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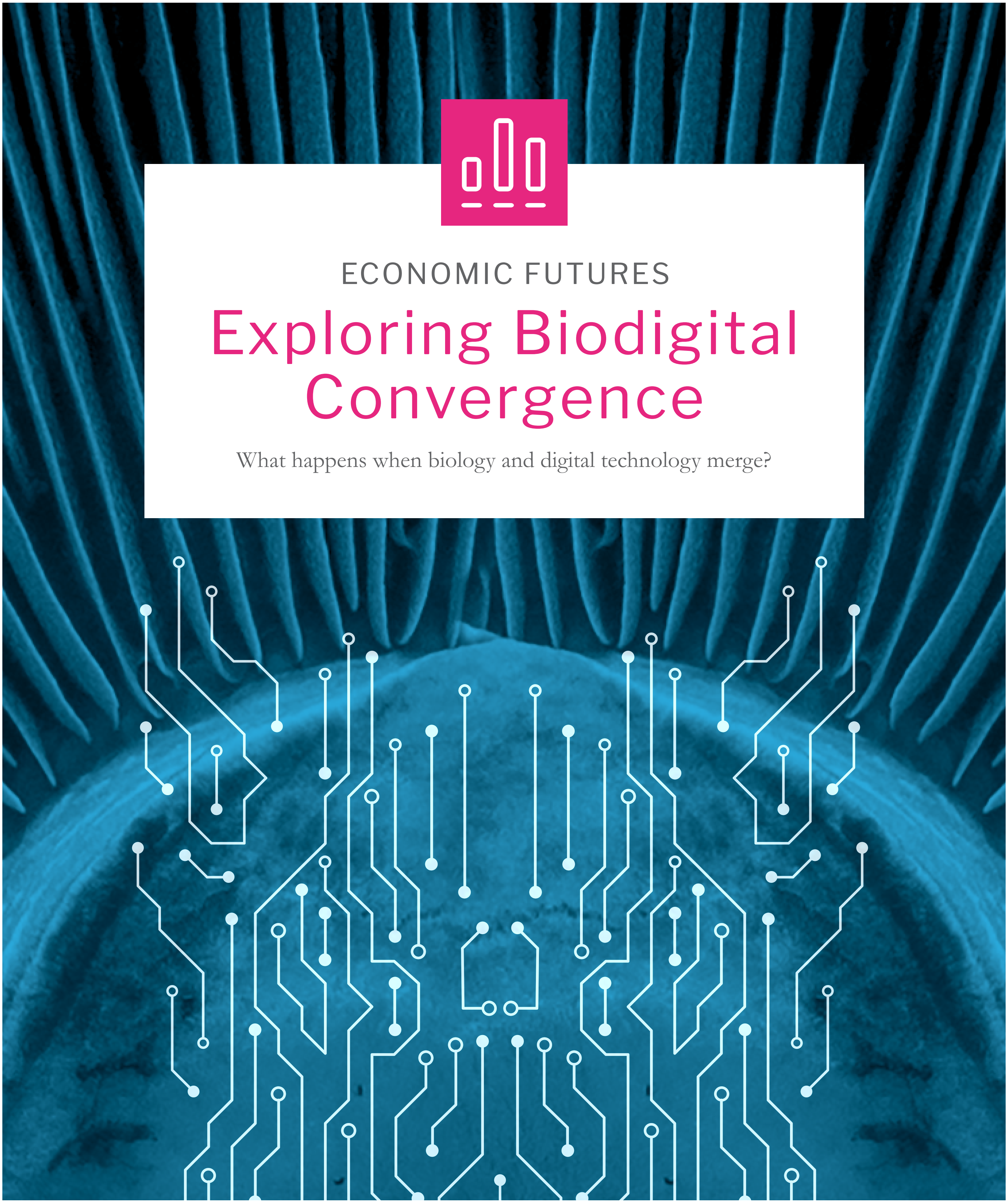

ECONOMIC FUTURES

Exploring Biodigital Convergence

What happens when biology and digital technology merge?

Canada

Exploring Biodigital Convergence

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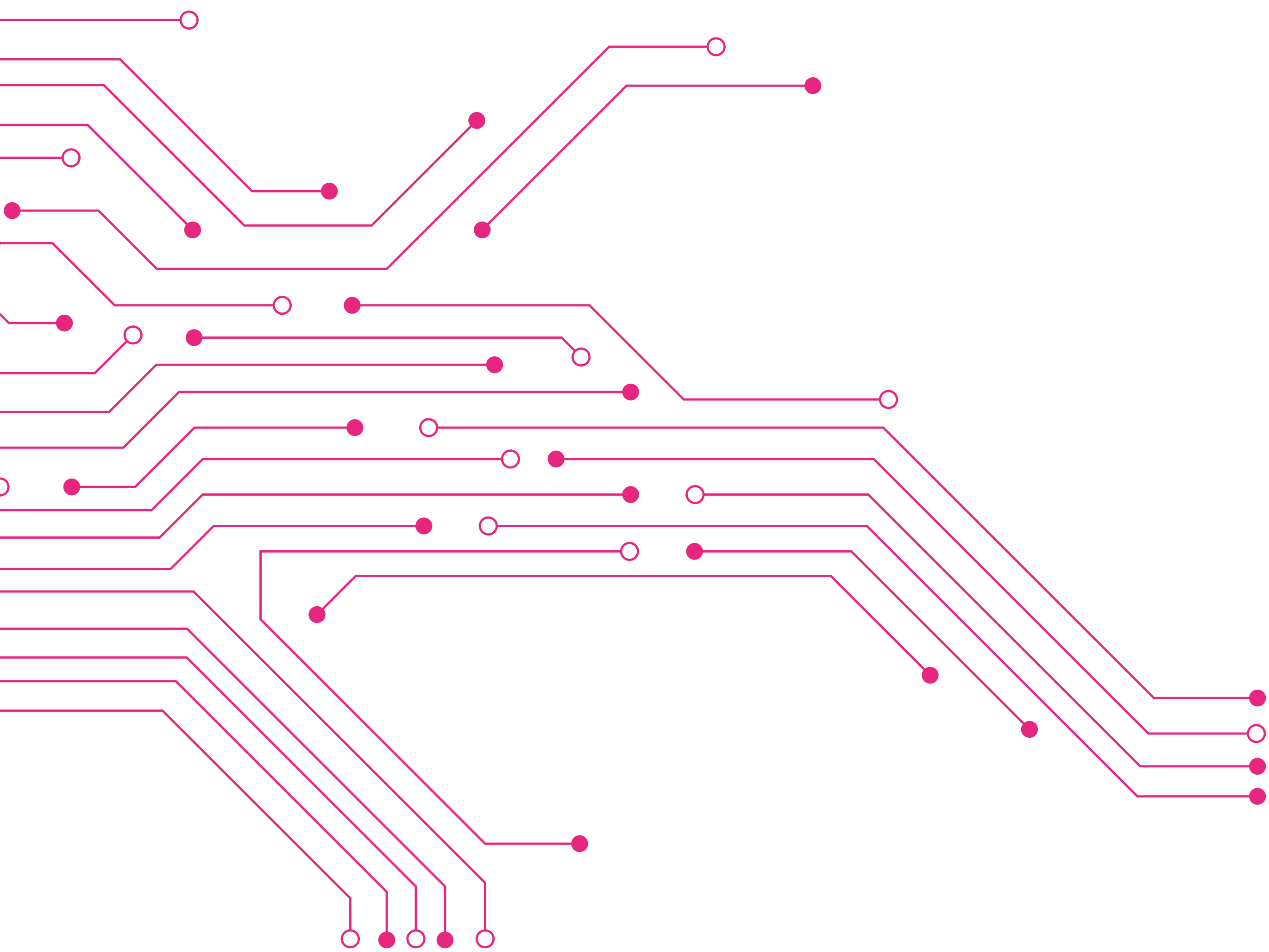

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Foreword

In the coming years, biodigital technologies could be woven into our lives in the way that digital technologies are now. Biological and digital systems are converging, and could change the way we work, live, and even evolve as a species. More than a technological change, this biodigital convergence may transform the way we understand ourselves and cause us to redefine what we consider human or natural.

Biodigital convergence may profoundly impact our economy, our ecosystems, and our society. Being prepared to support it, while managing its risks with care and sensitivity, will shape the way we navigate social and ethical considerations, as well as guide policy and governance conversations.

Guided by its mandate, Policy Horizons Canada (Policy Horizons) intends to start an informed and meaningful dialogue about plausible futures for biodigital convergence and the policy questions that may arise. In this initial paper, we define and explore biodigital convergence – why it is important to explore now, its characteristics, what new capabilities could arise from it, and some initial policy implications. We want to engage with a broad spectrum of partners and stakeholders on what our biodigital future might look like, how this convergence might affect sectors and industries, and how our relationships with technology, nature, and even life itself could evolve.

We welcome your comments and participation, and look forward to diving more deeply into the questions raised in this paper.

Kristel Van der Elst

Director General
Policy Horizons Canada

Summary

In the late 1970s and early 1980s, Canadians and policy makers began to understand that the digital age was upon us. Early movers seized opportunities, grappled with challenges, and initiated deft policies that have provided benefits for decades. We continue to see the powerful effects of digitization, and more are surely to come. But we may be on the cusp of another disruption of similar magnitude. Digital technologies and biological systems are beginning to combine and merge in ways that could be profoundly disruptive to our assumptions about society, the economy, and our bodies. We call this **the biodigital convergence**.

This paper sets out an initial framing to guide Policy Horizons' upcoming foresight work.

Three ways biodigital convergence is emerging

1. **Full physical integration of biological and digital entities**
2. **Coevolution of biological and digital technologies**
3. **Conceptual convergence of biological and digital systems**

Biodigital convergence is opening up strikingly new ways to:

- Change human beings – our bodies, minds, and behaviours
- Change or create other organisms
- Alter ecosystems
- Sense, store, process, and transmit information
- Manage biological innovation
- Structure and manage production and supply chains

Possible characteristics of the biodigital system

- Democratization
- Decentralization
- Geographic diffusion
- Scalability
- Customization
- Reliance on data

Initial policy-relevant questions

Economic

- Could traditional resource-based competitive advantages fade?
- Would education and training systems need to be adapted to address potential skills gaps?
- What could data protection and intellectual property frameworks look like in the biodigital era?
- How can policy foster a competitive business environment in a biodigital world?

Social

- Could social attitudes shift towards health and lifestyle?
- What policies could help address health inequality?
- What policies could foster trust among partners and stakeholders?

Environmental

- What changes could occur in land use and the natural environment?

Geopolitical

- What policies are necessary to compete in a global biodigital world?
- What is needed to protect citizens' security in the biodigital world?

Governance

- How can regulation and policy making take social concerns about biodigital advances into account?
- Is the current tax framework suited for the biodigital world?
- Do public finance systems need to be reassessed to be sustainable in the biodigital world?

What is biodigital convergence?

Biodigital convergence is the interactive combination, sometimes to the point of merging, of digital and biological technologies and systems. Policy Horizons is examining three ways in which this convergence is happening.

1 Full physical integration of biological and digital entities

Digital technology can be embedded in organisms, and biological components can exist as parts of digital technologies. The physical meshing, manipulating, and merging of the biological and digital are creating new hybrid forms of life and technology, each functioning in the tangible world, often with heightened capabilities.

Robots with biological brains[01] and biological bodies with digital brains[02] already exist, as do human-computer and brain-machine interfaces.[03] The medical use of digital devices in humans,[04] as well as digitally manipulated insects such as drone dragonflies[05] and surveillance locusts,[06] are examples of digital technology being combined with biological entities. By tapping into the nervous system and manipulating neurons, tech can be added to an organism to alter its function and purpose. New human bodies and new senses of identity[07] could arise as the convergence continues.

2 Coevolution of biological and digital technologies

This type of biodigital convergence emerges when advances in one domain generate major advances in the other. The coevolution of biological and digital sciences and technologies enables progress in each domain that would be impossible otherwise. This could lead to biological and digital technologies that are developed as integrated or complementary systems.

Complex living systems – bacteria, fungi, plants, and animal life including humans – are increasingly subject to examination and understanding by digital tools and applications such as machine learning. This deeper understanding, enabled by digital technologies, means that biology is subject to influence and manipulation that was not possible a few years ago.

For example, gene sequencing combined with artificial intelligence (AI) leads to understanding genetic expression, which is then used to alter existing organisms to create organic compounds in new ways[08] or even entirely synthetic organisms.[09] The CRISPR/Cas9 approach and other new gene editing techniques would have been impossible without the evolution of digital technology and bioinformatics. Advances in digital technologies have helped the advancement of the biodigital.[10]

We also see a greater understanding of biology, which is fueling progress in the field of biological computing. Neural nets – computer systems that are designed based on biological brains – are an example of how biological understanding is shaping digital technology.

There is also a blurring between what is considered natural or organic and what is digital, engineered, or synthetic. For example, biosynthetic vanilla is created using ferulic acid, eugenol, and glucose as substrates, and bacteria, fungi, and yeasts as microbial production hosts. Although it does not come from a vanilla plant, under both U.S. and EU food legislation, its production from "microbial transformations of natural precursors" allows it to be labelled as a "natural flavouring".[11]

3 Conceptual convergence of biological and digital systems

A third form of biodigital convergence involves a shift in perspective that could reshape our framing and approach to biological and digital realms, facilitating the blending of the two.

As we continue to better understand and control the mechanisms that underlie biology, we could see a shift away from vitalism – the idea that living and nonliving organisms are fundamentally different because they are thought to be governed by different principles.[12] Instead, the idea of biology as having predictable and digitally manageable characteristics may become increasingly common as a result of living in a biodigital age. Any student of biology today will have grown up in a digital world, and may consciously or subconsciously apply that frame of reference to bioinformatics and biology generally.

From a digital perspective, we see a potential shift in the opposite direction. Computing began as a means of producing predictable, replicable, and relatively simple outcomes. As digital technology became more complex and connected, the system began to mimic the characteristics of the biological world, leading to the notion of technological ecosystems. Biological models are also being used to develop digital tools, such as AI based on neural nets.

Three ways biodigital convergence is emerging

1

Full physical integration of biological and digital entities

Digital technology can be embedded in organisms, and biological components can exist as parts of digital technologies.

2

Coevolution of biological and digital technologies

Coevolution emerges when advances in one domain generate major advances in the other.

3

Conceptual convergence of biological and digital systems

Conceptual convergence involves a shift in perspective that could reshape our framing and approach to biological and digital realms, facilitating the blending of the two.

Why explore biodigital convergence now?

There are enough signals to give shape to potential biodigital futures. These signals suggest that biosciences and biotechnology may be at the cusp of a period of rapid expansion – possibly analogous to digital computing circa 1985.

That year, Microsoft introduced Windows 1.0, Atari released the Atari ST home computer, and the first domain name, symbolics.com, was registered. Computing was entering the mass market, creating value across many more types of organizations and contexts than it had during the decades of giant mainframes.

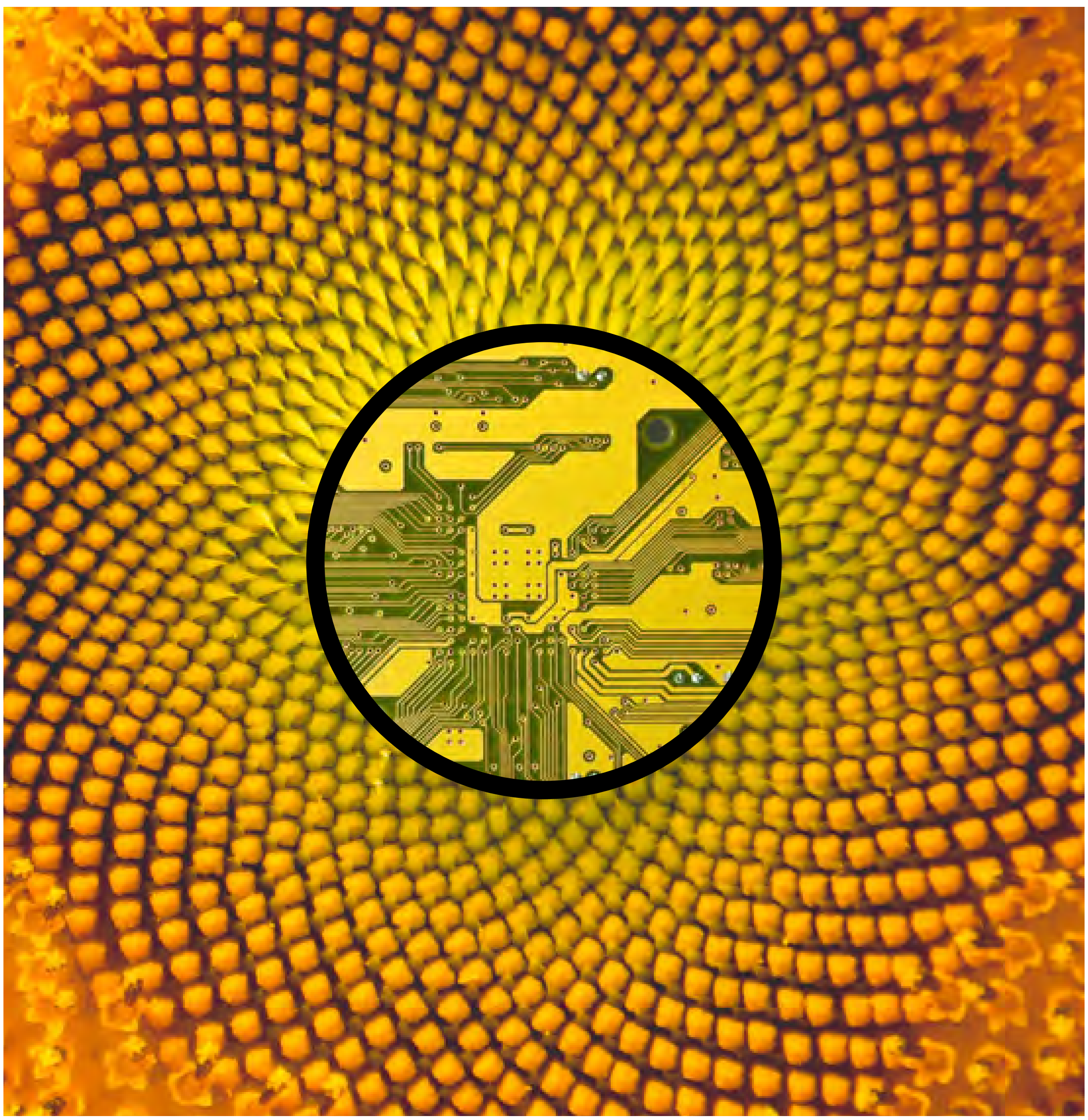
Biodigital convergence is showing signs of a similar trajectory – moving away from the centralized models of pharmaceutical and industrial biotech toward widespread commercial and consumer use. These range from bioprinters that create organic tissue, to synthetic biology machines that can be programmed to create entirely new organisms. For example, Printeria is an all-in-one bioengineering device that automates the process of printing genetic circuits in bacteria. It is intended to be as easy to use as a domestic desktop printer and is projected to cost $1,500.[13]

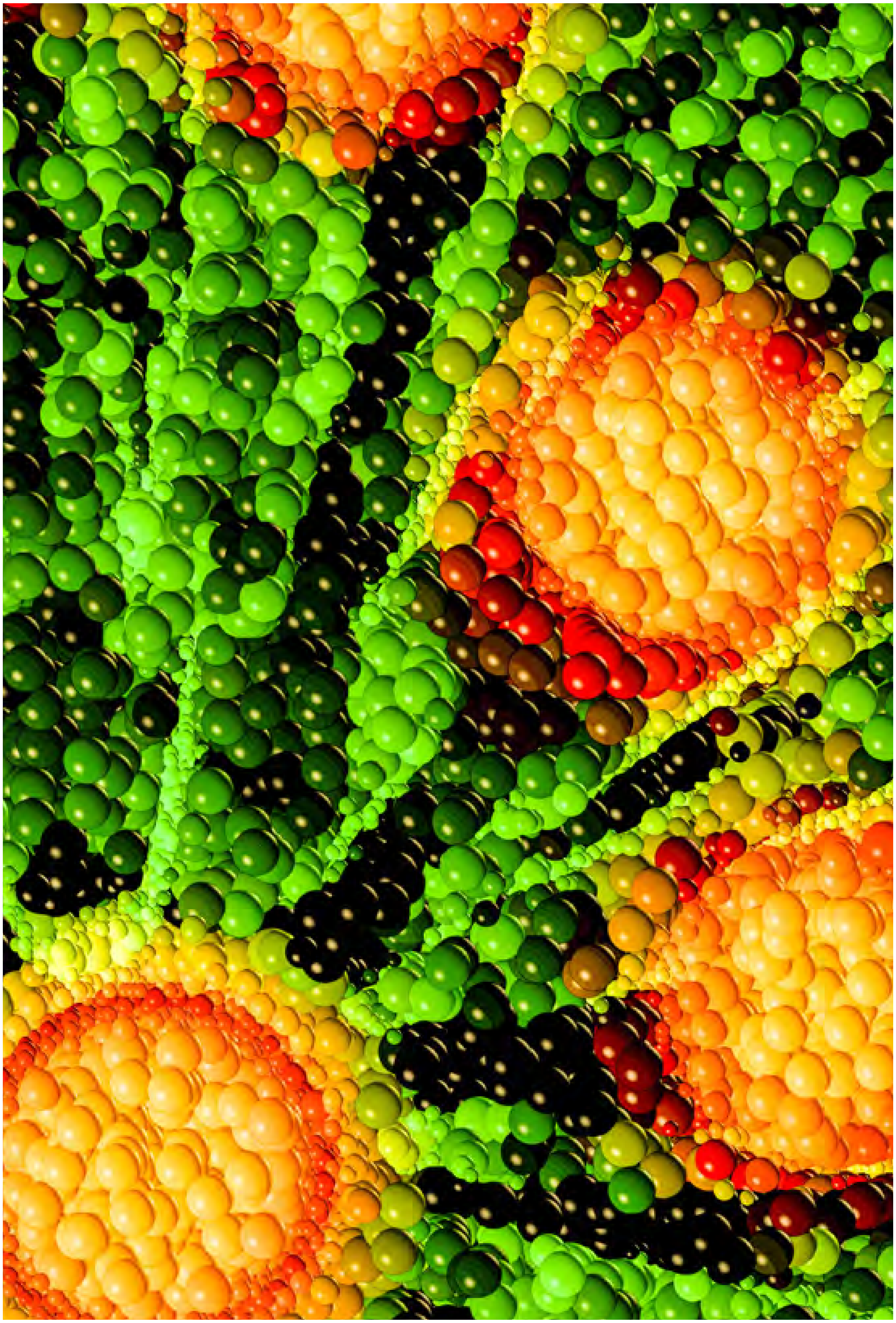
Rapid progress in biological technologies has benefited from the low-cost, broad availability, and increasing capabilities of digital processing, storage, and communication.

However, the biological realm's own unique and special attributes are simultaneously influencing digital systems. New forms of biological capabilities are being built into digital networks as well as AI applications and computation, making them more efficient and creating new opportunities.

Biodigital convergence involves a rethinking of biology as providing both the raw materials and a mechanism for developing innovative processes to create new products, services, and ways of being.

Today's rapid rate of change and innovation compels us to reassess our understanding and expectations about biological and digital systems. The convergence of these domains could cause systemic change across sectors and have policy implications. Governments can expect to be called upon to help manage the risks and seize the opportunities that could arise.





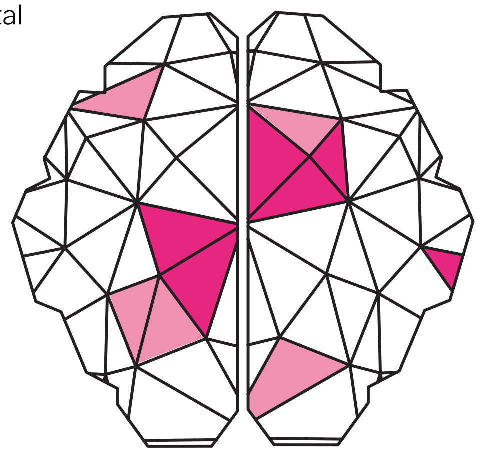
Good morning, biodigital.

Many factors could affect how biodigital convergence technologies could impact different societies, countries, cultures, environments, and people around the globe. The following is one of many possible narratives depicting some of the innovations in a future biodigital world.

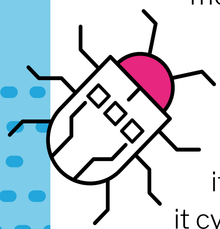
I wake up to the sunlight and salty coastal air of the Adriatic Sea. I don't live anywhere near the Mediterranean, but my AI, which is also my health advisor, has prescribed a specific air quality, scent, and solar intensity to manage my energy levels in the morning, and has programmed my bedroom to mimic this climate.

The fresh bed sheets grown in my building from regenerating fungi are better than I imagined; I feel rested and ready for the day. I need to check a few things before I get up. I send a brain message to open the app that controls my insulin levels and make sure my pancreas is optimally supported. I can't imagine having to inject myself with needles like my mother did when she was a child. Now it's a microbe transplant that auto adjusts and reports on my levels.

Everything looks all right, so I check my brain's digital interface to read the dream data that was recorded and processed in real time last night. My therapy app analyzes the emotional responses I expressed while I slept. It suggests I take time to be in nature this week to reflect on my recurring trapped-in-a-box dream and enhance helpful subconscious neural activity. My AI recommends a "forest day". I think "okay," and my AI and neural implant do the rest.

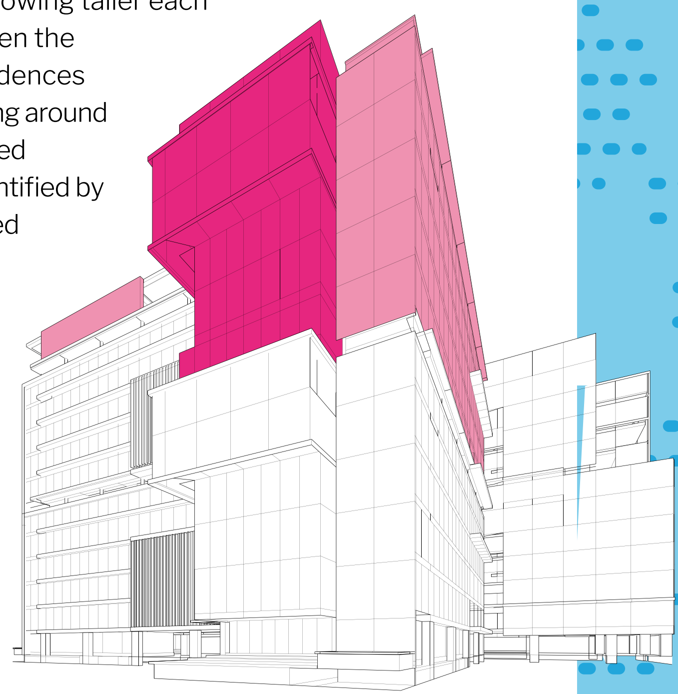


The summary of my bugbot surveillance footage shows that my apartment was safe from intruders (including other bugbots) last night, but it does notify me that my herd of little cyber-dragonflies are hungry. They've been working hard collecting data and monitoring the outside environment all night, but the number of mosquitoes and lyme-carrying ticks they normally hunt to replenish their energy was smaller than expected. With a thought, I order some nutrient support for them.

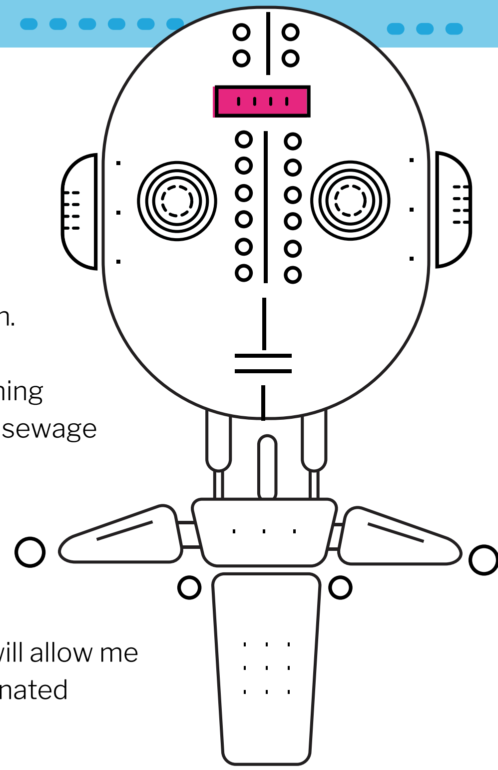


My feet hit the regenerative carpet and I grab a bathrobe, although I don't need it for warmth. My apartment is gradually warming up to a comfortable 22 degrees, as it cycles through a constantly shifting daily routine that keeps me in balance with the time of day and season. Building codes and home energy infrastructure are synchronized, and require all homes be autoregulated for efficiency. Because houses and buildings are biomimetic and incorporate living systems for climate control wherever possible, they are continuously filtering the air and capturing carbon. I check my carbon offset measure to see how much credit I will receive for my home's contribution to the government's climate change mitigation program.

As I head to the bathroom, I pause at the window to check the accelerated growth of the neighbouring building. Biological architecture has reached new heights and the synthetic tree compounds are growing taller each day. To ensure that the building can withstand even the strongest winds – and to reduce swaying for residences on the top floors – a robotic 3D printer is clambering around the emerging structure and adding carbon-reinforced biopolymer, strengthening critical stress points identified by its AI-supported sensor array. I am glad they decided to tree the roof of this building with fire-resistant, genetically modified red cedar, since urban forest fires have become a concern.



While I'm brushing my teeth, Jamie, my personal AI, asks if I'd like a delivery drone to come pick up my daughter's baby tooth, which fell out two days ago. The epigenetic markers in children's teeth have to be analyzed and catalogued on our family genetic blockchain in order to qualify for the open health rebate, so I need that done today.



I replace the smart sticker that monitors my blood chemistry, lymphatic system, and organ function in real time. It's hard to imagine the costs and suffering that people must have endured before personalized preventative medicine became common.

Also, I'll admit that it sounds gross, but it's a good thing the municipality samples our fecal matter from the sewage pipes. It's part of the platform to analyze data on nutritional diversity, gut bacteria, and antibiotic use, to aid with public health screening and fight antibiotic-resistant strains of bacterial infections.

Supposedly, the next download for my smart sink will allow me to choose a personalized biotic mix for my dechlorinated drinking water.

Today's microbiome breakdown is displayed on the front of my fridge as I enter the kitchen. It's tracking a steady shift as I approach middle age: today it suggests miso soup as part of my breakfast, because my biome needs more diversity as a result of recent stress and not eating well last night.

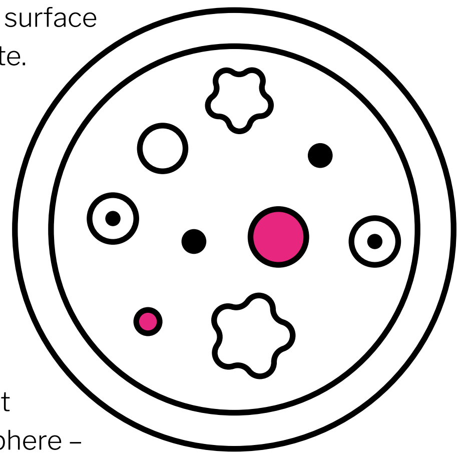
The buildings in my neighbourhood share a vertical farm, so I get carbon credits by eating miso made from soybeans produced on my roof and fermented by my fridge.

My fridge schedules the production of more miso and some kimchi in preparation for the coming week. It also adds immune-boosting ingredients to my grocery order because we're approaching flu season, and a strain that I'm likely to be susceptible to has been detected only a few blocks away.

I take my smart supplement, which just popped out of my bioprinter. The supplement adjusts the additional nutrients and microbes I need, and sends data about my body back to my bioprinter to adjust tomorrow's supplement. The feedback loop between me and my bioprinter also cloud-stores daily data for future preventive health metrics. The real-time monitoring of my triglycerides is important, given my genetic markers.

As my coffee pours, I check my daughter's latest school project, which has been growing on the counter for the past week. She's growing a liver for a local puppy in need as part of her empathy initiative at school. More stem cells are on the way to start a kidney too, because she wants to help more animals. I grab my coffee, brewed with a new certified carbon-negative bean variety, and sit on the couch for a minute.

It appears the nutrient treatment I had painted on the surface of the couch and chairs has allowed them to rejuvenate. I'll have to try the treatment on my bioprinted running shoes, as they're starting to wear out.



Oh wow – is that the time? I have only 10 minutes before my first virtual meeting. I tighten the belt on my skeleto-muscular strength chair, lean back, and log into my workspace. First I get the debrief from colleagues finishing their work day on the other side of the world. I shiver momentarily as I think about how intimately we're all connected in this digital biosphere – then it passes. Let the day begin.

This story may sound far-fetched, however all the technologies mentioned exist in some form today. While they are not yet commercially available in the form presented here, a world where we take the interaction between biological and digital technologies for granted is already starting to emerge.

While this is a representation of technologies that could be part of a biodigital world, it does not represent the only plausible future. Rather, it is an imaginative vignette outlining the radical shifts that could take place within an optimistic biodigital future. Varying levels of access, adoption, and alternative realities could exist.

What new capabilities arise from biodigital convergence?

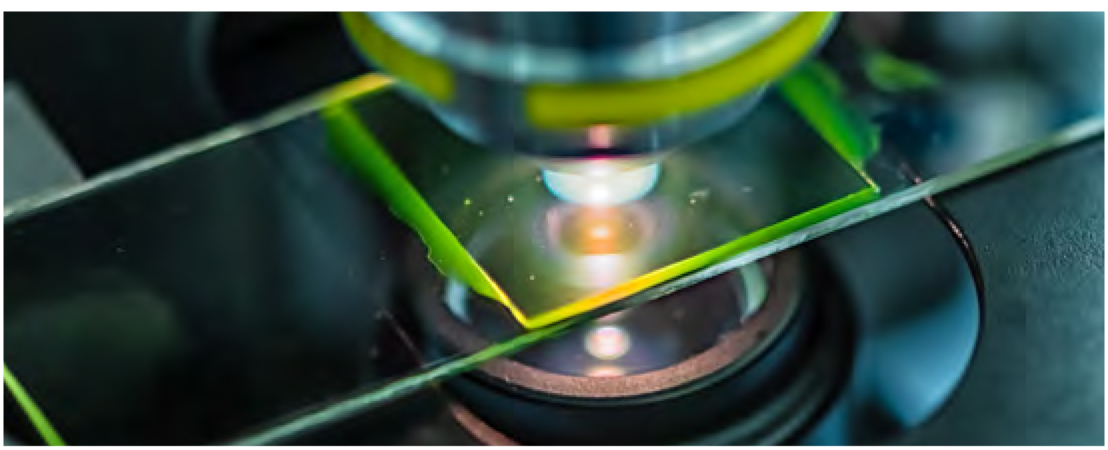
We are already experiencing the combination of digital and biological systems through new products, platforms, services, and industries.

Biodigital convergence is opening up strikingly new ways to:

- change human beings – our bodies, minds, and behaviours
- change or create other organisms
- alter ecosystems
- sense, store, process, and transmit information
- manage biological innovation
- structure and manage production and supply chains

Table 1: New capabilities produced by the convergence of digital and biological systems

What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to change human beings – our bodies, minds, and behaviours		
Altering the human genome – our core biological attributes and characteristics	• Advances in gene sequencing and editing, such as CRISPR/Cas9 • Machine learning helps scientists predict which genes to target for editing	• The world's first babies to have their genome edited are born in China[14] • Molecular biology enhanced by tools from computer science[15]
Monitoring, altering and manipulating human thoughts and behaviours	• Neurotechnologies read brain signals to monitor attention and manage fatigue • Digital apps can help enhance brain health	• SAP and EMOTIV collaborate to help SAP employees manage stress[16] • Americans spent 1.9 billion USD last year on apps to keep their brains sharp[17]

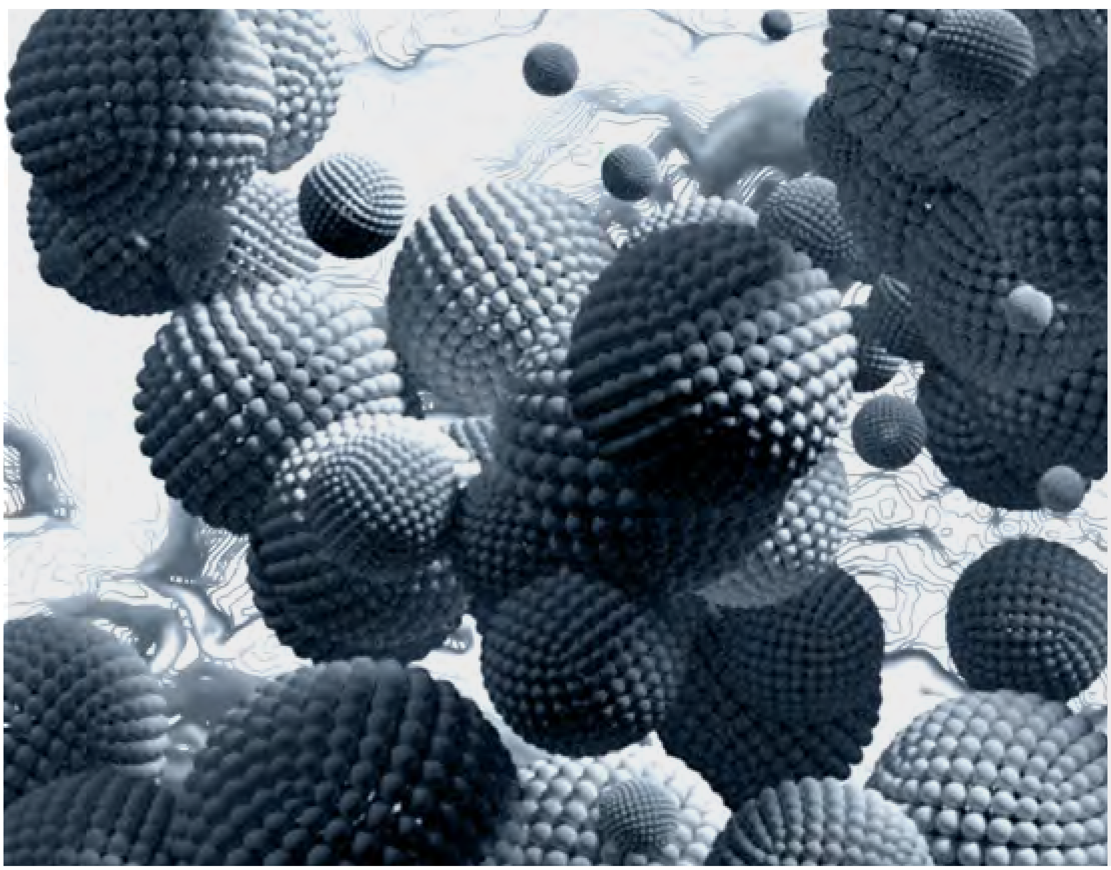


What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to change human beings – our bodies, minds, and behaviours (continued)		
New ways to monitor, manage, and influence bodily functions, as well as predict, diagnose, and treat disease	• Gene sequencing entire samples helps us understand complex environments such as the human microbiome • Digital devices can be worn or embedded in the body to treat and monitor functionality • Machine learning systems can predict mortality and treatment outcomes	• Guardant's liquid biopsy proves more accurate and faster than tissue biopsy in patients with lung cancer[18] • University of Waterloo researchers develop a self-powering sensor for medical monitoring[19] • Amazon patent will allow Alexa to detect a cough or a cold[20] • AI gives reliable coma outcome prediction[21]
Creating new organs and enhancing human functionality	• 3D-printed tissues based on digital designs and production tools can create customized organs • Biohacking with implanted digital devices to enhance bodily functions	• Bioengineers successfully 3D printed structures that mimic lung tissue and blood vessels[22] • Lab-grown kidneys shown to be fully functional in animal recipients[23] • Implanted chips for a highly personal version of two-factor authentication[24]

What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to change human beings – our bodies, minds, and behaviours (continued)		
New ways to experience and interact with the world	• Brain-machine interfaces that enable machines to be controlled through brain signals • Prosthetics that use machine-learning algorithms to expand functionality and sensitivity	• Neuralink announced an integrated brain-machine interface platform with thousands of channels[25] • Infinite Biomedical has its deep-learning-driven prosthetic control system approved by FDA[26] • FDA releases regulatory guidance on brain-controlled prosthetics[27]
Creating new organs and enhancing human functionality	• Machine-learning techniques for simulating protein folding and contributing to drug design • 3D printing tissue to test therapies • Nanobots and nanomaterials can operate and precisely deliver drugs within living creatures • Machine learning can predict the outcome of clinical trials	• AI protein-folding algorithms solve structures faster than ever[28] • New Zealand scientist Shalini bio-prints tumour cells, hoping to grow tumours to see what treatments work best[29] • Tiny robots crawl through mouse's stomach to heal ulcers[30] • MIT researchers apply AI techniques to predict clinical trial outcomes[31]

What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to change or create other organisms		
Changing the type or amount of inputs that organisms need to grow	• Advances in gene sequencing and editing, such as CRISPR/Cas9	• Enhanced photosynthesis in transgenic tobacco plants makes them 40% more productive[32]
Creating entirely new organisms with tailored characteristics	• Synthetic biology draws inspiration from biology, engineering, computer science, and physics for the design and construction of new biological entities • Artificial intelligence can help design microorganisms with specific characteristics	• Like computer-aided design (CAD) tools, many open-source software help researchers to analyze and design complex genetic circuits in living organisms that meet specific functions[33] • Gingko Bioworks designs custom organisms "to replace technology with biology"[34] • Scientists use machine learning to speed up biofuel production[35] • Like digital circuits, a 'biomultimeter' called PERSIA allow researchers to measure biological functions of genetic circuits in vitro and in real time[36]

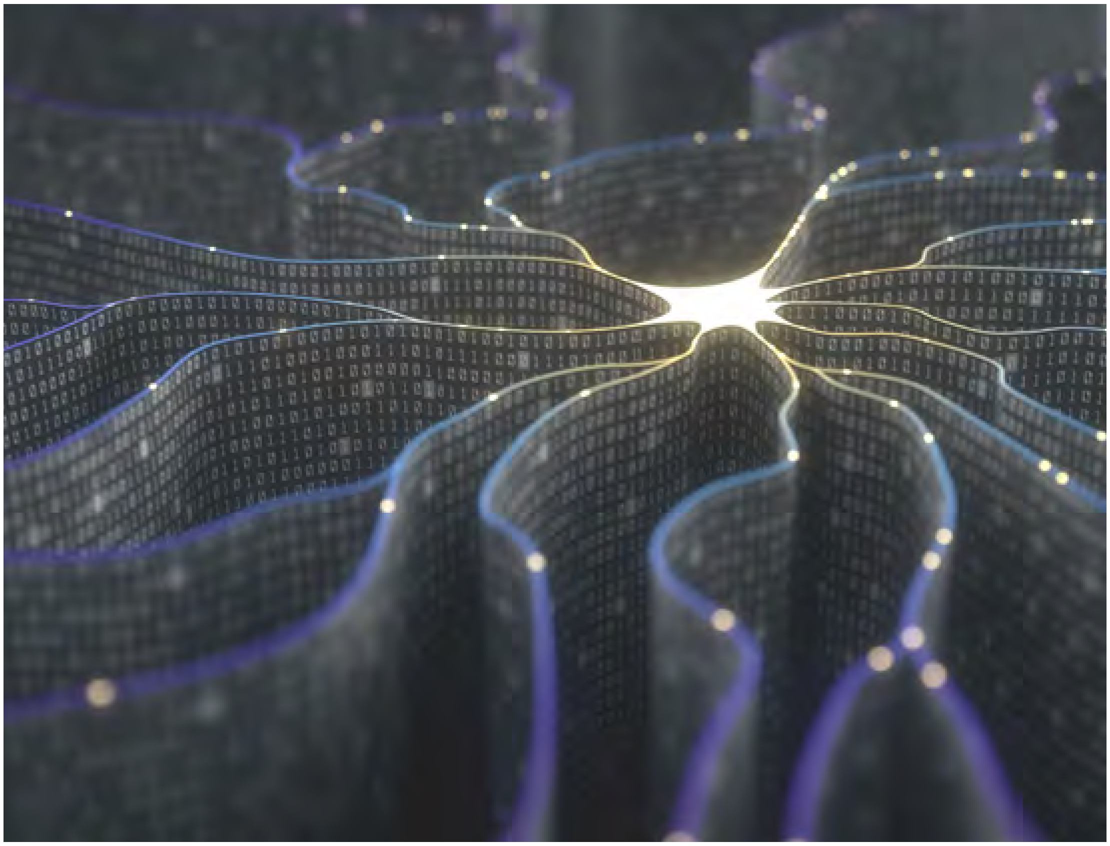
What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to change or create other organisms (continued)		
Changing what and how organisms produce substances	• Advances in gene sequencing and editing, such as CRISPR/Cas9	• Researchers use bacteria to synthesize butanol from water, C02, and sunlight[37]

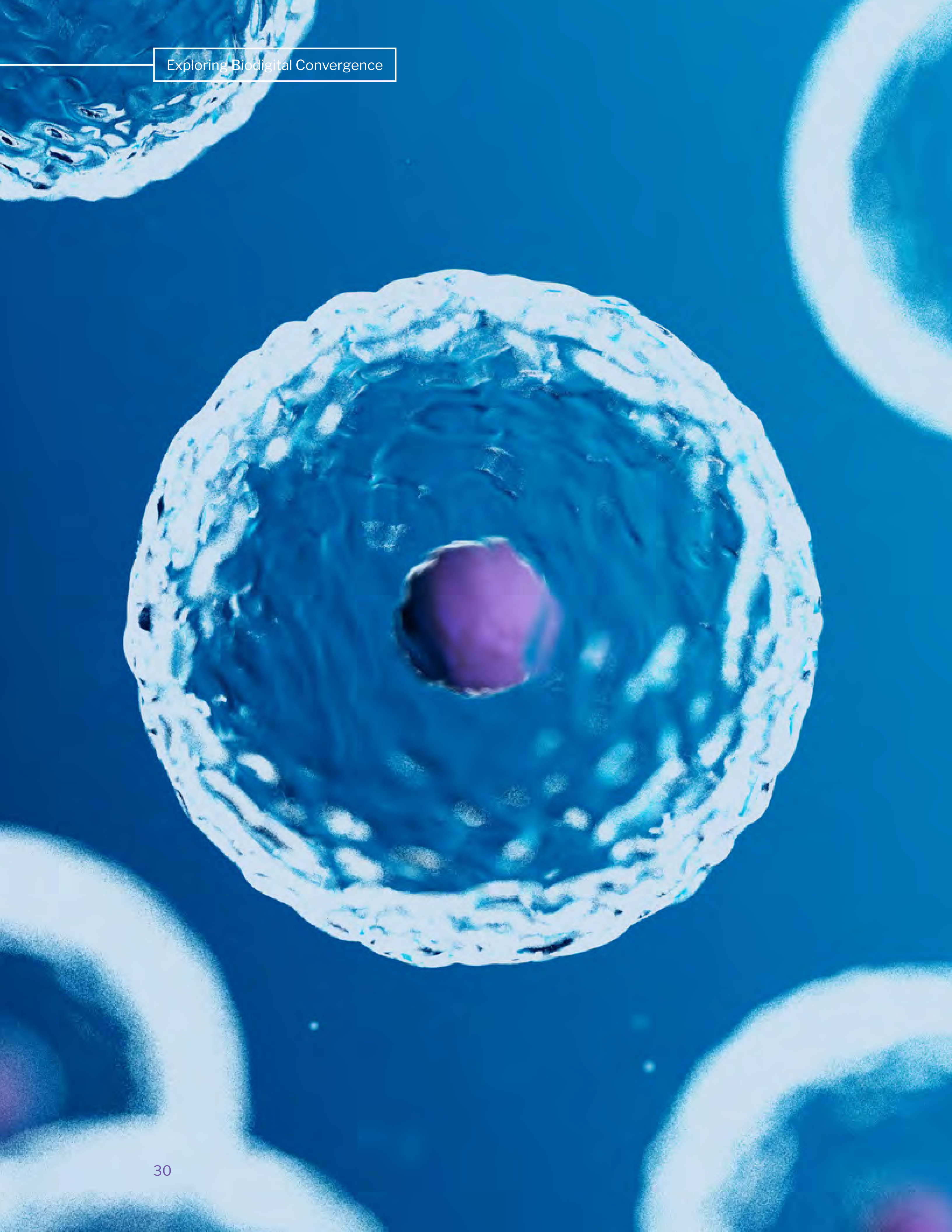


What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to alter ecosystems		
Changing and eradicating entire species	• Germline editing using approaches such as CRISPR, and gene drives that create new ways to alter ecosystems or wildlife	• Target Malaria releases genetically modified mosquitoes in Burkina Faso in gene drive trial[38]
Altering the natural environment at scale	• Geoengineering approaches that accurately model carbon capture or solar reflectance	• Engineering microorganisms in peatland to store and capture carbon and offset climate change[39]
Predicting and managing the spread of organisms	• Digital epidemiology relies on digital communication technologies and analytics to track diseases	• Flutracking[40] and InfluenzaNet use digitally connected networks of volunteers to track flu outbreaks
New ways to sense, store, process, and transmit information		
New ways to store information using biological systems	• Storing large amounts of digital information in biological systems for longer periods than current technology	• Microsoft and University of Washington demonstrate first fully automated DNA data storage system[41]

What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to sense, store, process, and transmit information (continued)		
Turning organisms into biocomputers	• Using biological organisms and attributes to perform computation	• CRISPR used to build dual-core computers inside human cells[42]
Creating biomimetic materials	• Drawing inspiration from biological systems to design more efficient electronic and digital systems	• Researchers create artificial skin and nervous systems with higher sensitivity than human skin[43]
New ways to manage biological innovation, production, and supply chains		
More efficient and scalable research and production approaches	• Using digital systems to scale up biological production • Using digital systems to automate research	• Fraunhofer automates the cultivation of microalgae in photobioreactors[44] • Lab automation is speeding up research[45] • Robot farmers have successfully planted and harvested barley by themselves[46] • Toward autonomous antibiotic discovery[47]

What new capabilities are opening up?	What combinations of biological and digital technologies allow this?	What is possible today?
New ways to manage biological innovation, production, and supply chains (continued)		
Increasingly open and efficient supply chain management	• Machine learning and distributed ledgers can track materials and aid in auditing	• Blockchain becomes a 'source of truth' for biopharma[48]
Open collaboration on cell lines and genomes to support research	• Digital networks to assist in the efficient exchange of biological materials and code	• The Frozen Farmyard: creating a clean meat cell line repository[49]

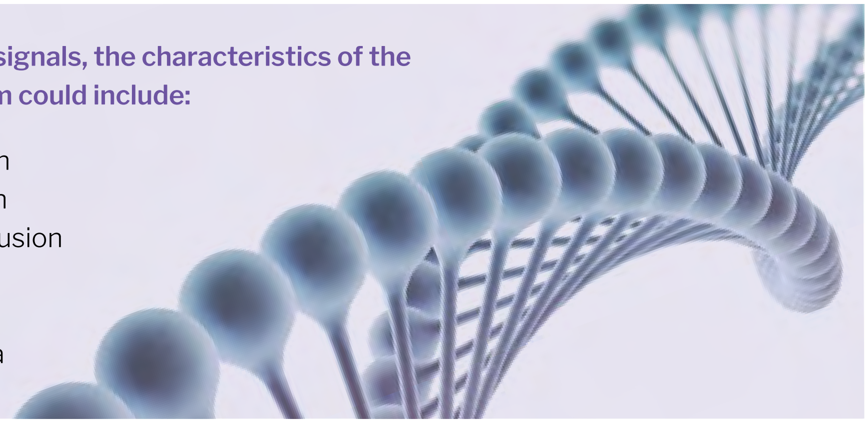




What are possible characteristics of the biodigital system?

Based on initial signals, the characteristics of the biodigital system could include:

- democratization
- decentralization
- geographic diffusion
- scalability
- customization
- reliance on data



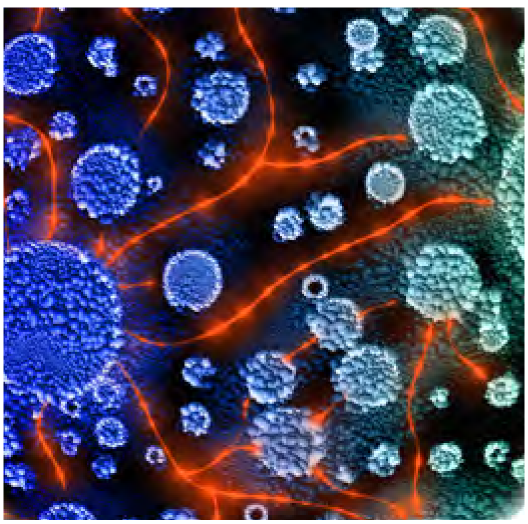
The following outlines each potential characteristic of the biodigital and their potential impact.

Democratization

Until recently, cell biology and biotechnology were generally developed and produced in sterile labs and specialized factories, using expensive equipment and expertise.

Now, advances in software and hardware are removing these restrictions on biosciences and biotech production. The ability to control systems remotely and transmit instruction sets in digital form, as well as higher levels of automation, are shifting biology-based production closer to consumers.

For example, mail-order bioengineering or CRISPR kits allow biohackers to purchase and practice genetic alteration at home. A range of relatively affordable online consumer options include a 30 USD "Genetic Design Starter Kit" allowing a novice to insert a gene into a jellyfish to make it glow, from the comfort of their kitchen table.[50] Another CRISPR kit allows purchasers to make genome edits in bacteria that can reproduce for 159 USD.[51] A third "molecular biology and genetic engineering" starter kit costs less than 170 USD.[52]



The decreasing cost of genome sequencing is another example of biotech becoming more broadly available. The first whole genome sequencing (reading all 3 billion base pairs) in 2003 took 13 years and cost more than 3 billion USD. By 2016, the price had dropped to approximately 1000 USD. In July 2019, it cost 599 USD, and personal genetics company Veritas Genetics predicts that it will drop to below 200 USD by 2022.[53] As a result, a consumer market for genotyping (which sequences less than 1% of the genome) has emerged to support people interested in their heritage or in uncovering targeted health information, typified by services such as 23andme.com.

Decentralization

We may see more decentralized production as the capabilities of synthetic biology increase. Products that needed to be created or extracted in a specific geographical location could be produced more widely as humans get better at assembling – or growing – organic and nonorganic compounds through faster, cheaper, and customized chemical and biological processes.

This includes the ability to create food and engineer meat without the need for arable land.[54] Lab-grown meat – cells that develop to produce muscle cells and cultured meat in a monitored environment – could be a game changer in decentralizing multiple industries from farming to shipping.

The Japanese biotech company Spiber has developed a genetically modified protein called Brewed Protein[55] that can be used as a textile in the fashion industry, or as a robust material in the construction and automobile industries. And biomass produced locally by algae-based bioreactors[56] capturing carbon dioxide could be transformed into products such as fuels, plastics, and cosmetics.

Geographic diffusion

Decentralization could allow economies lacking in natural resources to compete with resource-rich nations for the production of goods, using biodigital technologies to produce materials that previously needed to be imported.

Increasing interest in open-source and publicly available research could allow rapid geographic diffusion. More generally, diffusion of biodigital knowledge could proceed rapidly if there is a willingness to share information. Some researchers are allowing access to all of their data. For example, pioneering bioengineers at the University of Washington are commercializing recent breakthroughs in 3D organs. Through their company, Volumetric, they have made all the source data from their experiments on 3D-printed vascular networks freely available.[57]

Scalability

Rapid scaling may be possible in both the digital and biological worlds. Data can be copied quickly, and simple biological organisms can generally replicate easily. This means an additional unit of production in both domains may be created quickly and easily.

In other words, the biodigital economy could be characterized by very low marginal production costs. Provided there is competition among providers, this characteristic could significantly reduce the cost of many biodigital goods or services for consumers.

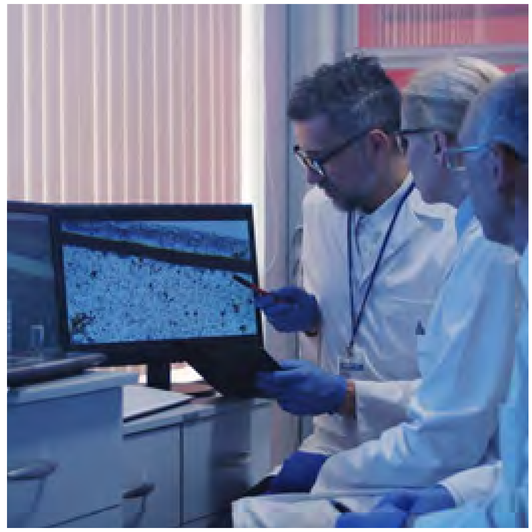
Low marginal production costs and ease of replication also mean that innovations in the biodigital convergence economy could be highly scalable.

Customization

Biological systems are simultaneously simple and complex. As dynamic systems, they can respond in unanticipated ways, or cause multiple impacts that cannot be easily disentangled. This complexity is a feature of biological systems rather than a bug, as it means systems can be highly adaptable and varied. This suggests that there may be many pathways to obtaining desired outputs and consequently the potential for high degrees of customization.

Production approaches and devices could leverage this complexity to produce multiple customized biological outputs from single systems. For example, economies of scope allow companies developing synthetic biology to produce hundreds of different organisms and outputs with similar processes.[58]

In a healthcare context, one example of biological complexity is reflected in our expanding understanding of the human microbiome – the trillions of non-human bacteria living in and on our bodies, estimated to equal or outnumber our own human cells. Our microbiome influences many different aspects of our lives, from digestion to mood to body odour. Biodigital therapies targeted at microbiomes, personalized for maximum efficiency, may emerge first.



Reliance on data

The technologies and applications featuring biodigital convergence will not be able to operate without a lot of data. For example, the field of bioinformatics uses digital tools and data analysis to understand biological systems,[59] including deploying deep learning algorithms to analyze images of cells to detect patterns that humans would find impossible to discern.[60] Techniques such as next-generation gene sequencing are hugely data intense, creating new challenges with sharing, archiving, integrating, and analyzing this data.[61]

The global bioinformatics market is projected to grow from 7.73 billion USD in 2018 to 13.50 billion USD in 2023, at a compound annual growth rate of 14.5%.[62] The rate of data growth to fuel this expansion could exceed this.

The data required is highly varied. Upstream of the production processes, data may also be an important asset in the form of genomes, phenotypes, and environmental contexts of a diverse set of humans and a wide range of unique organisms. Bioprospecting is already an important aspect of drug development, and may rise in importance – and provoke greater controversy in healthcare.[63]

The full potential of biodigital convergence may therefore require a constant flow of data. Capturing, managing, sharing, and governing this data could become a resource-intensive process and a more highly developed industry in itself.

What are some initial policy questions?

The dynamics of the biodigital world described above – democratization, decentralization, geographic diffusion, scalability, customization, and data reliance – may require individuals, governments, organisations, and industry to change the way they operate.

Policy Horizons will explore potential implications of the biodigital convergence in an upcoming in-depth foresight study. The following section highlights some initial policy-relevant questions concerning the economic, social, ecological, geopolitical, and governance domains.

Economic

Could traditional resource-based competitive advantages fade?

Production systems – their structure, who controls them, and who benefits from their value – could markedly change during the biodigital convergence.

Demand for many traditional commodities, including raw materials, may fall if we develop biologically derived alternatives. A shift to distributed bioengineered production could decrease the primacy of land or other natural resource distribution among countries and regions.

Democratization and decentralization of production could challenge countries, regions, communities, and enterprises that have relied on scarce natural resources or unique geographic factors to produce goods and services. Manufacturers who rely on proximity or special access to currently scarce resources may come under pressure to develop or adopt new technologies and approaches[64] to stay competitive.

Would education and training systems need to be adapted to address potential skills gaps?

The production and end use of biodigital technologies may become simpler, but its design and development could remain technically demanding. Both digital and biological skills could rise in demand as biodigital convergence progresses, and those who can act at the intersection of the two might be highly sought after. Demand for talent may exceed supply, at least temporarily.

What could data protection and intellectual property frameworks look like in the biodigital era?

The potential impact of biodigital services may spur shifts in national or global intellectual property rights regimes, particularly in response to emerging breakthrough health therapies, innovations in agriculture that are particularly important for food security, and approaches that could mitigate climate change.

Intellectual property and data protection rules could be bottlenecks in the biodigital world, both incentivizing and restricting innovation. Alternatively, democratized access to biodigital tools could facilitate the reproduction of many proprietary biodigital innovations using parallel but distinct approaches, increasing competition and decreasing the rent generated by intellectual property.

How can policy foster a competitive business environment in a biodigital world?

Platforms may play an important role in a world where biological and digital systems are tightly coupled, as they have with online advertising, social networking, and e-commerce. Data policy could influence whether large organizations have an advantage in a biodigital economy, based on exclusive abilities to access, purchase, manage, and secure large amounts of data.

The data-reliant nature of biodigital convergence means that the demand for data could increase substantially – particularly human, animal, plant, and bacterial data. Large platforms could potentially gather and control large amounts of information about individuals, their context, and the natural world. Some platforms could attempt to capture value by operating a closed biodigital ecosystem.

"The future ain't what it used to be"

The biodigital could unfold in numerous ways, and a future where it is part of human existence could be quite different. The following narratives, although hypothetical, describe scenarios that could emerge as biological and digital systems converge.

Radical life extension: Following a decade of simulating human biochemistry using machine learning, an Asia-based company becomes the first to develop and patent a radical life-extension therapy. Based on altering the human genome in cells throughout the body, the therapy dramatically slows cellular deterioration, adding up to 15 years of healthy life to users, but effective only for people under the age of 40. The treatment is marketed worldwide at 10 million USD per course. More than 5,000 patients register for treatment within the first month of the announcement, including a reported 120 Canadians.
Inspired by: Barclays Beyond 100 report on Longevity[65]

Food customized to your unique digestive system: One of the fastest-growing companies in the food sector uses microbiome analysis to create personalized and dynamic nutrition plans. By designing food precisely for your body – and the trillions of non-human organisms that make up part of your microbiome – MyBestBiome promises that you will have more energy and will feel better. Furthermore, 90% of the animal protein is sustainably sourced from specially engineered insects. The catch? You have to grant the company access and data rights to your entire biome to receive the product and its purported health benefits.
Inspired by: Food Design To Feed the Human Gut Microbiota[66]

Neurotech nightmare: A leading Canadian supermarket is having a bad year. It's been embroiled in a scandal over several features of its loyalty program. The "Your Choice" program offers special discounts and preemptive ordering if you allow it full access to your "digital twin" – essentially giving it full access to your life and activity. A leaked internal report suggests that this data is being used in conjunction with intrusive neurotechnologies to encourage members to consume more. At the centre of the scandal is the fact that the supermarket is essentially selling access to the minds of "Your Choice" members, outsourcing targeted consumer manipulation on a massive scale.
Inspired by: Towards new human rights in the age of neuroscience and neurotechnology[67]

Social

Could social attitudes shift towards health and lifestyle?

What it means to be healthy may shift during a biodigital convergence, affecting social relationships. Today, healthiness is mostly associated with the ability to avoid illness and to engage in a full range of human activities.

In a biodigital convergence, detailed mediated knowledge of the human body, the microbiome, and biological functions may create new opportunities to understand and influence our health. Maximizing healthiness could involve a broad array of more precise behavioural and nutrition-related interventions. As data becomes more widely accessible, health could become a status symbol. Access and funding for nootropics (drugs to improve brain function) could raise social policy issues.

While advances could significantly improve health, some may perceive improved biodigital technologies as a way to mitigate the effects of unhealthy lifestyles.

What policies could help address health inequality?

Biodigital convergence could accelerate the development of technologies that raise human abilities above the norm, whether via drugs, nutritional supplements, prosthetics, or neurotechnologies. Uneven access to expensive technologies could further compound economic inequality.

While uneven access could affect disadvantaged and vulnerable groups, democratization of biodigital health products and services could offset some of this gap. For example, if we can produce life-saving or life-enhancing medicines safely, reliably, and cheaply, health inequality could decrease accordingly.

What policies could foster trust among partners and stakeholders?

Biodigital convergence relies on a wide array of biological data, which may change the way citizens relate to businesses that provide services. The relationship between firms and individuals may require higher levels of trust, as firms seek access to highly intimate data about our lives and bodies.

For example, human “digital twins” could become valuable assets beyond healthcare. Social services, the justice system, environmental services, and education providers may all need to be trusted with, manage, and act on increasingly intimate data that relate to people and the world around them.

Publicly acceptable data policy may sometimes enable biodigital convergence, and sometimes create roadblocks. The ease with which many parties could extract or make use of personal data related to an individual’s genome, biome, health markers, and context could create new demands for regulation, beyond existing personal health information protection laws. As genetic sequencing becomes cheaper and more common, privacy concerns that have been largely limited to the justice system and insurance practices could arise in other areas of human activity.

Ubiquitous genetic sequencing could have privacy and consent implications for families and communities, given that a single individual's DNA test provides information about their biological relatives. For decades, Indigenous communities have been leaders in articulating community-focused ethics for research, particularly relating to genetic and health information.[68] Governments may need to think beyond individual privacy and consider the concept of collective privacy, particularly when genetic data could affect the rights or freedoms of others.

Environmental

What changes could occur in land use and the natural environment?

Biodigital convergence could change our tools and values related to land and the natural environment.

If demand shifts away from some traditionally produced raw materials, their resource prices may soften, resulting in land use changes. Industrial districts may rise in value at the expense of agricultural land, while areas of particular biodiversity may gain new value and significance if they offer data, ecological services, and raw materials for bioprospecting.

The scale of the climate challenge could make geoengineering and bioengineering more attractive and feasible. Releasing customized microorganisms could help make peatlands more efficient at absorbing carbon dioxide.[69]

The biodigital could change the trajectory towards sustainability and the circular economy, making more efficient use of materials and lowering the impact of production and resource extraction on the environment. For example, Fraunhofer IGB has developed a novel approach to make bioplastics that are biodegradable and safe for food use. The resulting inorganic-organic hybrid polymers prevent gases and vapours from affecting food, and can be applied to both bioplastic and paper packaging, allowing coated products (such as the packaging for takeaway food) to be fully biodegradable.[70]

Geopolitical

What policies are necessary to compete in a global biodigital world?

The economic benefits of biodigital convergence are already spurring national competition, as well as efforts to protect industries and prevent foreign takeovers of domestic innovation in some countries. For example, a number of deals involving foreign investors in U.S. biotech firms have collapsed since updates to the Foreign Investment Risk Review Management Act were signed into law by congress in 2018. Administered by the Committee on Foreign Investment in the United States, the amendments limit international investment in U.S. biotech firms.[71]

Nations could also start competing based on rigour and speed of regulatory approvals. Some countries may try to attract investment by offering regulatory environments that favour rapid biodigital progress, potentially at the expense of prevailing bioethical norms and practices enforced elsewhere.

What is needed to protect citizens' security in the biodigital world?

Synthetic biology could include many dual-use technologies, potentially applied for both civilian and military purposes. Microorganisms can produce disease-causing agents or toxins. Managing the malicious use of technologies – particularly those that are distributed – in the biodigital world is already a concern.[72]

Biosecurity could be important in a world that depends on biodigital systems. For example, DARPA's Safe Genes initiative seeks to develop tools to control, counter, and perhaps reverse the effects of genome editing, including gene drives, in biological systems.[73]

There is also the potential for malicious, reckless, or accidental release of deadly lab-made viruses. For example, a virologist at the University of Alberta was able to use synthetic biology techniques to recreate horsepox (a virus similar to smallpox) by stitching together DNA ordered by mail to match the horsepox genome sequence published in 2006.[74]

Governance

How can regulation and policy making take social concerns about biodigital advances into account?

There is an important distinction between what is technologically possible and what is socially acceptable. Biodigital convergence might expose policy and regulatory gaps and lags, both within and across governments. It may also provide opportunities for new integrated and responsive regulatory approaches to biodigital systems, much like other emerging technologies that enable governance systems to be more agile.[75]

Social license can be pivotal to the path of technological and regulatory developments, particularly when linked to human reproduction and food systems. For example, disparities in the legal and social response to GM crops, driven by divergent philosophical risk management approaches and different power dynamics between private and public sectors, has resulted in very different regulatory environments between North America and Europe.[76] Regulatory barriers to entry could affect smaller operators, particularly in food and healthcare areas, which are highly regulated and jurisdiction-based.

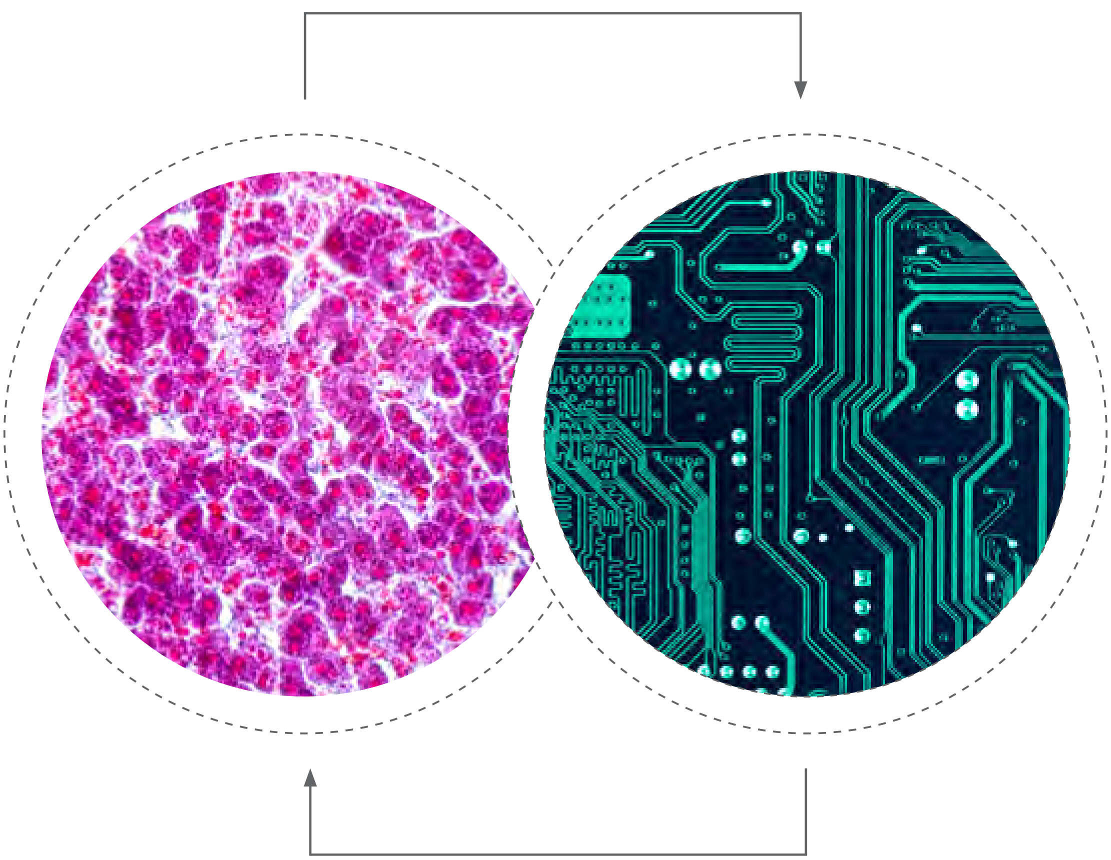
Social concerns often impact regulatory systems and reform processes – particularly regarding security, safety, pricing, access, and labour rights. And social license can often be a more powerful driver than the legal remedies or enforcement in driving compliance.[77] Perspectives on biodigital technologies may vary across groups, and multiple ethical traditions including Indigenous perspectives[78] and knowledge could help shape thoughtful responses.

Is the current tax framework suited for the biodigital world?

The characteristics of the digital domain could extend to the biodigital domain, making it difficult to track and collect taxes. This could in turn create challenges regarding what gets taxed and by which jurisdiction.[79] The value from the potential licensing of a biodigital good comes from its components, rather than the combined end product. This could limit opportunities for authorities to assess and charge tax on the sale of the end product, potentially lowering the total receipt of value-added taxes.

Do public finance systems need to be reassessed to be sustainable in the biodigital world?

In addition to the benefits of longer lives, increased life expectancy could challenge tax, social security, healthcare, and housing systems, should the health benefits of biodigital convergence be significant. Retirement funds, public healthcare expenses, and elderly accommodation could see both positive and negative impacts.



Policy-relevant questions arising from biodigital convergence

Economic

- Could traditional resource-based competitive advantages fade?
- Would education and training systems need to be adapted to address potential skills gaps?
- What could data protection and intellectual property frameworks look like in the biodigital era?
- How can policy foster a competitive business environment in a biodigital world?

Social

- Could social attitudes shift towards health and lifestyle?
- What policies could help address health inequality?
- What policies could foster trust among partners and stakeholders?

Environmental

- What changes could occur in land use and the natural environment?

Geopolitical

- What policies are necessary to compete in a global biodigital world?
- What is needed to protect citizens' security in the biodigital world?

Governance

- How can regulation and policy making take social concerns about biodigital advances into account?
- Is the current tax framework suited for the biodigital world?
- Do public finance systems need to be reassessed to be sustainable in the biodigital world?

Conclusion

We could be on the cusp of a long-term biodigital transformation of our economy, society, institutions, and environment. This biodigital convergence could disrupt the way we produce and consume goods and services, relate to one another, maintain and augment our bodies, acquire and process data, make decisions, and manage our place in ecosystems.

In the late 1970s and early 1980s, Canadians and policy makers began to understand that the digital age was upon them. Early movers seized opportunities, perceived challenges, and initiated deft policies that have provided benefits for decades. Now could be the time to make similar investments and make thoughtful decisions to guide Canada through the beginning of a biodigital convergence.

Policy Horizons looks forward to collaborating with partners and stakeholders to develop policy-relevant foresight in this area.

Acknowledgements

Policy Horizons is spearheading an area of foresight called the biodigital convergence. This scoping paper is the initial framework for a forthcoming in-depth foresight study. As this new domain emerges, we will continue to examine plausible futures for biodigital convergence and the policy questions that may arise.

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We look forward to collaborating with partners and stakeholders on the study of biodigital convergence.

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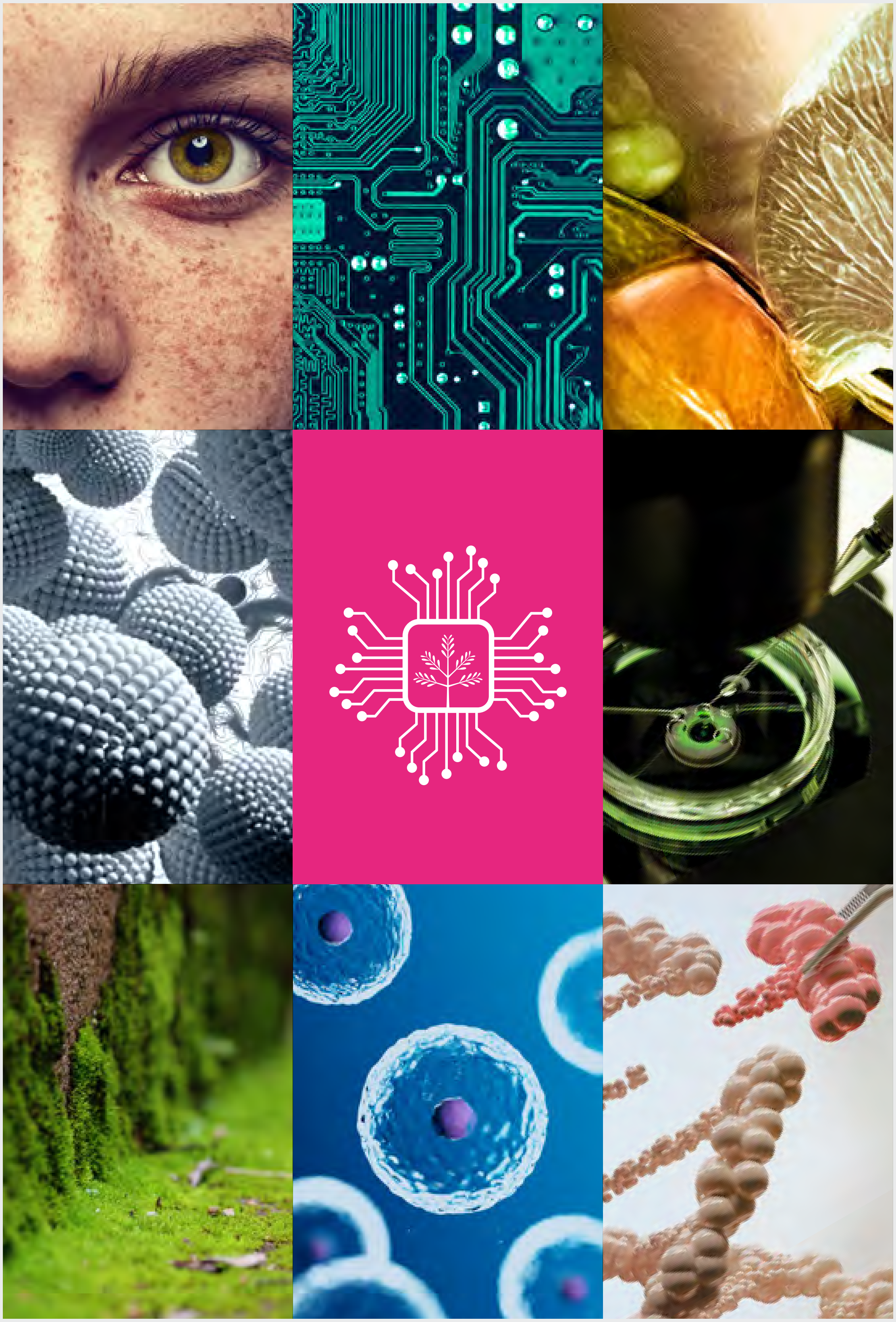

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