/r4-4
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 attention is required to better understand, predict and plan for these mass movements. 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. 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 CO₂ 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.
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. 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.

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. 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. 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.
A circular economy overcomes the “take, make, waste” of traditional linear economies by attaching costs to the creation of waste and pollution and to the over-exploitation of resources. Circular policies also create financial incentives to make the waste from one process the feedstock for another. The goal is to create giant closed loops that recycle and reuse Earth’s resources for as long as possible.

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.

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.
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.

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.
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.

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The importance of diplomacy in science and the importance of science in diplomacy 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 though, with respondents predicting maturity won’t be achieved for another 17 years. Getting there will be a long-term project and will be impossible to achieve without breakthroughs in multi-stakeholder diplomacy, which was judged to have low awareness and will require considerably more attention going forward.

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. The European Union Science Diplomacy Alliance, established in 2021, brings together the members of several research projects on science diplomacy.

In 2018, S4D4C published a useful review of work and approaches in this area, 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.

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/r4-5
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. 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 to tackle these issues and then bringing together the relevant stakeholders to establish global governance frameworks would be key goal for science diplomacy.

**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.
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. 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.

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.

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.
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. Similar multinational science projects include the ITER fusion project, Eumetsat and COVAX. 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 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 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.
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. 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. 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.
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 resolving 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, and 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 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 elaborate 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.
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 the 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.
While it may be true that today’s fortune tellers are more systematic and analytical than their predecessors, they still cater to only one way of using the future. They are just responding to our demand for prediction, a desire for certainty and a massive bias towards using the past to imagine the future. At first blush it might seem that the problem is the lack of transparency regarding the underlying assumptions or the excessive faith put in the prognostications of a person or a group. Of course, a good dose of skepticism and an eye for rigour is important when assessing probabilistic projections of what might happen. But this is not the main problem. The fundamental flaw in relying exclusively on the all too familiar anticipatory systems and processes of prediction is that it confines our imagination to a narrow purpose and reinforces a dangerous bias towards the pursuit of an illusory certainty.

Everyone knows that the future cannot be observed. Thus, it cannot be studied or assessed. Most people also know — at least intuitively, on the basis of their own life, which unfolded in ways that were unimaginable in advance — that complexity as the creative nature of our universe is unavoidable. Uncertainty or change is the only certainty. Yet we are addicted, particularly at the level of the stories we tell ourselves about security and the role we expect humans to play in the world, to controlling tomorrow. By confining our imagined futures to the realisation of what might be characterized as a ‘god-like’ role we under-utilise the power of our imagination to go beyond the pursuit of certainty with its obligation to describe the future on the basis of what we already know — that is the past. We can use the future for emergence or to liberate our perception of the present from the blinkers of futures-imagined in order to colonise tomorrow. Futures Literacy Labs offer evidence that everyone is capable of engaging their imagination in an effort to describe images that are not framed by what we know from yesterday and today. Images that are inspired by another purpose, to discover the differences that emerge all around us all the time.

Letting go of the imperative to colonise the future also opens the door to diversifying how we imagine the future. Once you expand the reasons for imagining the future it also becomes evident that we need to expand the ways in which to do so. Planning the future, efforts to control and dominate tomorrow, bring a strong bias towards imagining the future on the basis of probability — the past extrapolated into the future — and the projection of current preferences so you can plan a better or desired future.

Anticipation for emergence calls for another set of tools: ones that attempt to let go of the past, including the past desire to control the future. These are required in order to enhance our capacity to sense, make-sense and invent the novel phenomena all around us: aspects of the world that were unimaginable a moment before or do not yet have a name or even a story that can be told. This capacity to improvise is the opposite of planning. Anticipation for emergence welcomes uncertainty, changes that make the world different from moment to moment, because it is the music that inspires the dance of improvisation. This is agility beyond continuity, a way to embrace transitional changes, the ones that may, or may not lead to transformation — the previously unimaginable.
More prosaically, being futures literate helps us to be in the world differently. To value, as well as to put into practice, the maturity and wisdom that can only arise from learning through experience. If what we can perceive in the present is powerfully influenced by the futures we imagine then the key is to become better able to use the future to sense, and make sense of, the experiences we are having now: the novel emergent present that is not knowable in advance. If we are locked into the fear and arrogance that accompany our efforts to impose our will on tomorrow then we diminish our ability to appreciate the richness of a complex universe characterised by constant creativity, the well-spring of difference. This matters a great deal for many of the most pressing issues facing humanity today. Blinded by our sense of superiority and the arrogant belief that we can and must, for glory and power, control the future, we wreak havoc on the universe around us and become apologists for the proposition that the ends justify the means. Failing to use the future fully we alienate ourselves from the entangled and mortal nature of this universe, contributing to conditions that make existing systems fragile and make resilience, as a process of transformation, not statis or continuity, less practical.

Climate extinction and pandemic fragility are unintended consequences of human activity, but not just because of overt acts of consuming carbon or ignoring the world around us. There is an underlying source of our incompatibility with complexity, a failure to use our imaginations to live with an awareness and appreciation of our universe. The industrial societies facilitated by the advent of universal reading and writing offered plenty of signs of toxicity — from genocides to the vacuity of mass consumer culture — but that was not enough. Now the planet and viruses are offering us an opportunity to get the message. Anticipatory systems and processes are fundamental to all forms of life, and are part of the evolutionary condition. Our imagination plays a huge role in fostering our consciousness, shaping our fears and hopes, motives and reactions. Up until now we may have not been mature enough to realise the importance of understanding these anticipatory systems and processes. Maybe we didn’t have the means, the necessary scientific knowledge and historical experience. So conditions have changed and perhaps we can surprise ourselves, improvise outside the plans, dance with complexity.
Opportunities
So... What can we do about it?

The scientific emerging topics and breakthroughs at 5, 10 and 25 years presented in the Science Breakthrough Radar have been identified, discussed and described by scientists in their respective fields.

The Radar discussions do not consider the social contexts in which science takes place, nor how they relate to the grand societal challenges of the 21st century. They do not include reflections about the reality of politics, the broader geopolitical trends or the current status of multilateralism. They simply present a state-of-play of what is happening in the laboratories today and a neutral vision about what may happen in the future from the point of view of those who are working on this future every day in their laboratories.

However, each of the 216 breakthroughs brings risks as well as opportunities, because they contribute to our evolving understanding about what makes us human, how we are going to live together and our relation to the planet. These risks are already debated by citizens globally, as shown in Section 2.

One of the risks that comes with these 216 breakthroughs is that people around the world could miss the opportunities for development and well-being that the breakthroughs might be able to bring. However, that risk can be mitigated by anticipation and honest brokering about what is cooking in the labs.

This is the purpose of our rolling annual GESDA Science Breakthrough Radar, a tool that facilitates an important political debate about the Radar topics without pre-empting any conclusion that might come out of it. Ultimately, the necessary conclusions must be drawn by politics and diplomacy in charge at national and international scale, after debating with citizens, entrepreneurs, NGOs and the scientists themselves.

In that sense, this Science Breakthrough Radar is primarily an information tool to assist discussion and, ultimately, decisions.

The annual Geneva Science and Diplomacy Summit, which has its inaugural meeting following the release of the Radar, is another tool, this one designed to take the pulse of diplomacy and accelerate discussions on what to do and how to cope with the science breakthroughs presented by the scientists.
In doing so, we move from scientific anticipation to anticipatory science diplomacy.

Here we enter the action and impact part of the process that the Breakthrough Science Radar introduces, with the primary aim of being honest brokers of such a process. This will enable the international community to respond more effectively and more quickly to emerging and future challenges, and to help multilateralism adapt to the acceleration of science and consequently to the evolution of the world.

This first requires the discussion to be contextualised. Therefore, in this section, we go a step further and introduce reflections about the significance of the Radar’s breakthrough predictions, how they interact with diplomacy and how they relate to the challenges of the 21st century as described first in the UN 2030 Agenda and the Sustainable Development Goals (and more recently in the new UN Secretary-General Common Agenda for the Future released on September 10, 2021).

This section builds bridges between science anticipation, global societal challenges and a renewed multilateralism. This is a necessary step in order to ensure that science anticipation can ultimately benefit the global community.

The opening essay from the Science Breakthrough Radar on Getting Value from Science Anticipation highlights the need to create a common language between all disciplines and communities through a continuous dialogue with society. Then “Anticipatory impact on people, society and the planet” provides the views of the global scientific community consulted – as informed citizens – on how breakthroughs in their respective fields will affect those three existential questions.

Short essays from Swiss Federal Councillor Ignazio Cassis and GESDA Diplomacy Forum Chairman Michael Møller discuss the authority of politics in global affairs and the transition to a renewed multilateralism. These pieces are key to understanding how science anticipation can be used for the common benefit of humankind. Sir Jeremy Farrar, a member of GESDA’s Board of Directors, explains what the Covid-19 pandemic can teach us about anticipation in diplomacy.

Following on from that, four case studies display the demand side, explaining how science anticipation is already used in practice by international organisations, and their hopes and expectations about its future.

Finally, “What’s next - Opening the discussion on 16 initial topics of interest for diplomacy” presents the 16 topics coming out of the Radar as subjects of debate in the first Edition of the Geneva Science and Diplomacy Anticipation Summit. This helps catalyse discussions and enable common actions by the diplomatic community along with the scientific, impact and citizen communities.

By doing so, the Summit convenes an extended audience and provides it with a kind of Anticipatory Situation Room for multilateral discussion and action. The Summit thus links two key features of GESDA methodology:

The Foundation brings Swiss and World science to the multilateral table as one global community and works with it to identify what will emerge from the laboratories in 5, 10 and 25 years’ time. This is an exercise that the scientific community does not spontaneously undertake, although it is commonplace in the political and diplomatic world, as shown by the UN’s Agenda 2030 published in 2017. This is the specific contribution of science diplomacy in full bloom.

By doing this, GESDA, although an initiative of the diplomatic world, reverses its usual order of priority. The work does not start from the listed challenges or objectives of each international organisation, but from the scientific trends that are already at work in the world and independent of such challenges. It then looks at how these scientific developments can help the wider diplomatic world and all its stakeholders in its daily work.

The second edition of the Radar due to August 2022 will report on the development of this discussion and actions among the actors of multilateralism.
Opportunities

Getting Value from Science Anticipation

Opening Essay from the Advisory Board to the Science Breakthrough Radar

The anticipated breakthroughs at 5, 10 and 25 years presented in the trends section of the report represent the views of leading scientists and technologists in the field. They are neither an absolute prediction of what will happen, nor do they have the intent of projecting a vision of a desired future. Rather, as described in the Debates section of the report, they are presented to encourage reflection on what might emerge so they can be discussed, analysed and debated by citizens across the globe with different opinions, sentiments, values and worldviews according to cultural, geographical, generational or economic backgrounds.

In our history as a species every component of a new technology has been considered to have both positive and negative consequences. With the rapid pace of change now occurring, and its pervasive impacts, more engaged dialogue with these developments is important. Such dialogues with all sectors of all societies must be nurtured in order to create a common language that allows the best use of science anticipation for a positive shared future.

The GESDA Science Breakthrough Radar therefore welcomes further dialogue and broader engagements with the communities, and aims to be an honest broker between disciplines, communities, regions and world views.

The International Science Council, as a global body composed of over 140 national and regional scientific organisations, will be a key partner in facilitating this engagement. We call on each interested scientist, policymaker and citizen, from the public and the private sector, to contribute—in particular, to expand the contributions of formal, natural and social sciences.
Of course, as important as the anticipation of the possible science breakthroughs is, the anticipation of the possible societal, political and ‘diplomatic’ implications also matters. This requires a thorough assessment of the potential opportunities and threats of the anticipated breakthroughs as well as the corresponding appropriate diplomatic and policy toolbox to address them.

As described in the coming pieces, this involves moving from a traditional multilateralism towards a “polylateralism” that integrates and networks a broader set of actors. Such a move necessitates the creation of space for common dialogue that does not shortcut the political system and the citizen. Social sciences, the humanities and the arts (and other knowledge systems) are a critical part of this process. Not only do they help us understand how science and technology are embedded in society and the relation between scientific and social progress, they also are disciplines in their own right, on equal footing with the more technical sciences, where anticipation is needed as well.

Building on the work already done in the development of the first edition of the Science Breakthrough Radar, this component will be fully fleshed out in the development of the subsequent editions. Institutions such as The Graduate Institute of International and Development Studies in Geneva and the International Network of Government Science Advice (INGSA) will be key to work towards the systemic inclusion of political, societal and diplomatic considerations in the next editions of the Radar.

To get the most value possible from science anticipation, and to capitalise on the anticipation potential mapped out in the radar, we must ensure that it:

1. Involves a continuous, dynamic observation of science and technology trends in the coming 25 years, including a broadening of the emerging topics considered and a questioning about which breakthroughs may have the most critical impacts that need consideration.

2. Considers and, to the extent possible, anticipates the interrelation of specific science and technology breakthroughs with the broader societal and political contexts.

3. Establishes a constant and interactive dialogue with society in order to create the common language and, jointly with all relevant actors, design solutions that will benefit human and environmental wellbeing globally.

The 2021 GESDA Science Breakthrough Radar is only a first step towards ensuring that the opportunities and existential risks from potential science and technology advances at 5, 10 and 25 years are taken into account, and seriously discussed and debated. This is a pre-condition to avoid mistakes of the past, accelerate the responses to some of humanity’s most pressing challenges, and increase the preparedness for future emerging issues.
Anticipatory Impact on People, Society and the Planet

We asked the scientists who wrote the anticipatory breakthroughs to imagine some of the impacts of these technologies on the human being, on our society, and on our planet. This does not imply that these are desired developments, but they are possible impacts nonetheless, honestly brokered by scientists in each field to a wide audience, acting as informed citizens.

Discussion of these challenges and opportunities, and reaction to the anticipated impacts — and the potentially complex interactions of these impacts — needs an interdisciplinary dialogue between sciences; more, it requires the involvement of a much broader set of stakeholders, including diplomats, policymakers, and society at large.

1.1 Advanced Artificial Intelligence

Impact on people: Advanced Artificial Intelligence will become more deeply embedded into the devices we use daily. Personal assistants will increasingly suggest what we should do and will occupy a growing part of our attention. Human-machine collaborations enabled by AI will become widespread, blurring the differences between interacting with other humans and with machines.

Impact on society: Advanced Artificial Intelligence could improve medicine, healthcare, energy, transport and infrastructures, support lifelong education, accelerate scientific discoveries, and transform the field of defence. AI could profoundly disrupt the job market, making entire professions obsolete, but could create new business opportunities and create jobs. It might also bring disparate parts of humanity closer through automatic translation.

Impact on the planet: AI can play a key role in improving efficiencies of existing systems and developing new paradigms for decreasing the environmental impact of all human activities. The energy-intensive nature of machine learning makes it important to find alternative approaches to artificial intelligence.
1.2 Quantum Technologies

**Impact on people:** Quantum sensors bring improvements in medical imaging that could vastly improve diagnostic precision and disease monitoring. Discoveries made in the field of quantum biology may usher in new therapies for physical and mental health conditions, some of which will have had previously known no effective treatment options.

**Impact on society:** Quantum communication will eventually create a mainstream culture of privacy; banking and credit card fraud will be dramatically reduced. As with any encryption technology, there are potential negative impacts for those monitoring criminal and terrorist activity. Researchers will enjoy vibrant career opportunities but find their work subject to domestic and international restrictions because of the geopolitical implications of their work.

**Impact on the planet:** Quantum computers could uncover new methods of carbon fixation, CO₂ sequestration and nitrogen fixation. Quantum-derived materials in batteries may lead to better storage of electricity. Networks of quantum sensors will allow us to monitor weather, climate change and geological processes. The much finer detection of seismic activity and thereby of nuclear explosions could help enforce international treaties of non-proliferation.

1.3 Brain-inspired Computing

**Impact on people:** Personal brain-inspired computing devices will be a new generation of wearable, perhaps implantable devices that could fundamentally change the way we use and interact with information-processing technology. Efforts to build these “neuromorphic” computers could speed up understanding the principles by which the human brain operates.

**Impact on society:** The knowledge we gain through the effort to build neuromorphic computers could benefit education, and influence law enforcement and procedures for dealing with criminal behaviour.

**Impact on the planet:** The low-power nature of neuromorphic computers is in contrast to the energy-hungry nature of our current computing efforts. Most of this energy is wasted as heat. Any progress we can make in reducing our reliance on standard silicon-based processing will have a positive environmental effect.

1.4 Biological Computing

**Impact on people:** There is great scope for biocomputing research to make important discoveries about the pathways of disease, to find ways to diagnose illness based on molecular signals. Once the body is shown to be performing a form of computation, philosophical implications about the purpose of living organisms within their environment may become a subject of debate.

**Impact on society:** Applications of biocomputing will improve our society’s quality of life through protections of public health and safety through environmental monitoring and safeguarding (and improving) food production processes.

**Impact on the planet:** Sensors engineered through understanding of biological information processing are likely to be a vital tool in monitoring the natural world. The convergence of information processing and biosynthesis means that bio-computation should be able to engineer populations of organisms that can remediate environmental problems such as chemical spills.
2.1 Cognitive Enhancement

**Impact on people:** Memory is central to human identity, so the ability to manipulate memory function could alter an individual’s personhood. Beyond their potential therapeutic applications, neuromodulation devices — non-invasive devices in particular — will become available to the healthy people, for cognition and memory enhancement purposes.

**Impact on society:** Neuromodulation devices have the potential to increase societal inequalities by creating a “cognitive elite” — a sub-section of the population that can afford, or has greater access to, these technologies. In the long term, peer pressure would make it difficult to opt out of cognitive enhancement implants lest one be a second-class citizen.

**Impact on the planet:** Successful memory enhancement technologies could alleviate the social and economic consequences of diseases like Alzheimer’s. Hybrid intelligence could help us better interface with AI. This could help to advance healthy people’s ability to move science forward and find solutions to the problems that appear intractable today.

2.2 Human Application of Genetic Engineering

**Impact on people:** The potential to mitigate diseases of ageing, in which germline edits eradicate vulnerability to pathogens, could create a population with reduced medical problems. To ensure equality in access and make these therapies universally acceptable — without which it does not impact society beyond a very small wealthy percentage — measures need to be taken.

**Impact on society:** Health improvements brought on by human applications of genetic engineering could reduce the cost of dealing with an ageing population. However, adverse ethical and even economic consequences are potentially numerous, and present enormous risks and ethical challenges.

**Impact on the planet:** Genome editing has the potential to become a major tool in managing a sustainable future. By extending longevity, anti-aging therapies and enhanced medicine may increase the world population and the subsequent pressure on our natural resources.
2.3 Radical Health Extension

**Impact on people:** Radical health extension research will allow individuals and societies to begin their exit from the era of medicalised ageing. It would not just lift the burden on the elderly and their carers; younger cohorts are likely to benefit from the advances too.

**Impact on society:** The ultimate goal, at a societal level, is a fundamental decoupling of ageing and disease. If successful, this will change national demographics, and possibly economies. The potential to mitigate diseases of ageing using germline edits could create a society free of many preventable medical costs. The ability to restore the youth of organs could mean that organ donation waiting lists become a thing of the past.

**Impact on the planet:** In the long term, improvements in medicine and education reduce the number of children that women bear during their lifetimes, and so it is likely that the innovations of radical health extension could mean fewer people sharing the planet.

2.4 Consciousness Augmentation

**Impact on people:** Applications of consciousness augmentation will initially range from the fun (like VR and recreational drugs) to the serious (those convicted of hate crimes being rehabilitated in VR environments to learn empathy). However, later-stage implementations, including direct brain-to-brain communication, will change human experience and potentially the understanding of what it means to have a self.

**Impact on society:** A scientifically validated understanding of the neural correlates of consciousness will lead to radical shifts in the legal system: attribution of responsibility and guilt, and attribution of character traits like altruism will need to be rethought and reframed at a societal and systemic level.

**Impact on the planet:** Discovery of increasing similarities with other animals would be transformative. We will have more empathy for provably conscious animals, and thus more motivation to preserve their habitats. Properly handled, the erosion of the boundaries between us and other living organisms will increase our desire to care for our common home.
3.1 Decarbonization

Impact on people: If we cannot accelerate the decarbonisation of our activities, climate change (with increased flooding and more frequent wildfires) will affect housing, with many people losing assets. Governments will be forced to impose taxes to pay for decarbonisation costs. With significant reductions in air quality, personal health will also continue to be compromised.

Impact on society: Failing to meet decarbonisation targets will have serious consequences on human societies. Temperature rises and more frequent extreme weather events will create problems for those trying to produce enough food to supply the growing human population. The change in hydrological conditions is likely to make access to water problematic for many populations. Mass migrations might be the result.

Impact on the planet: Since the industrial revolution, human resource requirements are out of balance with the rest of the planet. It is not clear how long this situation can continue. The anticipatory impact of decarbonisation is likely to go a long way towards keeping Earth habitable – for humans and other species.

3.2 World Simulation

Impact on people: Our ability to simulate the world will transform how humans and machines learn together to better manage social-ecological systems. However, measures will be required to create a human-centered future where elites are not able to dominate the new social-technological infrastructure.

Impact on society: It is impossible to be certain which policy preferences humans will have in the future. This is important for social-ecological foresight. First, future states of a social-ecological system are also impossible to predict. Second, it suggests that the ultimate purpose of digital twins is to support democratic deliberation by providing citizens the best-available evidence for evaluating the consequences of their decisions.

Impact on the planet: Radical improvement in our ability to model integrated human and planetary systems will help us to curb our destabilization of Earth’s life support systems. Perhaps the most transformative consequence will be the erosion of the distinction between human, society and planet. Over the next 10 to 25 years, humanity can come to view life on Earth as an inherently interconnected, holistic system.
3.3 Future Food Systems

Impact on people: The future of food will impact everyone on the planet, but in different ways. For many, access to food is a foundation stone of survival. For those in nations where nutrition is assured and consumer choice rules, new monitoring technology — increasingly paired with genomics — will allow people to fine-tune their nutritional intake to optimize their health.

Impact on society: Globally, the challenges of equitable access to sustainably produced food will grow alongside the pressures of population growth and climate change, with low-income countries particularly at risk. Extensive international cooperation between governments, agribusiness, scientists and supranational bodies will continue.

Impact on the planet: The future of food and the wider future of our planet are tightly bound together. Only by adopting a combination of sustainable agricultural practices and high-technology solutions will we be able to avoid the impending catastrophes of irreversible climate change, widespread hunger, and massive soil degradation.

3.4 Space Resource Stewardship

Impact on people: Data streams from space are likely to become a firehose feeding weather “nowcasts” and positioning details for almost every object on the planet via the Internet of Things. It will also allow crowdsourced monitoring of pollution and emissions that will engage individuals more fully in sustainability issues.

Impact on society: The 21st century space race to put people on the Moon, Mars and beyond will increase competition between world powers. However, commercial efforts to send humans to Mars will drive the development of detailed legislative frameworks that govern human rights, and access to resources in off-world locations.

Impact on the planet: The first community on Mars will amplify calls to begin terraforming the Red Planet as a possible fallback habitat. These communities will rely on self-contained biosphere research on Earth, which itself could help humans learn to live sustainably on their home planet. Off-world resources, should they become economic to exploit, could also have a significant impact.

3.5 Ocean Stewardship

Impact on people: Shifting from a paradigm of the ocean as a final frontier for resource extraction and growth to a shared responsibility that connects the world is crucial. This will naturally feed a tendency towards exploration before exploitation and centering the blue economy around pillars of equity and inclusivity.

Impact on society: The challenges here will be around how nations coordinate their efforts in sustainable ocean management and share the benefits of the ocean equitably. These benefits will come not only in terms of the sustenance the ocean provides, but also the scientific advances associated with understanding the ocean at a genetic level.

Impact on the planet: Learning more about the ocean through observation will enable us to unpick the interconnectedness of its ecosystems and help us to make the best decisions for long-term sustainability. Expanding marine protected areas is one instrument for safeguarding marine biodiversity.
Opportunities - Anticipatory Impact on People, Society and the Planet

4.1 Complex Systems for Social Enhancement

**Impact on people:** The complexity of society makes it uniquely vulnerable to influences that are hard to tease apart. Digital tools have the potential to empower citizens in a way that strengthens democracy, improves quality of life and allows for a more sustainable and resilient operation of society. Their deployment raises issues of equality of access and the possibility that certain citizens may be disenfranchised.

**Impact on society:** Powerful computer models will allow us to better understand society and to test potential outcomes from different courses of action. Many societies will blossom thanks to actions designed to boost efficiency, sustainability and resilience. Some societies could suffer from decisions designed to reduce freedom and to undermine democracy.

**Impact on the planet:** An important goal for society is to live within its means as far as the Earth’s natural resources are concerned. The tools for modelling and understanding collective techno-socio-economic-environmental behaviour will allow for greater advances towards large-scale sustainability and resilience.

4.2 Science-based Diplomacy

**Impact on people:** The computational models might allow individuals to simulate potential outcomes for themselves. Consequently, it may become the norm to use computational techniques to reach agreement in a wide variety of circumstances. However, the veracity of data used in these situations will become an increasingly important focus of attention and indeed a battleground itself.

**Impact on society:** A clear trend in recent history is an increase in regional conflict. Advances in computational diplomacy will help identify, model and prevent such conflicts. The exploitation of social media platforms will remain a challenge for those looking to defuse potential conflicts, but they can also be harnessed for peacekeeping purposes.

**Impact on the planet:** Climate change will dramatically increase the pressures that trigger conflict in the coming decades, and techniques for modelling these conflicts will play an important role in managing conflict. Computational diplomacy has the potential to become a valuable instrument in the task of helping humans live within their means.
4.3 Innovations in Education

Impact on people: As digital technologies allow more people to access education, the impact of online courses combined with an increase in remote working practices and better infrastructure for online engagement means that people who are well-educated and motivated can enter the global labour market wherever they are in the world.

Impact on society: A better educated society is a healthier society. It is also worth noting that an educated population is one that takes more interest in the processes of government. Finally, education brings spending power, and thus stronger, more resilient economies that foster a more stable society. However, it will be important to ensure that the new developments in education are equally distributed across all regions.

Impact on the planet: More educated populations lower their birth rates, reducing our environmental footprint. Technologically driven improvements in education play out, particularly in the developing world where online access and remote certification will have a dramatic impact.

4.4 Sustainable Economics

Impact on people: The challenge is to allocate accessible resources in ways that reconcile the basic needs of populations with the life-support functions of their ecosystems. With the right economic policies, people will be better able to find an equilibrium between material prosperity, environmental sustainability and personal contentment. Emerging trends in automation will have profound long-term impacts on individuals, but could result in a better work-life balance.

Impact on society: There are pathways where societies can respond appropriately to the anticipated challenges of the 21st century. If we can narrow the gap between rich and poor, and if businesses can internalize their externalities and ensure they create value for society with their output, we can increase the sense of inclusiveness in civil society.

Impact on the planet: Failure to limit global warming will lead to droughts, famines and conflicts on an unprecedented scale. However, it should be possible to sustainably manage Earth’s resources in a way that allows humanity to flourish. Well-designed and well-implemented economic policies can meet the challenges of creating and maintaining a safe global habitat suitable for generations to come.

4.5 Advances in Science Diplomacy

Impact on people: A growing focus on science diplomacy will move scientific research and technological development centre stage of diplomacy. Increased attention will be paid to the equitable distribution of science and technology products such as vaccines and drugs, heat-resistant crops, big science experiments and machine intelligence. However, much work will be needed to avoid concentration of wealth in the hands of the few as a result of these initiatives.

Impact on society: With non-state actors becoming increasingly powerful on the global stage, finding ways to integrate them will have a great impact. This process will give a greater voice to grass roots organizations, allow cooperation to emerge on regional and city scales rather than just national scales. The increased complexity of this landscape will require careful navigation with new skills in science diplomacy.

Impact on the planet: The global commons are planetary resources that require the utmost care and diligence to preserve. The new discipline of science diplomacy places a new focus on these resources while bringing to bear a greater understanding of their significance for ecosystems, economies and entire cultures. This approach has the potential to safeguard them for ourselves and for future generations.
Diplomacy, multilateralism, the role of states and the involvement of society are rapidly evolving. Science and technology are driving change but so are global challenges such as climate change, geopolitical tensions, migration, inequalities and nations’ efforts to achieve growth.

In order to tackle these challenges, it makes sense to accelerate the use of the opportunities offered by advances in science. But this depends on relations between scientists, politicians, diplomats, entrepreneurs and citizens — whose agendas, mindsets, experiences, as well as responsibilities, expertise and legitimacy to act differ fundamentally.

This complexity is difficult to integrate effectively into the reasoning of each party because it requires a minimum understanding of the contexts in which these different communities operate. The difficulty is amplified by the fact that these operations occur in economic and cultural contexts that are extremely different from one corner of the world to another.

In this context, scientific anticipation makes sense: an open dialogue with scientists can help politicians, diplomats, citizens, entrepreneurs collaborate in order to facilitate the resolution of emerging challenges of the future.

However, it is not enough for scientists to give one-off advice to politicians, or ideas to the private sector, civil society organisations and citizens.

On the contrary, as the two following essays show, we observe among the political and diplomatic authorities a growing demand for an anticipatory science diplomacy acting as an honest broker between the different communities and institutional agendas of each (political actors, diplomats, companies, media, citizens, civil society organisations, scientific global community, etc.) without shortcutting the political processes; be it:

• for accelerating the implementation of the 17 sustainable development goals set out in the UN’s 2030 Agenda within the next 10 years of which the 2021 SDG Report provide the status of progress towards each SDG Goal.

• for taking up emerging challenges, in particular the 6 medium-term transformations presented by the UN at its 75th anniversary in 2020, in the UN75 Future Possibilities 2020 Report, which identifies six global transformations of systemic and global nature that will affect the world in 10 to 20 years:

  • The Exabyte Economy: Hyperconnected devices, data and people
  • The Wellbeing Economy: Redefining health
  • The Net Zero Economy: Scalable low-carbon solutions
  • The Circular Economy: Waste not, want not
  • The BioGrowth Economy: New agriculture and biomaterials
  • The Experience Economy: From ownership to usership
In parallel, the question of emerging technologies is increasingly drawing attention from the UN. The UN Secretary-General report on Our Common Agenda presented by António Guterres on September 10, 2021 frames the future of multilateralism as a choice between “breakdown or breakthrough” and contains recommendations for concerted action across four broad areas.

It calls for “A Summit for the Future” to address the main challenges of the 21st century and propose governance improvements to the international system.

The impact of emerging technologies on international affairs is also being discussed by various UN bodies notably the Security Council.

All these moves highlight the evolving nature of multilateralism, the role of science and technology as a driver of societal change but also contributor to solving some of the challenges of the 21st century.

That is why a demand is rising from all sides for a continuous interaction bridging science and diplomacy. In order to set the broader diplomatic frame in which science anticipation unfolds, we invited Swiss Federal Councillor Ignazio Cassis, Michael Møller, Chairman of the GESDA Diplomacy Forum, and Sir Jeremy Farrar as Member of the Board of Directors of the GESDA Foundation, to write about geopolitical trends, the main forces shaping a multilateralism in transition and the contribution of science diplomacy and the role of anticipation.

Contextualising GESDA’s Work Today and Tomorrow

Analysis of the geopolitical trends and a Swiss perspective on science diplomacy and a renewed multilateralism

Federal Councillor Ignazio Cassis, Vice President of the Swiss Federal Council, and Head of the Department of Foreign Affairs

While the global challenges become ever more pressing, it is increasingly difficult to create convergence within the international community. It is increasingly difficult to adopt new international law instruments. This trend results in an increasing use of soft law, which bypasses the role of parliaments and, thus, disrupts democratic processes. The domestic policy-making procedure is not fully exploited in relation to soft law, which reduces opportunities for meaningful political debate that would otherwise be available as part of the legislative process or in the context of approving international treaties.

Another trend is the use of science and technology within geo-political considerations. 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 have them.

We as nation states must reflect 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.

That brings me to science diplomacy, not really a new discipline, but it is now literally exploding. I am convinced that the hallmark of a 21st century global governance will be to fully capture what science and technology have to offer in terms of foresight, understanding, and solutions.

This is because of the phenomenon of the convergence of sciences – think of bio-, nano-, neuro-, info-sciences etc. This development is expanding the field of scientific discovery and significantly accelerating scientific progress.

All that will change the face of humanity and, hence, change the way humanity is governed globally. We don’t know what exactly that will be, but we know it will happen, and sooner rather than later.

This great convergence of science is a double challenge, for states as well as for international governance: for the states as the building blocks of the international community, and for international governance as the means the states go about their shared interests.

Switzerland’s position is precisely at this intersection. We are, on the one hand, a member of the international community, defending and promoting our interests, just like any other state.

But at the same time we are the Host State of International Geneva, one of the foremost centres of global governance and, indeed, the operational hub of the international system.

In that capacity, it is our declared ambition, and, may I add, our proven track record, to offer to the international community the best conditions possible for effective and impactful governance.

And so, to this double challenge Switzerland offers a double response.

Firstly, the domestic measures in terms of policy and organisation: we have reframed our foreign policy goals in our general Foreign Policy Strategy 2020-2023 and in a series of regional and thematic strategies, such as the Digital Foreign Policy Strategy.
As a consequence of these strategies, I have created a dedicated Digital Foreign Policy Unit in my Ministry which is headed by Ambassador Benedikt Wechsler and I have appointed Ambassador Alexandre Fasel as Switzerland’s Special Representative for Science Diplomacy, based in Geneva. I have amongst other things tasked him to draft, together with his colleagues at Foreign Affairs in Berne, Policy guidelines for science diplomacy, drawing also on the contribution of GESDA Foundation.

And secondly, GESDA Foundation - the Geneva Science and Diplomacy Anticipator producing this Science Breakthrough Radar, which has been conceived as a new tool at the service of effective multilateralism in Geneva and in the wider international governance.

Let me express five considerations on the vision which led to the creation of GESDA Foundation: anticipation, participation, impact, sense of urgency and universal aspiration.

1. Anticipation

All too often, the international community acts only when faced with the immediate effects of a major crisis.

We all know how World War II led to the redesign of the international system which is basically the same to this day. There is some hope that the current pandemic may give rise the new ways in international affairs. We shall see.

But my point is this: Would it not be a sign of maturity, if the international community were able to act earlier, based on anticipation providing a good understanding of the challenges and opportunities ahead? I think it would - and I am happy to see that this is what GESDA Foundation sets out to achieve.

2. Participation

We all know from experience in preventive diplomacy regarding mass atrocities that early warning is good, but in fact not enough. Early action is critical. But who feels really responsible to act in a timely manner upon clear signs of things to come?

This raises the question of participation, which I consider as important as anticipation.

We need to involve all those in our work we seek to influence and support with our foresight. What is commonly referred to as the multi-stakeholder approach is not new in international affairs.

I very much appreciate the GESDA Anticipatory Situation Room. It is a good thing, but not enough: We shouldn’t forget that we are an intellectual elite with a weak democratic legitimacy and must make sure that our work on the international level is grounded in our domestic democratic structures and processes.

3. Impact

But participation is not the solution as such. It is rather the method by which we build convergence and realise concrete solutions to practical problems that have been anticipated.

Here lies finally the legitimacy of what we are doing. The international community at large, states and non-state actors, will be judged by their actions and by the impact they have.

That is also true for what we are trying to achieve through the GESDA Foundation.

4. Patiently with a sense of urgency

What we are trying to achieve with GESDA is new and, hence, difficult.

To link anticipation – that looks far ahead – with action – that is immediate – is a major challenge in itself. And the method by which we are attempting to do it is new and challenging for all the participating scientists, diplomats, policymakers, citizens, private sector players and philanthropists.

But do have we the choice? I personally haven’t seen any better proposal yet on how to use science diplomacy at the service of a 21st century governance of world affairs. We have to get into it - patiently but with a sense of urgency.

5. Universal aspiration

With the GESDA Foundation we are creating an instrument that is based in, and operates out of Geneva.

That seems natural on account of Geneva’s significance as a global centre of governance.

But our aspiration is universal.

We are working for the global commons, and when this work is not happening in Geneva, then Geneva content and Geneva methodology can be brought to the fore whenever and wherever the conversation is taking place.
Opportunities - Taking the Pulse of Diplomacy

Multilateralism in Transition

Michael Møller, Chairman of the GESDA Diplomacy Forum, former Under Secretary-General of the UN in New York, Director-General of the UN Office in Geneva from 2013 to 2019

We are all painfully aware that the past year-and-half has put the world at large through a massive existential test. COVID-19 has revealed dramatic failures of our societies: long-ignored environmental crises, economic and social inequality, political ineptitude, social divides—all of this and more has been brought into painful focus by the global pandemic.

A bleak picture, to which I would like to answer by, perhaps counterintuitively for some, sounding a counter-note of optimism.

An optimism rooted in experience and based on fact: the experience of the past 7½ decades, and the extraordinary progress they brought humanity.

If you were born today, and in spite of the headlines bombarding us with negative news, the current pandemic and the current geo-political tensions, you will be less likely to live in poverty; less likely to be illiterate; less likely to confront intolerance and oppression; and less likely to be killed in a war than at any time in human history.

These achievements happened over the course of just a few decades. And all that progress is real. It has been broad, and it has been deep.

The last 75 years have brought a level of peace, rights and well-being to humanity that quite simply has never been seen before. And it’s no accident that the progress we have achieved since 1945 coincided with the establishment of a multilateral structure with the United Nations at its heart.

The audacity of the ideas that underpinned the creation of this multilateral architecture remains astounding to this day: to replace violence with the rule of law as the basis for global governance; to give each state—whether rich or poor, large or small—one vote; and finally, to declare human rights unconditional and universal.

Of course, there were, and are, places in which reality made, and still makes, a mockery of these ideals. But not only did we avoid open confrontation between the superpowers—and with it a third world war—war itself came to be considered “illegal”, an idea that would have seemed simply absurd to earlier generations.

And with these political changes came sweeping economic changes, leading to the incredible gains in global wealth, in life expectancy and opportunity. Multilateralism in practice!

But not only did we avoid open confrontation between the superpowers—and with it a third world war—war itself came to be considered “illegal”, an idea that would have seemed simply absurd to earlier generations.

And yet, for all the peace and prosperity underwritten by the international structures put in place since 1945, today, we once again find ourselves engulfed in crisis— even before COVID-19 brought the world to its knees.

So, what happened?

Sometime over the past decades, a complacency set in—a naive belief as it turned out—that things would just invariably get better: that, despite some backsliding here and there, forward movement was inexorable and large-scale conflict a thing of the past. It was through this lens that many just assumed technological progress and globalisation would produce benefits that, ultimately, would reach all.

This complacency bred inaction, and the twin forces of globalisation and technological disruption, left unchecked, ultimately triggered the global backlash we are confronting today.

And so today we hear troubling echoes of the past—from eroding trust in the democratic order to the outrage at rampant inequality.

But what concerns us today has to do with the breakdown of global cooperation, with the return of international politics as zero-sum competition, with the weakening of international solidarity—a sad and worrying reality, reinforced by the global mismanagement of the pandemic and its economic and financial fallout, that we all live in, and suffer from, today.

The international system that was built 75 years ago, and has served us extremely well, is no longer able to deal effectively with the challenges confronting us. We no longer live in a bipolar or unipolar world; our world is increasingly becoming multipolar. And we are in a chaotic transition phase.

For example, the relationship between the three most important powers—the United States, China and Russia—has rarely been as dysfunctional as it is today. The weaponisation of the pandemic by China and the US, and their increasingly robust race towards technological supremacy are some of the clear examples of the move away from a rules-based order to one of greater power competition.
The examples are proliferating every day. This evolving process of geopolitical polarisation is happening in a more economically interconnected world and all indications are that technology rather than ideology will be the determining element in the evolution of Great Power spheres of influence.

Power relations are becoming unclear; with the fragmentation of actions; with impunity and unpredictability prevailing; and with national and isolationist agendas superseding mutual trust and international cooperation.

The point here is, unfortunately, that we have been there before — and that should worry us. Multipolarity without strong and accepted multilateral instruments — just as we saw in Europe in the wake of the First World War — might be a factor of some equilibrium, but it is certainly not a factor of peace. It’s inherently unstable, volatile, and dangerous.

Yet to say that the world is poised on the brink of another 1914, as some suggest, is too simple. International relations work differently today, and so does politics.

One obvious difference is the diffusion of power. Power that used to be firmly in the hands of the state has metamorphosed into something much more diffuse. Whether it is non-state actors challenging the state’s monopoly of violence; whether it is private corporations evading effective regulation by any one state (and some having greater financial clout than many states); whether it is wealthy private individuals with the means to affect international social and economic realities; power, and therefore governance, in international relations today is altogether a more complex, messy affair.

Whereas in the past, international relations were centralised — with core and periphery, with top-down commands and control — today, we live in an “age of entanglement”. Global politics has been reconfigured. The traditional “chessboard” of inter-state diplomacy may still exist, but it is joined by a new complex web of networks made up of governments, parliaments, companies, cities, NGOs, terrorist groups, philanthropists and countless others, all wielding influence and cooperating or clashing at various points in time.

In response to all of this, multilateralism is changing too. We seem to be moving towards what, Pascal Lamy1 calls Polyilateralism which, by necessity, must, and hopefully will, become more collaborative, more integrated, more networked, more inclusive and more preventive — with its legitimacy conferred by the results and impact of its actions, not by the reality of its structural existence. The upshot is that today, and certainly tomorrow, a multiplicity of different actors will be part of the networks that will have a role in defining the way multilateral global governance will evolve.

And the need for these intricate connections is mirrored by the major existential challenges we face, which are more and more interlinked; and are more and more interfering with each other: whether in addressing the looming climate calamity; the collapse of biodiversity; the growing inequality; the fever pitch of geopolitical tensions; the onslaught of new technologies, or indeed a global pandemic.

None of these challenges emerged in a vacuum. The prosperity we have enjoyed these past decades has clearly come at a steep price. Our planet is in dire straits; our very survival may be threatened. And we are now facing a global crisis of trust, challenges threaten to overwhelm us just as interests fragment, power is diffuse, and the only constant is disruptive change.

Where do we go from here? The answer has everything to do with a re-invented multilateralism in general, and the 2030 Agenda for Sustainable Development, our collaborative and integrated global roadmap for the way forward, in particular. Because even now, as we see entire regions set back years in a matter of a few months by the pandemic, as millions of people are being pushed into extreme poverty, I am convinced that the only credible path forward is multilateral.

If anything, Covid-19 has reinforced the urgent need for a renewed and more effective multilateralism. This crisis is not a failure of the notion of multilateralism. The temporary failures of our governance systems that we are living through right now lies in the absence of multilateral actions defined by an increase in nationalistic, inward-looking, defensive postures.

The operative word here is temporary — because we simply have no choice but to revert to international cooperation and solidarity if we want to ensure a healthy future for our planet: a collaborative system that is also strongly based on gender parity, geographical diversity and inter-generational dialogue. Today we have a surplus of multilateral challenges and a deficit of multilateral solutions.
Opportunities - Taking the Pulse of Diplomacy

In that context, the importance of science and technology in how we manage the problems of our world and in how we shape our future is becoming more evident than ever. And this is where the GESDA Foundation, the Geneva Science and Diplomacy Anticipator and the new focus on science diplomacy comes in. As you all know the GESDA Foundation was created to help ensure that the technologies of tomorrow are shaped to maximise their benefit to humanity and, in doing so, to provide tangible proof that truly collaborative, multilateral approaches to problem-solving have the best chances of success. It does so by anticipating the science of tomorrow and aligning it with the global needs of tomorrow. Anticipation ensures better prevention and thus better and more impactful action.

GESDA seems to have caught the new geopolitical reality at the right time. The global governance transition we have been living in for some years now is beginning to crest, and has brought the world to a fork in the road. To one side we move further down the road of nationalism, division, fragmentation and the increasing abandonment of a multilateral management of the affairs of our planet. To the other side lies a reinvigorated sense of solidarity that translates into a new determination to collaborate in the search for urgent solutions to the massive existential challenges humanity is faced with. A collaborative, integrated, de-siloed, networked and preventive polylateral structure that may give us a chance to secure a sustainable and liveable planet.

The GESDA model we are in the process of elaborating, the objectives that we have set, the subjects we have chosen to deal with, the extraordinary people who have chosen to associate themselves with our initiative, the growing universal interest in our activities by scientists and policymakers alike, as well as by the public, tells us that GESDA is well on its way down the latter road.

We are leveraging the proven ability of scientists across the globe to work across geographical and political divides, and the growing realisation in policy-making and project implementation circles that science needs to be brought back urgently to the decision-making table. In doing so, I am convinced that GESDA will be able to contribute in a major way to the development of powerful solutions to the major existential problems facing humanity, and in so doing, help reinstate the indispensable trust in science and in the ability of leaders, political and otherwise, to deliver the required solutions for the maintenance of our future well-being — and thus to do its bit to nudge the world down the right road.

As we look ahead — to building forward better, to coming out of this stronger — we do well to remember the lessons of the past. Not everything has to be reinvented. Some of it has to be reinforced and reapplied. We have, and will have, the knowledge and expertise, the tools, resources and instruments we need to overcome the current existential challenges, whether in health, climate, development, corruption, armaments, finances, technology etc. But we need to strengthen our collective will to act. From the awakening that this current crisis is triggering, we have a chance, and the responsibility, to create a more preventive and effective polylateralism in which everyone can and must play an active part.

International Geneva, the capital of so many of the initiatives that daily impact human lives the world over — in peace, humanitarian action, human rights and now, also in action in the digital and new technologies sphere, among many others, the operational heart of the multilateral system, a city whose unique ecosystem contains a multitude of international organisations, some 700 NGOs, representatives of over 180 states, a large and vibrant private sector and world-class academic institutions, is the place where — every day — new partnerships are formed and innovative solutions are developed to improve the lives of people the world over.

That is what the GESDA Foundation is being built to do as an important catalytic building block towards a new, effective, polylateral governance structure.

1 Pascal Lamy is currently President of the Paris Peace Forum representing the Mo Ibrahim Foundation in the Executive Committee. He served as Director of the World Trade Organisation (WTO) in Geneva from 2005 to 2013. He chaired the Commission that edited the 2013 Oxford Martin Report “Now for the Long Term”.

The GESDA 2021 Science Breakthrough Radar
Anticipation in Diplomacy: the lessons of a pandemic

Sir Jeremy Farrar, Director of the Wellcome Trust in London, Member of the Board of Directors of the Geneva Science and Diplomacy Anticipator Foundation (GESDA)

Why did Covid-19 catch so many countries so unprepared and then unable to respond?

After all, just such a pandemic has been widely predicted for many years, and many governments should, on paper, have been well equipped to respond.

The problem is social and political myopia. We are not looking deeply enough into what the future might hold.

Some of those hit hardest by Covid-19 — the UK and the US notable among them — in principle had plentiful social and economic resources to deal with a novel pandemic, including detailed plans for tackling one.

But in practice those proved inadequate in the face of its complex health, social, economic and political ramifications.

The result was indecision and delay, with some politicians who apparently believed matters should simply run their course failing to mount any meaningful response at all during the critical early phase of the pandemic.

Such fatalism is unwarranted.

We cannot control the future, or predict it, but the history of humanity is one of acting today to prevent — and when needed mitigate — problems we might encounter tomorrow. The challenges we face are complex, but that does not mean we cannot anticipate the risks they create.

On the contrary, we have predictive models of remarkable power and increasing precision, as well as unprecedented capabilities to act on them. No previous generation could have understood the spread of Covid so well, or created drugs and vaccines against it, as we have done.

But we have to learn the lessons of this crisis and commit to doing better when another inevitably arises. And to do better, we need to get better at anticipating what the future may hold.

The best place to start is with emerging science and technology, which is key both to developing tools that help us anticipate what is coming and building the resilience to deal with it.

We were fortunate that we could turn to early research and development on vaccines for other epidemic threats (MERS and SARS-1) and to other fields (oncology) for the mRNA-based vaccines which have been crucial in tackling Covid-19.

Under-appreciated advances in other fields may also hold the keys to other 21st-century challenges, such as climate change, biodiversity loss and socio-economic inequality.

Identifying future trends and those critical advances is a key objective of the Geneva Science and Diplomacy Anticipator (GESDA) Foundation on whose Board I sit. This radar is the first report setting out socially significant research areas.
But this is not in itself enough. Covid has seen a catastrophic failure of global diplomacy, with vaccine nationalism now delaying the exit strategy from this pandemic.

Many of the other challenges we face are also inherently global and multidimensional: to pick one example, climate change respects national boundaries no more than Covid does; and its consequences are both complex and myriad.

Science will be central to identifying and solving them, but anticipating them will require more than science alone: political vision and diplomacy are also needed if we are to avoid a dangerously fragmented and inequitable world.

So a second part of GESDA’s mission is to bring together all the parties needed to tackle these challenges — not just natural scientists and technologists, but also those working in the social sciences and, crucially, in the policy, governance, investment and citizen or industrial communities.

This represents a far broader range of participants than is typical of the foresight activities currently carried out by most governments, national academies or think tanks.

In the Swiss tradition of multilateralism — GESDA was established by the Swiss government, and is deliberately hosted in a neutral, international city — we seek to ensure that there is representation from all over the world.

We hope to welcome this broad spectrum of delegates to our inaugural Summit in Geneva this October 2021 — a hope which itself depends on the continuing effectiveness of multilateral, collective and cross-disciplinary action against Covid-19.

Virologists and epidemiologists helped us understand Covid-19, but responding to it has required government, international agencies, behavioural specialists, academia, big pharma companies, economists, philanthropists, and more working in close concert.

Anticipating the need for such coalitions, and assembling them in advance rather than reacting to them after the fact, will help us mitigate against loss of wellbeing, life and prosperity.

But the lessons we could learn from Covid are in danger of being forgotten already.

We are on the verge of the rich world neglecting the needs of everyone else just when those needs are greatest.

In a globally integrated world, mutual co-operation is a matter of enlightened self-interest, not charity. A fragmented world is always a dangerous world, all the more so given the global nature of the challenges we face.

Covid-19 is the first really acute crisis of the 21st century and the first real test of the global science, political and diplomatic system. It has not gone well. We cannot allow the same approach to pervade the other great challenges of the 21st Century.

Other than perhaps during the Apollo 11 moon landing, there has been no time in my life when science has been so front and centre in people’s lives.

That engagement, born of necessity, must be turned to good use, but we all have work to do here.

Scientists need to take their place at the table, rather than declining to take responsibility.

Policymakers need to recognise and engage with what the science is advising them and be willing to act before they feel they have to react; and industry needs to re-discover purpose beyond profit.

GESDA hopes to provide a forum for that meeting of minds to take place: the Geneva Science and Diplomacy Anticipation Summit. No one individual can see what the future holds; but together, we can do our best to anticipate it, prepare for it and learn how to respond earlier and better to its challenges.

The future of humanity depends on it.

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

radar.gesda.global/op3
Opportunities

Anticipatory Science in Practice

Examples of International Organisations

Many multilateral actors already engage in anticipatory science diplomacy in order to fulfil their missions. Confronted with the high pace of science and technology and its impact, finding ways to anticipate trends and translate this knowledge into practical tools has become essential for many organisations.

This section provides four short examples showing how selected actors engage in science anticipation in practice, what it means for their work and what challenges they see. Their views are based on three questions and were collected through interviews and written statements. Their responses represented the views of the experts consulted and offer a practical grounding for thinking about anticipatory science and diplomacy and how the GESDA Science Breakthrough Radar can contribute to some of the world’s current challenges. We asked the following questions:

1. What does your organisation do already to integrate advanced science and technology into its work?
2. In which domains of your work would anticipatory science be most useful?
3. What are the difficulties in anticipating and what is the added-value?

Ulrike Till
Director IP and Frontier Technologies Division, World Intellectual Property Organization (WIPO)

Science and innovation are in the DNA of WIPO, which is sometimes called the world innovation agency. WIPO is integrating advanced science and technology in its work in three different ways. First it uses cutting-edge technology to expand or develop new tools to make its services easier, more accessible, faster and more efficient. An example of this is the use of artificial intelligence for translation, automatic text and image recognition. Second, WIPO is constantly scanning technologies that might potentially be disrupting the IP field, such as, for example, blockchain, on which WIPO is preparing a white paper. Thirdly, there is the broader horizon-scanning where WIPO tries to identify technologies further down the road that could support the mission of WIPO, innovators and creators, or impact the global IP system. WIPO aims at fostering a balanced system that works for everyone and this requires sharing information, exchanging views and building the necessary resources.

One of the difficulties with anticipation is to find the time to balance the urgency required by the present while allowing space for reflection on the longer-term issues. Having the ability to step back and reflect in order to anticipate future science and technology developments brings real benefits. Also, as the issues get deeper — especially in the context of IP issues — there is a need to introduce a level of simplicity and explainability in issues that are becoming ever more complex.

Science and technology anticipation has huge value if it is able to develop the language to make its insights understood beyond the core group of narrow specialists. As science and technology is developing at a very rapid pace, with very complex implications, the right communication tools are needed to make sure that the knowledge gap between stakeholders is not widening.

This raises another challenge, which is to gather a broad range of stakeholders with very different backgrounds, knowledge, and levels of understanding about the issues involved, to discuss advanced science and technology. The difficulty lies in convening these discussions without giving the impression of an implied agenda. This requires a lot of information sharing and a transparent and open way to engage in a topic.

Finally, there is a need to strike a real balance: our faith that future science and technology breakthroughs will help to solve some of the big challenges must be weighed against the fact that some of the issues that we are facing now could be alleviated in the present by focusing on behavioural or societal measures.
On the UNDP Accelerator Labs:

‘All 60 Accelerator Labs became fully operational in 2019, bringing new talent and skills into UNDP. [...] In 2020, the 60 Accelerator Labs addressed 147 development challenges covering all 17 SDCs. They introduce a new way to work within UNDP that consists of identifying key learning questions and a roadmap of activities (e.g., experiments, explorations, mapping grassroots solutions and partnerships) to understand sustainable development challenges better and generate learnings faster. Last year, the Accelerator Labs also documented over 1,700 grassroots solutions and used 48 different innovation methods and approaches’

Innovating in an Uncertain World: One Year of Learning and Breakthroughs - UNDP Accelerator Labs 2020 Annual Report

The United Nations Development Programme (UNDP) works at the applied end of science and technology. Through its network of Accelerator Labs, today consisting of 91 labs covering 115 developing countries, UNDP looks to understand what is working on the ground, in terms of the solutions that people are finding for the problems they face. A strong focus is on how to find, share and scale technologies that are applicable in very local development contexts.

Traditionally, the strategy with development was to go into a developing country, to try to understand its problems, and then to bring a solution in from elsewhere. But the reality is that it doesn’t work that way. Long before any development worker turns up in a location and tries to solve a problem, the people in that location have been working on solutions. Therefore, UNDP – through the Accelerator Labs in particular – builds up capacity to find and understand the local contextualised solutions that people are building for existing challenges, so that these can be tested, shared and scaled elsewhere. By connecting and combining portfolios of local solutions in this way, larger scale change can be catalysed.

Interestingly, when considering the science and technology components of the solutions, quite a few use advanced technologies. This is particularly true in the digital realm, where it is quite easy as a local entrepreneur to have access to cutting edge materials or tools such as 3D printing, which allow local production of even quite advanced solutions. The ability to make local products, at cheap cost and at scale, exactly where they are needed, is going to be transformative in a number of different sectors.

UNDP frames innovation not just as technology, but also considers social innovation, policy innovation or economic innovation. The Accelerator Labs in particular also look for innovations in terms of different social structures or different policy-making approaches. Solutions to concrete problems such as climate change, food systems or access to jobs and opportunities require understanding of local contexts and a stack of solutions across scales and sectors.

One of the elements that is important in policy discussions with governments is to understand which technological innovations are on the horizon. However, it is not about picking or advocating specific scientific solutions, but rather about creating the space where policy discussions that genuinely and rigorously look at options can take place. With the pace of the challenge we are facing right now increasing almost exponentially, this is vital. Conversations about governance arrangements needed for the development and application of science and technology need to happen in an open space without implying that they are being endorsed.

One of the biggest, most frequently-encountered challenges with working in the policy space is the degree to which policymaking genuinely understands the pace at which change is happening. In most countries, including the most advanced, policymaking still under-appreciates the scale of exponential changes in climate science, material systems, food systems, and others. On top of that, policymakers have to make decisions today that will often have implications for the next 10 or 20 years. The exponential rate of change creates a dilemma where policy decisions that prioritise short term needs and perspectives also need to catch up as things move forward. This is very expensive and increasingly unaffordable for a range of countries.
The question here is how are we to build the loop between the anticipatory perspective and the concrete policy and capacity-building support UNDP provides on the ground? Part of the answer is to make policymakers understand that anticipation does not mean prediction. What is going to happen in 25 years can’t be foreseen. It is possible, however, to build analytical and policymaking skill sets that anticipate potential developments and create policy decisions that maximise potential benefit.

For UNDP, the main domains of actions relevant to science anticipation are climate change, planetary emergency, energy production and the digitalisation of almost every form of human interaction. In those areas, having the ability to sense what is likely to come out of the scientific and technology pipeline helps to inform governments about how to create the policy space to maximise the positive impact. This is where we see the biggest use and benefit of GESDA’s Science Breakthrough Radar.

Equal access to technology and connectivity (and by extension to advanced science and technology) are two themes of increasing relevance to efforts to accelerate the implementation of the SDGs. With the Covid crisis, this trend has only been amplified. At the SDG Lab, we have worked at a very operational level through the “convening/connecting” of different partners to incubate concrete partnerships, such as that between the International Telecommunication Union (ITU) and the Government of Niger, that support countries’ work to accelerate the access to connectivity and technology for all, in order to accelerate SDG results. At the policy dialogue level, we are currently working on identifying the most intelligent entry point that the SDG Lab could use to add value on the “very trendy” digital/technology/connectivity (DTC) trend. We are noticing that there is a growing pattern of DTC being portrayed as the silver bullet to reaching the SDGs, yet we are hearing from several governments and other stakeholders that we need to caution against this trend, as DTC is only a means to an end.

In a nutshell: countries could have access to all the DTC in the world, yet this would still not be enough to ensure equal access and to solve the major global challenges of our time (SDGs), as the needs for education, skill development, infrastructure etc. will persist. The SDG Lab is therefore thinking of taking up this “mismatch” between the growing narrative of DTC (by extension advanced science and technology) being the silver bullet and the reality on the ground. The aim is to encourage very open debates on the matter, with all relevant stakeholders (member states, UN, science, academia, NGOs, private companies etc.). We believe that Geneva is the perfect place to do so because of the presence of many of the key actors.

When reflecting on the value of anticipatory science, it would be particularly relevant to bring information about “what’s cooking in the labs” to informal discussions with, and among, member states of the UN and other stakeholders, including all the SDG active actors of International Geneva (the Geneva 2030 Ecosystem), through for example, the SDG Lab. This would allow member states and other actors to be aware of the upcoming future science trends and, when relevant, act upon them earlier rather than later. It would also allow stakeholders to appreciate the future political trends, so that the relevant actors can anticipate and start to build the bridges that are needed between science and diplomacy, prior to the anticipatory science becoming reality.
The SDG Lab would welcome anticipatory science as a key domain to help anticipate the trends that will influence the SDGs (and the next generation of SDGs). Conversely, this would help an entity like the SDG Lab to think ahead (anticipate) and identify the political debates that it (and other UN and non-UN partners) could help make happen.

From a political point of view, anticipation is never a very easy sell because there is already so much today that needs our immediate focus, time, and resources. This may have changed with Covid, which demonstrated how fundamental it is to anticipate. It would be very helpful to gather a series of real situations (such as Covid) and look at how anticipation on trends in science and in geopolitics could have provided a different outcome.

There is a unique opportunity today, through GESDA and Switzerland’s engagement in Science Diplomacy, to bring these issues to the forefront of political and policy debates. Let’s build on this momentum.

The International Committee of the Red Cross (ICRC) operates worldwide, helping people affected by conflict and armed violence, and promoting the laws that protect victims of war. Since it was established in 1863, the ICRC has continuously adapted to respond to people’s evolving needs in the best way possible. The organisation explores, tests and pilots new and emerging technologies, seeking opportunities to address problems and anticipate disruptions. One example is the partnership recently set up with the Swiss Polytechnic Schools EPFL & ETHZ – through which ICRC engages in cutting-edge projects that involve geospatial imagery, artificial intelligence, privacy-enhancing biometrics and a range of other technologies.

In the context of the ICRC, science anticipation is critical because the deployment and use of cutting-edge technology may impact people affected by conflict and violence. This is where it becomes important for the ICRC to understand the use and potential harm of those technologies. This ranges from the implications for the automation of warfare raised by AI and machine learning to, more broadly, the intertwined futures of environmental, human and animal health.

A key challenge with anticipatory work is translating it into terms that are relevant for practitioners — in the case of the ICRC, people who are busy dealing with emergencies every day. What does this mean for the problems they are already facing? A clear “so what?” is central to unleashing our collective intelligence.

The ICRC believes that strategic foresight is essential to developing the right approaches and skills to respond to tomorrow’s challenges. To this end, the ICRC is currently setting up a Strategic Foresight Forum — ICRC in 2040 — to explore future influences and disruptions to our mission and mandate by analysing perspectives from our staff and communities affected by conflict. Perspectives and insights from GESDA and other entities committed to anticipation are also being integrated into that context.

Federica du Pasquier
Strategic Advisor to the President · International Committee of the Red Cross - ICRC
What’s Next

After only 24 months of existence, the GESDA Foundation is going public by organising the first global Geneva Science and Diplomacy Anticipation Summit.

**What’s next - starting the discussion on 16 themes**

Building on the contents of the Science Breakthrough Radar, the Summit will act as an anticipatory situation room where the science breakthroughs most likely to impact people, society and the planet at 5, 10, 25 years are presented and discussed by a broad community composed of representatives from science, diplomacy, philanthropy, business and civil society.

The Summit kickstarts an open forum discussion on the implications of emerging science breakthroughs for international affairs and global governance. Under the framework of the SDG and the UN Secretary-General’s Common Agenda for the Future, it will host debates on whether and how diplomacy should embrace these advances for the greatest benefit of humanity.

This inaugural meeting will discuss 16 themes with the potential to transform the world. Discussions are informed by the Science Breakthrough Radar, an anticipatory tool for multilateralism that disseminates knowledge to the broader international community to help accelerate discussions about the potential impact of science breakthroughs for diplomacy and translate this knowledge into concrete solutions.

The science and diplomacy anticipation Summit launches a global consultation on the Science Breakthrough Radar that will keep it as a continuously updated rolling tool mapping advances across the four scientific frontier domains: advanced artificial intelligence and quantum revolution, human augmentation, eco-regeneration and geengineering, and science and diplomacy.

The Summit kickstarts the joint discussions on what needs to be done to maximise the benefits of science anticipation in order to fulfil GESDA’s aim to “use the future to build the present”.

The details below provides an overview of the 16 topics discussed at the inaugural summit, which will guide the participants in the work on initial solution pathways.

The 16 themes of the Geneva Science and Diplomacy Anticipation Summit at a Glance

**What?**

Sessions with a focus on anticipating what is cooking in the labs at 5, 10, 25 years.

**Human Augmentation**
- Engineering Pathways for Radical Health Extension
- Negotiating the Boundaries of our Genetic Future
- Learning from the COVID-19 to Prepare the Response to the Next Systemic Crisis

**Eco-Regeneration & Geo-Engineering**
- Utilising Space Resources for Collective Prosperity
- Advancing Science for Ocean Stewardship

**Science & Diplomacy**
- Reviving the Human Right to Science (linked to the forthcoming Brocher Symposium, December 2021 in Geneva)
- Designing an economic Compass for Sustainable and Resilient Societies

**So... What?**

Sessions with a focus on accelerating the discussion about the potential impact of science Breakthroughs for Diplomacy.

**Quantum Revolution & Advanced AI**
- Opening Quantum for the Benefit of Humanity
- Co-developing Accessible Advanced AI

**Human Augmentation**
- Establishing Neurorights

**Eco-Regeneration & Geo-Engineering**
- Accelerating the Active Decarbonisation of the Planet
Science & Diplomacy
- Revitalising Multilateralism through Anticipatory Science and Diplomacy
- Building Digital Models toNavigate the 21st Century’s Complex Ecological and Social Systems

Now What?
Session with focus on the tools we need to develop in order to translate into solutions this knowledge on those frontier issues.

Science & Diplomacy
- Enriching Science with Citizen Voices and Values
- Making Sense of Science Anticipation for Concrete Impact
- Catalysing Inclusive Growth through Anticipatory Science

The program of the Summit provides the rationale and the questions to be addressed for all the themes. The discussions will be summarised in the Proceedings of the Summit and taken into account in the 2022 edition of the GESDA Science Breakthrough Radar.
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 18 listed emerging topics as well as the collection of GESDA Best Read articles that appear throughout the radar.

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 Debates and Trends sections of the report.

For more information visit:
radar.gesda.global/apm

Cited Key Resources

Each of the 18 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 subfields 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