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Nature-like and Convergent Technologies

Driving the Fourth Industrial Revolution

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ABBREVIATIONS

4IR	Fourth industrial revolution
AI	Artificial intelligence
AR	Augmented reality
CRISPR	Clustered regularly interspaced short palindromic repeat
GMIS	Global Manufacturing and Industrialization Summit
IAI	Industrial artificial intelligence
ICNR	International Centre for Neutron Research
IDC	International Data Corporation
IFR	International Federation of Robotics
IIoT	Industrial Internet of things
IoT	Internet of things
NBICS	Nano-, bio-, info-, cogno-, and socio-technologies
NTI	National Technology Initiative of Russia
OECD	Organisation for Economic Co-operation and Development
PaaS	Products-as-a-service
R&D	Research and development
R&D&I	Research, development and innovation
SDG	Sustainable development goal
SLM	Selective layer melting
SMEs	Small and medium-sized enterprises
SSRS	Specialized synchrotron radiation source
STEAM	Science, technology, engineering, arts and mathematics
TVET	Technical and vocational education and training
UNDESA	United Nations Department of Economic and Social Affairs
VR	Virtual reality
WHO	World Health Organization

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While human ingenuity may devise various inventions to the same ends, it will never devise anything more beautiful, nor simpler, nor more to the purpose than nature does, because in her inventions nothing is lacking and nothing is superfluous.

Leonardo da Vinci

INTRODUCTION

Today we are faced with a crucial challenge of realizing sustainable development in the face of an ever-increasing demand for energy and natural resources, primarily water, food and other bio resources. As Kovalchuk et al. observe, the primary cause of the current crisis lies in the antagonism between biosphere (natural capital) and technosphere (manufactured capital) formed over the past 300 years.[1] Creating our civilization and interacting with nature, humanity behaved not as an integral part but as a dominant force, exploiting natural resources in unsustainable ways. Over the course of the industrial revolutions, people have perfected industry, which benefited from technological advancements. The scale of production increased, but its harm to the biosphere also increased, today approaching a critical threshold. The deep-seated contradiction between nature and the technosphere caused the ever-growing threat of natural resource depletion and of environmental, climatic and technological disasters.

The history of science, primarily physics, shows that the end result of an ever-deeper penetration into the properties of matter was the discovery of new types of energy: thermodynamics, steam energy (steam engines); electrodynamics and electricity (electric generators, electric motors); atomic physics and nuclear and thermonuclear energy (atomic and thermonuclear reactors). In the process of this development, energy generation grew by more than three million times, but human energy consumption grew even faster. Nature-like and convergent technologies are essential for collaborative engagement with nature in this new era of digitalization. A conjunction of digital technologies and nature-like technologies will allow us, for the first time, to understand the natural world, social events and humanity as complex, hierarchical systems.

Nature-like and convergent technologies promise unprecedented and previously unimaginable possibilities. The basis of convergent technology is connecting the capabilities of modern digital technologies, such as microelectronics, with the creations of nature. Advances in electronics, nanoscience, bioscience, information technology, cognitive science, social sciences and humanities, and their integration, will allow us to develop previously unachievable human-centred utilities and services to improve our lives and leapfrog traditional impediments. These technologies are also referred to as frontier technologies because they are innovative, fast-growing, deeply interconnected and interdependent and are driving the fourth industrial revolution (4IR) forwards.

In industry, emerging technology trends, such as big data, cloud computing, industrial artificial intelligence, additive manufacturing, industrial internet of things, blockchain and new materials are changing the face of manufacturing, manufacturing-related services and the future of work and industrial skills. Nature-like and convergent technologies are being used to create new values by designing new materials, products and processes in industry and to pursue circular economy, thus enabling sustainable consumption and production patterns. Technological convergence has also allowed creating nodes for convergence between previously separate industries and economic sectors, facilitating economic diversification. Industries traditionally led by a few leading companies are adopting open innovation models to bring perspectives from other industrial and economic sectors. Furthermore, agriculture is industrializing with new technologies, removing the limitations of land and of decreasing returns to scale in some subsectors.

FIGURE 1

Global Forum on Naturally Based and Convergent Technologies

From the plenary session on *Naturally Based Technologies as a Response to Global Challenges* at the Global Forum on Naturally Based and Convergent Technologies, with Mikhail Kotyukov, Minister of Science and Higher Education of the Russian Federation, Andrey Fursenko, Chairman of the Board of Trustees of the Russian Science Foundation, and Hiroshi Kuniyoshi, Deputy Director General, UNIDO

Source: UNIDO (2018).

The exponential technological progress of the 4IR, propelled by self-reinforcing processes of technological change, presents challenges and risks. Today's governance systems and accompanying institutions are inadequate to ensure a smooth transition to the 4IR. Their working principle had been to respond to the needs of the second industrial revolution, characterized by factory-based mass production, where economic development was conceived as linear and mechanistic. With 4IR evolving, laws, norms, standards, mind sets and regulations require change and adaptation. To this end, governments will need to work closely with academia, business and civil society.

Multilateral online and offline platforms are needed for expert dialogue on nature-like and convergent technologies, their implementation, governance, management and oversight. The transition from techno-optimism and techno-pessimism to a new, science-based agenda for governing and managing future disruptive technological changes needs to be informed by discussion among established authorities. One such initiative was the Global Forum on Naturally Based and Convergent Technologies convened in Sochi, Russia, from 28–29 September 2018 (figure 1).

The forum sought better understanding of the challenges and opportunities of nature-like and convergent technologies. The stakeholders it drew included convergent technology experts, government representatives, international development organizations, financial development institutions and the private sector. Panels covered new approaches to global challenges through nature-like technologies, the alignment of 4IR and nature-like technologies, operationalizing and commercializing nature-like technologies, megascience projects underlying the development of nature-like technologies, the role of development institutions and challenges to international security.[2] The forum was the first event of its kind organized specifically to discuss nature-like and convergent nano-, bio-, info-, cogno- and socio- (NBICS) technologies driving the 4IR. The key topics were:

- Recent industrialization trends and technological progress driving the trends.
- Key concepts and issues behind nature-like and convergent technologies—their current status and projected future.
- The importance of building awareness of nature-like and convergent technologies and their implications for inclusive and sustainable economic development in developed and developing countries.
- Lessons from enterprises and institutions conducting in-depth research and development and applying the emerging technologies in industry.
- The impact of nature-like and convergent technologies on the environment; on material, energy, and human resources; and on inclusiveness of marginalized countries and disadvantaged population groups.

- Benefits of standardization to ensure interoperability in industry.
- Barriers to the uptake of digital, nature-like and convergent technologies in industry in developed and developing countries, and policy implications.
- Industrial and technology trends, policy coordination and workforce skill requirements.
- Addressing skill mismatches at the national level, such as the lack of digital skills and qualifications in science, technology, engineering and mathematics.
- The role of financial development institutions and international organizations, such as the United Nations Industrial Development Organization (UNIDO), in supporting digital and convergent technologies, their application in industry and cooperation in relevant risk assessment, management and communication mechanisms.
- Follow-up actions to build awareness of the potential of digital and convergent technologies for supporting the 2030 Agenda for Sustainable Development and related Sustainable Development Goals (SDGs)—in particular SDG 9 for industry, innovation and infrastructure.

1

NATURE-LIKE AND CONVERGENT TECHNOLOGIES AS A RESPONSE TO GLOBAL CHALLENGES

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Aleksandr Sergeev, President, Russian Academy of Sciences

This session addressed opportunities of nature-like and convergent technologies, the concept of technological convergence through nano-, bio-, info-, cogno- and socio- (NBICS) technologies (figure 1.1) and biomimicry. The chapter is based on the conference presentations and research papers produced by the Kurchatov Institute staff, led by Mikhail Kovalchuk.

Technogenic and anthropogenic problems have driven the biosphere—the surface of the planet occupied by living things—to critical degradation. Each of the scientific and technological revolutions in the history of civilization resulted in economies of scale and scope but at the cost of a distorted balance between biosphere and technosphere, casting doubt on the preservation of civilization itself.

Our society has acknowledged the need to change how we treat the planet and its resources. Many anthropogenic environmental problems are discussed at the global level, as they become more destructive, such as urbanization, deforestation, unsustainable consumption patterns, contamination of natural water resources, and global warming due to excessive emission of greenhouse gases into the atmosphere.

Climate change is the most notable problem of modern society. Many scientists believe that the main factor contributing to global warming is the exhaustion of the ocean buffer to increasing temperatures—the straining of oceans' heat sink capacity as the carbon dioxide dissolved in them increases, changing their composition.[3]

The emergence of large urban communities and megacities (with a population of over 10 million) threatens 21st-century social and environmental sustainability. Megacities, in addition to their great environmental impact, pose significant problems for health and well-being. Some 92 percent of the world population lives in areas where air pollution exceeds the guideline levels set by the World Health Organization (WHO).[4]

At the global level, access to clean water and sanitation is a priority. As more and more people strive to control water sources, water has become a valuable resource due to its scarcity in some regions. In response, processes such as filtration using nature-like technologies may enable the provision of water similar to natural conditions.

Access to energy is another issue. The manufactured technosphere is extremely energy-intensive today. For instance, processing and receiving one simple voice message sent from a smartphone consumes the same amount of energy as boiling 1 litre of water (about 0.1 kWh). According to the International Energy Agency, by 2025 the share of energy consumed by the information and communication sector (terminals, user network equipment, network communications and data centres), without counting energy consumption by the information and computing infrastructure of the industrial sector, will exceed 30 percent of the world's electricity production.[5] This will create serious energy constraints for the digital economy in the near future.

Competition for natural resources has become a critical issue in economics and politics. It can cause conflict between states, even military ones. But the real pressing challenge has been largely ignored—maintaining the fragile balance between nature and economies to keep our planet alive, the antagonism between natural and man-made capital. To address this global challenge, the scientific community faces the difficult task of rethinking how humans and economic systems should interact with nature.

The only solution is creating a technosphere based on technologies that reproduce systems and processes of living nature in the form of technical systems and technological processes integrated into the natural resource flow. Scientists see the solution in nature-like and convergent technologies. According to Kovalchuk et al.,[6] such technologies should form the basis of a fundamentally new technological base of civilization. The purpose of creating a nature-like technosphere is to restore a kind of "metabolism" to nature—a natural self-consistent resource turnover that has been disrupted by today's technologies and torn from the natural context.

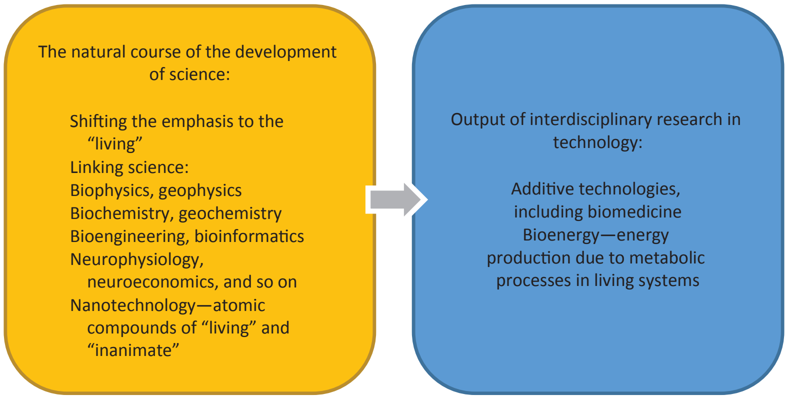
The nature-like technosphere is not an artificial speculative construction, but a natural, regular stage of the scientific and technological development of humanity.[7] The origins of the idea of nature-likeness, as well as the reasons for its recent identification, are rooted in the peculiarities of cognition. The historical cognitive and transforming activity of humans developed from their perception of the surrounding nature, as an incomprehensible but integral whole, through segmented models of nature that are accessible to analysis and through the formation of highly specialized sciences and economic sectors.

At the initial stages, there was natural philosophy. Subsequently, physics, biology, chemistry and other natural sciences stood out on the *natural* side, while the *philosophical* side became the incubator of the humanities—psychology, sociology, history and linguistics. That natural process accompanied the first industrial revolution, the era of geographical discoveries, when the thrust of new knowledge required the isolation of individual disciplines. Following the path of in-depth knowledge of the world, accompanied by the division of the subject matter into ever smaller fragments, science has studied many processes in detail but has lost an integral picture of the world.

Over time, the reverse process, the fusion of sciences, began on a new level of the dialectical spiral. Its origin dates back to the end of the 19th century, when linking sciences began to emerge, such as biochemistry, geochemistry, biogeochemistry and so on. The development of science was increasingly determined by the integration and interpenetration of various areas, which led to the emergence and expansion of the interdisciplinary research that has emerged today in technology (figure 1.1).

FIGURE 1.1

From interdisciplinarity to nature-likeness

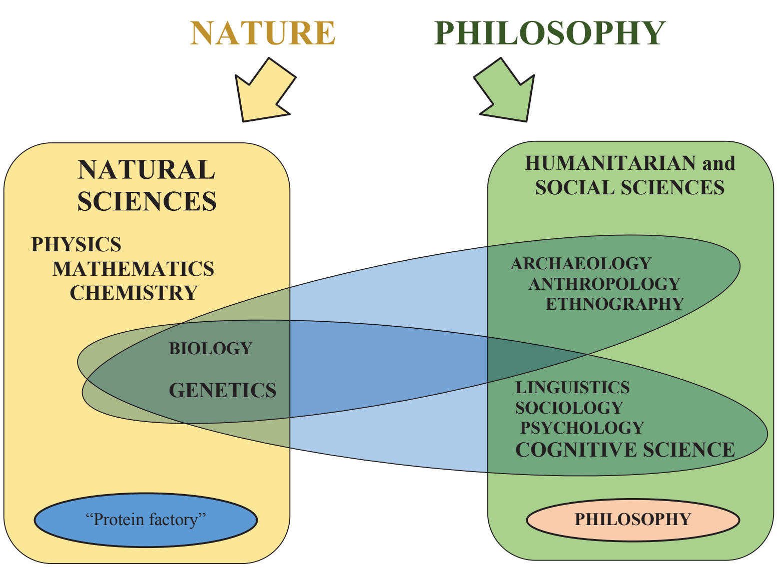


Source: National Research Centre (Kurchatov Institute).

These processes have spread to the human sciences, which combine with natural science. For example, cognitive research was originally carried out by the methods of linguistics, psychology and sociology. Today, the main tools for cognitive research are positron emission and computed tomography, magnetic resonance imaging and other physical methods. The results obtained are described in concepts and terms of physics, mathematics, computer science and other natural sciences (figure 1.2).

FIGURE 1.2

Natural, humanitarian and social sciences



Source: National Research Centre (Kurchatov Institute).

To search for tools for creating nature-like technologies, the emergence and rapid development of supra-disciplinary, supra-industry information technology and nanotechnologies are of great scientific and methodological importance. Information technology considers the storage, processing and transmission of information regardless of its kind. In this sense, it connects the living and nonliving at the information level. Nanotechnology, as a methodology for constructing materials of any type by atomic-molecular manipulation, connects living things with non-living things at the atomic level. Thus, nano- and information technologies return science to a holistic picture of the world and serve as the basis for creating tools for nature-like technologies.

Today, the convergence of nano-, bio-, information, cogno- and socio-humanitarian sciences and technologies (NBICS—or convergent technologies) serves as such a tool, with each part performing its own functions. Nanotechnology, operating with atoms and molecules, makes it possible to obtain a fundamentally new substance or material with desired properties, using the same technological methods as nature itself. Additive technologies make the product, while saving material and cutting waste. The symbiosis of nano- and biotechnologies allows not only reproducing living matter, but also creating fundamentally new bioorganic materials and structures. Such materials are already used, in particular in medicine. Information technologies make it possible to reproduce the natural processes of information transformation in artificial objects.

Synthesizing nature-like systems, humanity will approach the creation of anthropomorphic technical systems with elements of consciousness and the ability to know. To pursue this, cognitive science and technology are needed. At the next stage, we will talk about creating a community of anthropomorphic devices and systems that interact with each other and with the external environment, including humans, and are endowed with social functions. Finally, in order to make rational and effective use of the capabilities of convergent sciences and technologies, a radical transformation of human social consciousness is necessary. All this is possible only through the integration of nano-, bio-, informational and cognitive technologies with the achievements of social sciences and technologies.

A better understanding of the laws of nature will further scientific discoveries and innovation as well as increase energy efficiency without harming the planet, thus helping countries to realize sustainable industrial and economic development.[8]

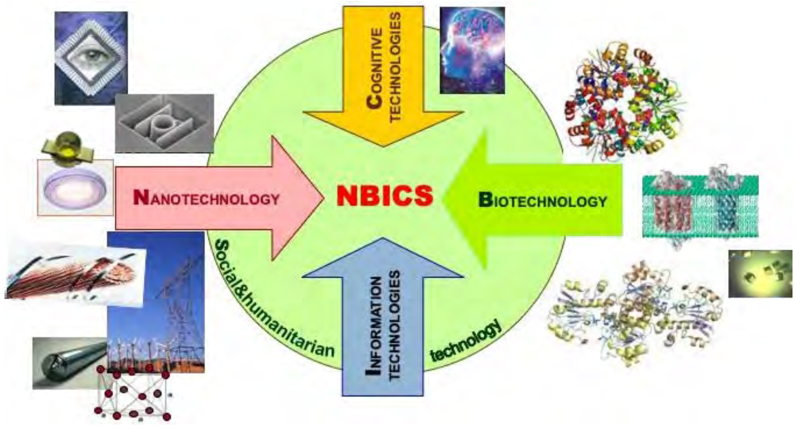
Convergence in sciences is merging scientific disciplines and technologies, creating biosimilar materials and devices and, in the long run, enabling harmony between the techno- and biospheres. Merging organic and inorganic chemistry in new materials and devices, coupled with information technology and the "vivification" of resulting systems with algorithms imitating the working process of a human brain, is a new stage of cognition. It is not simply an interaction between separate technologies for the sole purpose of achieving sustainability, but rather the collaboration of disciplines that at first sight are distinctly different.

The preservation and future of civilization depend on the emergence and development of convergent technologies—NBICS. The NBICS technologies will create a harmonious noosphere in which the biosphere, technosphere and sociosphere supplement each other and are closely interconnected and convergent. However, without a change in human consciousness and approaches to civilization, these prospects could be empty (figure 1.3).

According to Mikhail Valentinovich Kovalchuk, the President of National Research Centre (Kurchatov Institute), humans achieve significant breakthrough discoveries using still-developing principles based on the highly specialized study and analysis of the world around them.[9] Convergent sciences will raise civilization to a new stage of development that overcomes the main discrepancies of the modern technosphere—the techno physical objects in the environment—environmental

FIGURE 1.3

The nano-, bio-, info- and cognitive technologies converge to build a new noosphere



Source: Kovalchuk, Naraikin and Yatsishina (2012).

pollution, resource depletion, food scarcity and a resulting struggle to secure scarce resources.

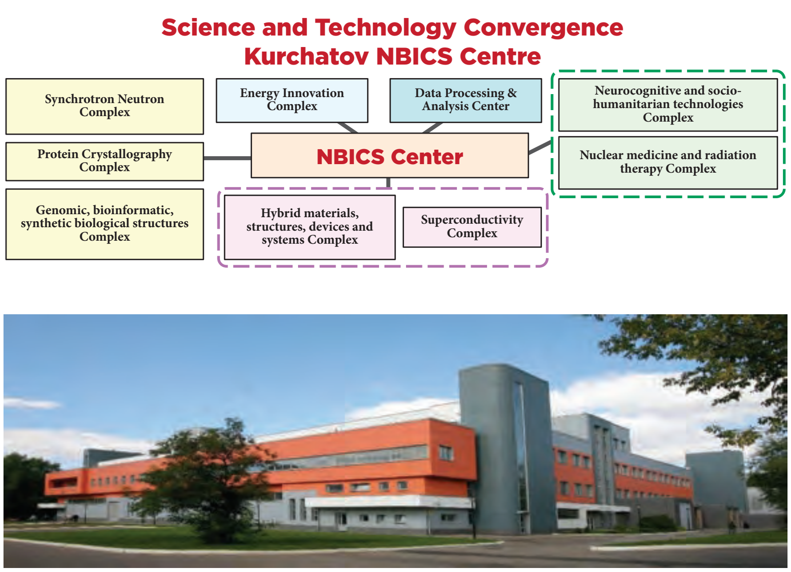
Convergent technologies will change how production is organized, and inevitably, socioeconomic relations. A modern human being as the subject of practical and cognitive relation to the world itself, sooner or later, becomes the object of scientific and technological influence. That is why the "S" component in NBICS—socio—is essential (figure 1.2). The emerging socio-humanistic issues must be solved jointly with scientific and technological ones.

In the early 1960s, it was predicted that if developing countries, for example China or India, reached the energy consumption level of the United States, a worldwide resource collapse would follow. Today, such a collapse would affect all socio-economic aspects of public life—economics, finance, energy, environment, social connections and political systems.

At the beginning of the first industrial revolution, our planet supported 500 million people, now the population has surpassed 7 billion. Without new technologies, it is impossible to provide even the minimum living requirements. The artificial technosphere (physical or man-made objects) has reached an unprecedented size. As a result, 60 percent of dryland territory is so intensely utilized that animal and plant life is running out of space.[10] Humans are consuming greater amounts of the biota,[11] causing imbalances, severe loss of species and growing threats and effects from climate change. For nearly 300 years, humans have constantly increased labour productivity and production output through scientific and technological progress, without considering the effects of that growth. Today the technosphere is an ever-greater burden on its surrounding nature.[12]

The Kurchatov Institute's NBICS Centre (figure 1.4)—where nanotechnologies are already being combined with the achievements of molecular biology, bio- and genetic engineering, and microelectronics—has established the infrastructure for convergent nano-, bio-, info- and cognitive studies. The centre uniquely combines mega-installations, synchrotron radiation and neutron sources, a supercomputer, nuclear power, electron microscopes science and clean room areas to develop super-pure semiconductors, new biomaterials and hybrids of living and non-living structures.

FIGURE 1.4
The Kurchatov NBICS Centre, Russia



Source: National Research Centre (Kurchatov Institute).

Among others, the goal of convergent technologies is a new energy industry, since only sufficient energy can ensure sustained development. Solar power models the natural process of photosynthesis by using a semiconductor structure, unlike green leaves that have a hard-to-reproduce bio-organic structure.

In nature each quantum of sunlight is used with high efficiency, because nature is a very economical power user. But in the artificial technosphere we use machines and mechanisms that consume a huge amount of energy, and nature-like conserving technologies may not provide enough for them to work. What's next? Following nature's example, one can build essentially new technologies and hybrid systems that consume a very small quantity of energy.[13]

The natural, self-sufficient and self-regulating processes of the biosphere are integrated and harmonious. They have maintained a cyclical exchange of energy and matter for millions of years. Human development over the ages has achieved significant scientific and technological feats, including greater labour productivity and unprecedented levels of production. At the same time, the relationship between the natural environment and the ambitions of humankind has created deep contradictions.

The disregard for nature has come at a great cost. For example, through industry's technological activity, five to six billion tons of living matter is lost each year. This collision between the biosphere and the technosphere has disrupted human consciousness. That is, "the man-made technosphere has triggered an antagonistic contradiction with nature."[14]

This is not new, as some have been quick to highlight. V. I. Vernadsky wrote, "In the geological history of the biosphere, a bountiful future will open up before mankind if it does not use its intellect and labour for self-destruction."[15] Human neglect of its responsibility has led to a systemic crisis encompassing civilization. To respond, the foundations of the entire technological enterprise must be restructured, with the “inseparable relationship of its scientific, industrial, sociopolitical, and humanitarian components.”

Human influence on the evolution of the biosphere has been of great importance, and the growth of industrial society made this more apparent. According to Vernadsky, “the biosphere of the 20th century is turning into the noosphere, created primarily by the growth of science, scientific understanding and social labour of mankind that is based on it.”[16]

Historically, with the accumulation of knowledge and the growing complexity of cognitive tasks, “man began to artificially partition unified, integral, and therefore extremely complex natural systems into simple segments accessible for analysis,”[17] making way for the appearance of branches of science. As knowledge expanded, the sciences took highly specialized directions giving “birth to segmental technologies and predetermined the segmental form of industrial organization.”[18] The segmented technologies are models of particular natural processes isolated from an integral natural system and replicated in artificial conditions to obtain certain products. Only the components of natural processes needed to make a product are replicated, and all other components are ignored.

The technosphere today, with such segmented principles, cannot be “objectively harmonized with the biosphere and converted into an organic part of nature.”[19] So technological solutions suggested for global ecological problems only have a local effect. The author infers that “mankind faces a complex and ambitious task: creation of fundamentally new technologies and energy systems, i.e. the replacement of today’s energy systems by ones that replicate living nature.”[20] The creation of a noosphere, where the technosphere will become an organic part of nature, is needed: “it is necessary primarily to discard the segmental approach to science and technologies and switch to a paradigm of convergence of science and the construction on its basis of fundamentally new convergent technologies.”[21] The scientific process no longer copies, but instead creates natural systems through the convergence of sciences and technologies.

An example is nanotechnology, developed by “a new technological culture based on the ability of direct manipulation of atoms and molecules to obtain fundamentally new substances, materials, structures and systems having preassigned properties. In this capacity, nanotechnologies are a super-segmental field of research and technologies, integrating special natural sciences. As a unified material basis, nanotechnologies make it possible for man once again to comprehend the world as a unified whole and, most importantly, to replicate this world using the same ‘technological methods’ that nature does.”[22]

To take advantage of this possibility and create a new technosphere harmonized with the natural environment, humanity “in essence faces the necessity of replicating objects of technology and technological processes.”[23] However, this is impossible without the mutually complementary combination of nanotechnological approaches with achievements in molecular biology, bioengineering, genetic engineering, and so on. Ultimately, an interdisciplinary symbiosis is needed.

The convergent technologies address human beings’ needs. The new materials and systems are used for housing, transport, medicine, production of goods, communication and environmental protection. The convergent technologies also increase people’s physical and mental abilities significantly. At the next stage science will become able to reproduce systems and processes of living nature (for example, synthesizing cells, artificial tissues and organs) like living organisms composed of proteins determined by DNA—biological structural elements of nanometre range.

Examples of nature-like technologies include:

- Light-harvesting photonic materials that mimic photosynthesis, structural composites that imitate the structure of nacre (mother-of-pearl), and metal actuators inspired by the movements of jellyfish.

- Architectural bionics—the use of natural forms in the construction of architectural objects, as part of the synthesis of nature and modern technology.
- Sonar for submarines, the principle of action that was inspired by dolphins.
- Boundary layer polymer fluids (polyethylene oxide and acrylamide), an analog of mucus covering the bodies of fish, for submarines that reduce hydrodynamic resistance and increase speed.
- Devices with bionic principles of movement and positioning.
- Biomineralization—controlled formation of biocomposites, which is promising for shipbuilding. Currently, options are being explored for biomineralization in coatings and structural solutions. Such processes can also serve as a platform for creating new interesting crystal structures for fields such as microelectronics, medical applications, biorobots and robotic systems.

Industrially significant nature-like technologies are presented in box 1.1.

The most promising areas for uptake of nature-like and convergent technologies include:

- Solar power engineering, enabling the construction of cheap solar systems for heating and hot water that can be used in developing and least developed countries.
- Fast bio-testing technologies, allowing rapid testing in order to confirm the presence or absence of specific substances in various environments.
- Filters, catalyst technology and other equipment and materials for water purification.
- Cheap autonomous buildings with self-sufficient energy systems adapted to local conditions for heating, cooling and cooking.
- Hybrid cars with combined engines operating from various sources, saving non-renewable energy sources, especially during stops.
- Cheap sensors at public places and industrial sites, allowing real-time monitoring for combating international terrorism and boosting industrial safety.
- Technologies for the circular economy and its effective use of material resources, by eliminating or significantly reducing waste production and the use of toxic materials in production.
- Radio frequency identification of commercial goods, allowing just-in-time supply chains and boosting industrial safety.
- Miniature computers that can be mounted in various items.
- Quantum cryptography, for using quantum methods to encode information when transmitted.
- Rural wireless communication systems, enabling wide use of telephone and internet communication.
- Genetically modified cereals and forest cultures, enabling production of food products with additional vitamins and trace elements; adaptation of grain crops to local conditions, permitting increased food production; and increased resistance to agricultural pests, allowing reduced use of pesticides.
- Targeted medical therapy in the human body, delivering the drug to a particular tumour or pathogenic microorganisms without harming healthy tissues and cells.

BOX 1.1

Examples of industrially significant nature-like technologies farthest advanced in Russia

Nature-like technologies and materials for medicine

Protein-based materials—analogs of natural cells: These materials are absolutely biocompatible with human cells, biodegradable to individual amino acids and nontoxic. They are used in regenerative medicine for manufacturing artificial vessels and artificial neurons, and for generating muscle cells of the heart and cartilaginous and bone tissue. A single gram of protein tissue is enough to cover thousands of stents or other transplants. Pilot facilities have been established and experimental–industrial manufacturing technology is being developed. These medical devices are currently being tested.

A new generation of drugs based on artificial monoclonal antibodies: At present, the technologies for creating artificial antibodies and their production in large quantities are being mastered by Russian pharmaceutical companies. The first Russian medication based on monoclonal antibodies, Azellbia, is currently available. It is used to treat lymphoma, a type of cancer.

Tissue-engineered bioartificial equivalents of human skin, trachea, airway epithelium and bile ducts based on recipient cells and artificial polymeric matrices: These elements possess the ability to stimulate the budding of blood vessels from the recipient tissue and the formation of a vascular micro network. The mechanical properties of the materials are identical to those of natural biological tissues. They are used in regenerative therapy, first of all in burn therapy, as well as for preclinical and clinical trials of medicinal, cosmetic and protective products.

Pilot industrial technology and equipment for 3D additive production of biomodels, implants and fragments of human organs: These use individual tomographic data of the patient, transferred remotely from medical institutions directly to the production centre. They have been tested in dozens of Russian clinics.

Neurocognitive technologies

A prototype of the neurocognitive interface intuitively controlled by brain activity: It can be used in control systems of biomedical devices (bioprostheses, wheelchairs for disabled people, and so on), pilotless aerial vehicles and robotic complexes.

Technologies for revealing the mechanisms of hidden human memory by using magnetic resonance imaging (a new generation polygraph): They can be used to solve a wide range of problems from rehabilitation of patients with brain disorders and central nervous system disorders to revelation of a hidden goal setting.

Source: National Academy of Sciences (2014), Russian Federation.

- Tissue engineering technologies, enabling the design and replacement of human organs.
- Improved methods of diagnosis and surgery that will increase the accuracy and effectiveness of surgical procedures, thereby reducing invasiveness and recovery time.

Sustainable economic development opportunities for nature-like and convergent technologies

Convergent technologies will provide breakthroughs and solutions for sustainable development. The new materials created have great potential for realizing energy efficiency and renewable energy, both in conversion and storage. They are more efficient and their environmentally acceptable industrial separation and cleaning processes are protecting the environment, and are enabling a circular economy.

Energy efficiency

Nature, existing for millions of years within the framework of a closed, self-consistent resource turnover, does not know resource crises or energy hunger. The explanation is in the striking balance of the natural system and the extremely high energy efficiency of natural objects. For example, the human brain consumes no more than 30 watts, while modern super-computers consume tens of megawatts (MW). At the same time, the effectiveness of all computers in the world does not reach the effectiveness and efficiency of the brain of an average person (see box 1.9). So, merely increasing energy generation is not enough; revolutionary changes are needed in energy consumption technologies.

In 2010, 15 percent of the world's population lacked access to electricity and 29 percent relied on traditional biomass for fuel. Energy is geostrategic and essential for the world's future. As the world population increases—it is projected to be around 10 billion by 2050—clearly energy is the single most important commodity for peace, commerce, security, overcoming poverty and ensuring quality of life.

According to Christophe Béhar, FAYAT Group, new energy sources never completely replace the preceding dominant source.[24] In view of the greenhouse effect, nuclear fission, nuclear fusion and renewables are likely to co-exist in the future. The key task in ensuring energy efficiency while imitating nature is to understand how fundamental energy processes work in living systems. Using the metabolic energy of organisms to produce electricity is an example of a nature-like technology in energy.[25]

About two billion years ago, seventeen nuclear fission events occurred naturally in Oklo, Gabon, in Western Africa. Despite their modest power output (100 kilowatts on average), the Gabon natural nuclear reactors were remarkable because they were spontaneous, and they continued to operate in a stable manner for up to one million years.[26] More recent work has tried to imitate the ways stars produce energy—by nuclear fusion. Many experiments are now conducted with new technologies in the field of renewables. If this new energy mix of nuclear energy and renewables replaces current energy production, future producers and consumers must be more closely connected to networks and storage capacity for usage to be efficient. Another challenge comes from local generation, which will enable users to be both producers and consumers. Future electricity supply has to be flexible, accessible, reliable and economic.

Future electricity networks will be similar to the internet because decision making will be distributed and bidirectional in flow. Artificial intelligence will direct smart grids to balance production and consumption. Huge quantities of data will be created, stored and analysed in real time. However, cybersecurity will become an even bigger challenge.

Energy storage systems can be based on mechanical factors, electrochemistry, batteries, the production of hydrogen, the use of magnetism, superconductivity and super capacitors or phase change materials for thermal systems. However, while there has not been a real breakthrough, nature-like or convergent technologies could help in finding a solution moving forward.

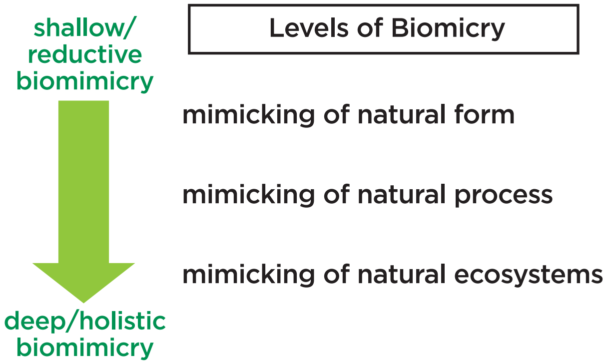
For example, nanomaterials will allow the production of new electrodes for hydrogen production or storage. Carbon nanotubes could help build supercapacitors or even increase the efficiency of fuel cells. Similar technologies need to be harnessed to reduce the use of non-renewable energy sources and to help the low-carbon power industry develop.

Biomimicry (figures 1.5, 1.6; box 1.2) is influencing sustainable design and innovation to save materials and energy in a variety of fields such as in industry and urban infrastructure planning, design and management.

Environmental management

Geospatial monitoring platforms use advanced sensors and satellite imagery in combination with large-scale data analytics to track and monitor activities in important environmental systems. The rapid development of satellites, drones and sensors, supplemented by intelligent algorithms and technologies, could provide a real-time flow of data on greenhouse gas emissions. These practices

FIGURE 1.5
Levels of biomimicry



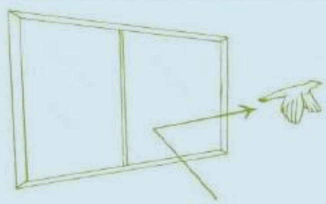
Source: Volstad (2008).

FIGURE 1.6
Examples of mimicking nature

Source: Biomimicry 3.8 (n.d.).

BOX 1.2
Biomimicry

Example: Safer windows inspired by spiderwebs



- Spiders weave UV-reflective strands of silk into their webs to prevent birds from flying through.
- Ornilux has created a transparent, bird-friendly glass including spider-inspired UV strands invisible to humans.

Source: Airbus (2018); Biomimicry Institute (2019); Aprilli (2014).

will significantly improve the transparency of reporting, monitoring and verifying data, all critical to the accountability and effectiveness of global climate agreements.

Advanced materials will change product design and manufacturing. Innovations in materials science and materials used will be critical to developing the next generation of environmentally sustainable technologies and products, including bioplastics (box 1.3), wind turbines, high-performance solar cells, electric vehicles, high-capacity batteries, low-energy desalination membranes, energy-efficient transportation systems and carbon technologies for high-performance data collection and storage.

Spatial monitoring and planning

Spatial monitoring and planning will also apply nature-like technologies. A 2017 strategic environmental assessment of the socioeconomic development strategy of the Novokuznetsk municipal district of the Kemerovo region offers a Russian example. The study assessed the average value of biodiversity of Novokuznetsk municipal district (thousand RUB /ha/year) and the value of ecosystem products and biodiversity resources of Novokuznetsk municipal district (million RUB/year). The assessments let municipal authorities consider the economic value of ecosystems and the economic damage and income generated from allocating land for various types of use.

BOX 1.3
Bioplastics

Plastic accumulation on land and sea is a rising global challenge that needs to be addressed urgently. Microplastics (smaller than 5 millimetres in diameter[1]) are polluting the environment, especially water. The debris, along with industry-related activities such as shipping, boating and fishing, damages fauna and flora in water bodies. It also harms coastal tourism, according to the *World Economic and Social Survey 2018*.[2] And floating plastics and debris can be breeding grounds for disease-carrying organisms and microbes.

Bioplastics—derived from renewable biomass sources, such as vegetable fats and oils, corn starch, straw, wood chips and food waste—offer a sustainable solution. They address "the needs of consumers without damaging our environment, health and economy."[3]

But the United Nations Department of Economic and Social Affairs has noted with concern that, as of 2014, bioplastics constituted less than 10 percent of the total plastics market. Furthermore, capacity for producing bioplastics was only 1.3 percent of total capacity for producing polymers.

Positive change will depend on the rate at which bioplastics can replace conventional plastics. Hence, investments in the plastics sector that can alter the way plastics are produced, consumed and disposed of, as well as in the production of bio-benign materials, should be encouraged.

Notes

1. https://oceanservice.noaa.gov/facts/microplastics.html.
2. University of Minnesota, Center for Sustainable Polymers (2018).
3. Peplow (2016).

Source: UNDESA (2018).

Nature-like technologies are also being used in the Russian Arctic for the restoration of disturbed lands. Methods for cleaning oil from the soil, such as dredging wetlands, active desorption of oil and microbiological methods, are used to combat oil pollution. The purification of old oil sludge with bio-preparations has proved to be more environmentally efficient than incineration or burial. The passive separation of oil sludge phases using bio-surfactants and the after-treatment of solid oil sludge with bio-methods turned out to be ecologically and economically more attractive alternative to soil-washing plants. Oil companies are actively cooperating with scientific institutions to improve such methods and to enable their practical implementation.

Virtual reality (VR) and augmented reality (AR) allow three-dimensional visualization of global changes on earth. The ATLAS VR virtual world, created from remote sensing data of earth from space, allows for visualizing changes occurring in ecosystems and for simulating the environmental consequences of planned projects. Using images taken from space, a digital copy reliably recreates the relief and landscape, flora and fauna, marked dump sites and simulated forest fires. These eco-monitoring data are then loaded into a virtual modelling system that demonstrates the progress of water, soil and air pollution and the effects on vegetation. The virtual space allows for modelling objects and complex phenomena and processes —natural disasters (fires, floods and hurricanes), artificial accidents and catastrophes—in variable scenarios. This artificial intelligence is used for risk assessment, strategy development and mineral resource estimation.[27]

Convergetics and synergetics

"Convergetics" denotes the entire multidisciplinary set of sciences, and the technologies based on them, that address nature-like and convergent properties. Convergetics is analogous to synergetics, the interdisciplinary scientific study of self-organization in living and non-living nature. Synergetics, from ancient Greek *synerge*—action—was proposed in the early 1970s by Hermann Haken, a German physicist at the University of Stuttgart, to designate a new discipline that studies the general laws of systems that organize themselves without external control. Synergetics studies systems with a very large number of parts, components or subsystems that interact in a complex way. Haken said that all phenomena in transition from disorder to order show a similar behaviour of elements with a cooperative, synergistic effect. Unlike traditional scientific fields, synergetics studies general laws of evolution—development in time and space—of systems of any kind.

This interdisciplinary methodology explains the emergence of macroscopic phenomena from the interactions of microscopic elements. The starting point for all research in synergy is an adequate description of a system at multiple levels.

Synergy covers all stages of the universal process of self-organization—its origin, development and destruction.

Synergetics provides an integral theory of order and chaos, describing the causes and mechanisms of emerging, relatively stable structures and their subsequent decay. The main properties and subjects of research are non-equilibrium, openness and nonlinearity. The last, nonlinearity, is an unusual reaction to external influences, when a "correct," although weak, impact influences the evolution of the system more than a stronger impact.

Convergetics refers to the convergence of sciences and technologies of a fundamentally new quality. The convergent development of knowledge through interdisciplinary research creates opportunities for a revolutionary effect—the emergence of a large number of breakthrough technological solutions and new applications (markets) in a fairly short time, due to a synergistic effect.

Convergetics includes the "big four" technologies: biotechnology, nanotechnology, information and communication, and cognitive technology. The future of the natural sciences lies in the development of these technologies and of interdisciplinary research in chemistry, physics and biology. According to M. Kovalchuk, in addition to these big four technologies there is a natural necessity to connect a fifth one, socio-humanitarian technology. Indeed, all these new principles of building the nature-like technosphere are only possible through their adaptation to society and to each human individual. Such humanitarian sciences as psychology, linguistics, culturology and art become more and more objective and measurable due to new physical IT methods and techniques that supply instrumental control and objectification to those sciences. Moreover, NBICS-technologies become part of everyday human life, through instruments and devices incorporated in medical care, activities, bodies and even minds, so that new principles of ethics, jurisprudence and social rights must be developed.

Information technology and nanotechnology should become the basis for the convergence of science and technology. Convergetics highlights the following modern developments in the natural sciences:

- A transition to nano dimensions.
- The development paradigm changing from analysis to synthesis.
- The rapprochement and interpenetration of inorganics and the organic world of living nature.
- An interdisciplinary approach in place of narrow specializations.[28]

Synergetics is fully included in convergetics and is a subset of it.

Convergence of life, bio- and medical sciences

Biotechnology offers methods and technologies for producing substances using natural biological objects (microorganisms and plant and animal cells) and their systems (cell membranes, ribosomes, mitochondria and chloroplasts), and the processes and products of their vital activity. Biotechnology is the field of knowledge and technological methods of manipulating living objects or their elements (components) to obtain biologically active substances, destroy harmful substances and materials and extract energy (box 1.4).

Technological development has allowed understanding the main properties of nanotechnology and exploring the structures and properties of inorganic, organic and hybrid biological material. Hybrid systems currently being developed, such as a microrobot with a bacterial flagellum as an engine, do not differ fundamentally from natural (virus) or artificial systems. The similar structure and functions of natural biological and artificial nano objects lead to a pronounced convergence of nanotechnology and biotechnology.

Combining cell, molecular and biological approaches with nanotechnology greatly increases the possibility of developing bio-artificial systems —functional anthropomorphic devices, materials and organs.

Bioartificial systems, since they can be used in place of people and other living beings, solve long standing ethical issues of testing treatments and modelling processes. Advances in non- invasive surgical procedures (no intrusion in the skin is created and there is no contact with the mucosa or internal body cavity beyond a natural or artificial body orifice), growing artificial organs and developing similar bioartificial products, all following nature-like principles for regeneration, and offer new medical opportunities. Understanding the organic processes of the natural environment and converging them with available innovations can make for great gains in biotechnology.

New high-tech industries using the principles of similarity and convergence include bionics (box 1.5) and synthetic biology (box 1.6). Constructive and systemic solutions inspired, initiated and tested by wildlife, formed the basis of the practical

BOX 1.4
The three revolutions: Molecular biology, genomics and convergence

The continuing integration of life sciences, physical sciences, medicine and engineering represents a third revolution in life sciences, building on prior revolutions in molecular biology and genomics.

Courtesy of Phillip A. Sharp, Massachusetts Institute of Technology.
Source: The National Academy of Sciences (2014).

BOX 1.5
Bionics

Bionics is a conceptual precursor to synthetic biology. It is a multidisciplinary field involving scientists, engineers, architects, philosophers and designers. They systematically investigate how nature has successfully solved a problem. Then they attempt to copy or redesign the process or object under study in a way divorced from nature. Bionics has branched off into many specialized fields, including construction bionics, sensor bionics, structural bionics, dynamic bionics, neurobionics, building bionics, process bionics, climate bionics, anthropo bionics/robotics and evolution bionics.

Processes and products in which bionics imitates the astonishing inventions of nature are classified into analogies and abstractions. Analogies include airplanes, spiroid winglets, new car tire profiles modelled on cats' paws and spider-like robots with autonomous legs. Abstractions include the lotus effect for self-cleaning surfaces, building elements that are modelled like trees or bones, riblet foils in imitation of sharkskin to reduce friction and Velcro in imitation of burrs. Other abstractions include swarm intelligence and ant algorithms, which create ant-like autonomous system behaviours.

Source: Sachsenmeier (2016).

technology for working with objects of biological origin.[29]

Bioengineering, an interdisciplinary field at the intersection of physicochemical biology, biophysics, genetic engineering and computer technology, creates new living systems and products with useful properties, applying technical tools and the principles of biology (box 1.7).

White biotechnology in the chemical industry has developed new processes, new raw materials and more sustainable and efficient use of resources (box 1.8).

In studying bio-informatic capabilities of the brain and the human body, a landmark goal is to uncover the mechanisms of action and achieve the level of efficiency created by nature (box 1.9).

Neurocomputers—based on nature likeness and convergence

Currently, the greatest potential of artificial intelligence (AI) lies in developing neurocomputers —neurosensors that allow, for example, the operator of a plant with different control systems to have a better overview of all its systems and processes. Current research aims at establishing hybrid systems to enhance or mimic particular human tasks, such as controlling robots through forward or direct kinematics, inverse kinematics, dynamic task allocation in multi-robot systems, and planning the route of the robot. While inverse

BOX 1.6
Synthetic biology

Synthetic biology dramatically shortens the time required for evolution. As an attempt to reshape creation, it is part of a long tradition. The nanoscale world of cellular building blocks is awe-inspiringly complex, and would be impossible to access without modern computers, data analytics and vast storage capabilities. In Germany, the Biotechnology 2020+ project brings together the major research institutions and networks in this field.

One important discipline of synthetic biology, DNA sequencing and synthesis, follows Moore's law and develops exponentially. While the first genome cost billions of dollars to sequence, the cost of an individual genetic test is now only a thousand dollars and is expected to decrease to just a few cents by 2022.

The following examples show existing products or indicate the directions of these novel technologies.

- Ginkgo BioWorks has an engineering platform with which it creates standardized microbes, or "biobricks," for all kinds of industries, while simultaneously contributing to an open source registry of biological parts.
- Protein Sciences uses worm cells instead of chicken eggs to develop novel vaccines, and hopes to disrupt the vaccine market by scaling faster than older methods.
- The U.S. National Aeronautics and Space Administration (NASA) has been investigating alternative foods for a long time. Seaweed has great nutritional value, which several algae companies, including Aurora Algae, Blue Marble Biomaterials and Solazyme, are trying to improve. Artificial meat grown in bioreactors is an attractive commercial target.
- At the Centre for Synthetic Biology and Innovation at Imperial College London, scientists are trying to feed pigeons a harmless lab-created microbe in order to make pigeon droppings much more environmentally friendly—thereby saving cities considerable cleaning costs.
- Defense Advanced Research Projects Agency (DARPA) has invested $135 million on one synthetic biology-related programme, Living Foundries. It focuses on the development of next-generation tools and technologies for engineering biological systems, with the goal of compressing the biological design-build-test-learn cycle by at least ten times in both time and cost, while increasing the complexity of systems that are created.[1]
- Sample6 Technologies develops sensors that detect harmful bacteria in the food industry in real time. Future markets include healthcare, retail food chains and water industries.
- Along with several industrial and public partners, Codexis is developing microbial genomes (biocatalyzers) able to absorb extraordinarily large amounts of carbon dioxide, in order to reduce emissions, and costs, and store carbon in alumina and fertilizer products.
- With the introduction of a tube of frozen, synthetically altered microbes, Mars could be terraformed and colonized. Photosynthetic algae and bacteria would trigger the development of a Martian habitable environment. Through bacteria, synthetic biology is the enabler of the colonization of other planets.

Note

1. Defense Advanced Research Projects Agency. https://www.darpa.mil/program/living-foundries.

Source: Sachsenmeier (2016).

kinematics helps determine the joint parameters (or angles) that provide a desired position for each of the robot's end-effectors (a device at the end of a robotic arm, designed to interact with the environment), forward kinematics will determine the coordinates of the end-effectors, given the joint parameters.[30]

The transition to neurocomputers is primarily associated with the limited placement of computing systems, as well as the need to implement effective control in real time. Mimicking the brain, technology is rapidly moving towards the systems found in nature, which are superior to today's computers—even supercomputers—in energy consumption, computing efficiency and parallelized workloads.

Developing neural systems like the ones found in humans is key to generalized artificial intelligence.

BOX 1.7
Synthetic biology and virtual evolution

Code engineering in synthetic biology will lead to virtual, rapid and often unforeseen evolutions. The structural analyses of proteins will be made easier because proteins can be changed artificially. Clustered regularly interspaced short palindromic repeat (CRISPR) is a recent innovation that enables alterations to any part of the DNA without unintended mutations and flaws. These advances have opened the possibility of targeting synthetic drugs directly at affected tissue, without the usual side effects to the whole human system.

New biomaterials can be created as implants, bone replacements or dialysis minilabs (if not as entire organs such as kidneys). Industrial enzymes will replace fossil oil–based chemical processes with biological processes. New minimal organisms will emerge as building blocks for a new biological diversity. Biomachines will turn straw into biofuel and will capture carbon dioxide from the atmosphere. Our artificial evolution will create living, surviving artificial cells and new biological species.

Source: Sachsenmeier (2016).

BOX 1.8
White biotechnology

White biotechnology, also called industrial biotechnology, applies science to living organisms and their products. In contrast to synthetic biotechnology, white biotechnology uses the existing biodiversity of nature to establish industrial processes that are often linked to expectations of ecologically beneficial effects. White biotechnology has old roots: humans have used living microorganisms in the production of breads, beers, wines and cheeses for centuries.

Today, enzymes and microorganisms are contained in many everyday items, ranging from detergents to creams, including high-value chemicals, drugs and vitamins, and are used in producing textiles, paper, leather and antibiotics. White biotechnology has strong links with bionics, for example, in the use of enzymes, the recreation of spider silk with the help of bacteria, and the production of highly elastic rubber from plants other than rubber trees. It encompasses the biosciences, chemistry, physics, information science and the engineering sciences. The research landscape of white biotechnology typically consists of institutes in collaborating clusters.

Source: Sachsenmeier (2016).

Neural networks have proven to be a stepping stone in the path to a more advanced artificial intelligence system. Research is promising but still has some ways to go.[31]

Neurochips and neurocomputers

The goal of developing neural network algorithms is to create an architecture resembling a neuron that is adequate for the problem scientists want to solve. To implement neural network algorithms using universal microprocessor-based tools, it is more efficient to create a special architecture than to use standard algorithms.[32]

Unlike other areas in the development of supercomputers, neurocomputers provide an opportunity to advance using the existing potential of the electronics industry.

The important features of research in this field are the following:

- Neural networks allow increasing performance of supercomputers without the need to develop exotic materials (for example, processors).
- Combining neural networks with others leading research and technologies allows improvement and breakthroughs such as optoelectronic and optical neurocomputers, molecular neurocomputers and nano-neuroelements. There is a need for universalization of CAD neurochips.
- Starting with nano-neuroelements, research is closely approaching new architectural

BOX 1.9
Power of the human brain

Human eyes capture about 126 megapixels. In one second our vision receives 21.45 gigabytes, while in the same second a video on the iPhone 7 will take in 375 megabytes.

There are about 100 billion neurons in the brain, each of which creates about 1,000 potential synapses permitting storage. The brain theoretically has 100 terabytes of information. By comparison one of the world's most powerful supercomputers, Titan, has a total system memory of 710 terabytes.

According to the scientific channel Veritasium, by 2020 the volume of all information stored by humans will reach 40 zettabytes. Now compare: the human body already contains 60 zettabytes of information.

Human genetic information takes up only 1.5 gigabytes of memory, about the same as the iOS 10 operating system. The brain uses as many resources as it needs at a particular moment. Its work can be compared with listening to the radio: it is always tuned to only one station, though there may be 100 in the available range.

About 100,000 chemical reactions take place in the brain per second.

The brain and the human body have a huge compensatory ability and can work even with serious injuries, a strength that cannot be matched by even the most powerful gadget in the world.

elements to improve high-performance computing systems.

Thus, neurocomputers are a promising direction for modern high-performance computing, and the theory of neural networks represents a priority area of computational science.[33]

Convergent or nature-like technologies in medicine

The development of healthcare with the help of NBIC technologies is extremely promising. The implementation of this very broad application has already begun.

Nanoscience will contribute to molecular or atomic convergence in some areas. Biotechnology makes it very easy to work with DNA. Big data will allow manipulation of huge amounts of information created in healthcare. Google, Apple, Facebook and their analogues in China, such as BATX, Alibaba, Tencent and Xiaomi are actively investing in this area. The area represents a huge market, especially if the average life expectancy of people increases.

Breakthroughs in medicine will come faster—much more will be done in the next 30 years than in the past 300. Humanity will change as a result. Many people expect changes for the better: we will be smarter and live longer. Disability, illness and old age will disappear. However, there is a risk of perpetuating current inequalities.

Nature-like technologies for active longevity

The new medical opportunities call for nature-like and convergent gerontological technologies. They may abolish the structural basis of aging and death, as regenerative processes are approved for the recovery and maintenance of the homeostasis of the organism, its systems and organs.

This arsenal of technologies is a "designer" assessing the state and age of the organism and its parts, evaluating possible treatments and individualizing the choice of rejuvenation methods and processes.[34] Rejuvenation methods can be divided into three groups: (1) cancelling the evolutionary genetically determined programme of aging and death, (2) eliminating "breakdowns" and disease states—both hereditary and those acquired during the lifetime, and (3) systematically renewing tissues through regenerative processes. The first group includes cell restoration technology. The second includes various technologies for eliminating non-cellular or partially non-cellular formations such as kidney stones, gallbladder, cholesterol and calcified vascular plaques, and fibrin fibres in the lungs in the case of fibrosis. The basic technology for solving problems in the first and second groups may be the same, but the specific methods are usually different. The third group would include the restoration of damaged nerve cells in the brain and spinal cord, regeneration or replacement of joints, teeth and lenses (box 1.10).

BOX 1.10

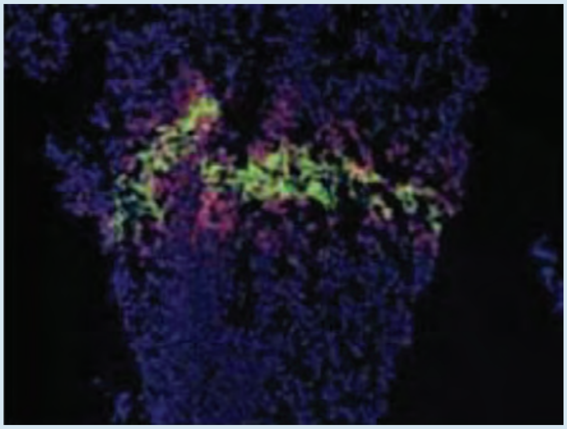
3D printing of living tissue

Applying 3D printing to the creation of functional, living tissue requires knowledge from three areas:

- Life sciences on sustaining the viability of cells throughout the printing process.
- Material science on biocompatible scaffolding to support the cells.
- Electrical and mechanical engineering to design and construct the device.

Academic, industrial, clinical and regulatory partnerships are required to transition printed tissues from the laboratory to health system use. Bringing together multiple fields to address this research frontier has led to progress that no single discipline could have achieved alone.

Convergence-led advances in 3D printing have allowed scientists to generate layers of different cell types to replicate the structure and function of human liver tissue. This cross-section of bio-printed human liver tissue shows hepatocytes (shown as blue nuclei), endothelial cells (red) and hepatic stellate cells (green).



Source: The National Academy of Sciences (2014).

2

FRONTIER TECHNOLOGIES DRIVING THE FOURTH INDUSTRIAL REVOLUTION

Speakers:

Christophe Behar, Energy Director, Fayat Group

Olga Dontsova, Head of Department of Chemistry of Natural Compounds, Lomonosov Moscow State University

Igor Drozdov, Chairman of the Board, Skolkovo Foundation

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Olgun Hayati, Professor, Solar Energy Institute, Ege University

Victor Ilgisonis, Director for Research and Development, State Atomic Energy Corporation Rosatom

Olga Memedovic, Deputy Director, Trade, Investment and Innovation Department, Chief of Business Environment, Cluster and Innovation Division, United Nations Industrial Development Organization (UNIDO)

Artem Oganov, Professor, Skolkovo Institute of Science and Technology

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Raif Vasilov, Chairman, Russian Society of Biotechnologists

Andrey Volkov, Rector, National Research Moscow State University of Civil Engineering

This session discussed the fourth industrial revolution (4IR) and its drivers, potential impacts of 4IR on the Sustainable Development Goals, challenges and the transition towards Industry 5.0 and Society 5.0.

At the very beginning of the 19th century, England was the first country to experience an industrial revolution—a shift from producing things by human-powered labour to producing things by heavily relying on steam- and water-powered industrial facilities. That historic event led to an unprecedented pace of economic and industrial development, spreading from England to continental Europe and, later, across the globe.

In the first industrial revolution the world economy increased manufacturing output by more than 200 times between 1800 and 2010.[35] The second industrial revolution, which began in the late 19th century and continued into the early 20th, fostered mass production by introducing electricity and the assembly line.[36] The third industrial revolution, between the 1960s and 1990s, widely used electronics, information technology and automation in manufacturing.

With technological innovation accelerating and converging, changing what we produce, how and where we produce it, and the way we live our lives, many economists argue that we have entered a 4IR. The main technological advances driving the 4IR are cyber-physical systems connecting the virtual world with the real one and information processing objects with material ones, on top of artificial intelligence (AI), machine learning (ML), robotics, additive manufacturing (3D printing), the internet of things (IoT), distributed-ledger technology (blockchain) and quantum computers and their integration with nano-, bio-, info- and cognitive technology and social and humanitarian sciences. These technologies are also referred to as frontier technologies because they are innovative, fast-growing, deeply interconnected and interdependent.

Exponential progress in frontier technologies is merging the physical, digital and biological worlds, influencing all socioeconomic sectors and scientific disciplines, while blurring the differences among them. The 4IR is leading to a paradigm shift that is profoundly altering how we work, live and interact. Innovation is becoming faster, more complex, multidisciplinary, collaborative, unplanned, unpredictable and disruptive. The rising affordability of 4IR technologies promises to deliver multiple economic, environmental and social benefits and to address pressing global challenges such as poverty, resource scarcity and climate change, ensuring sustainable development and equal access to resources.

Automation has brought enormous opportunities to the way people produce things. According to a 2016 McKinsey report, 45 percent of the activities people perform at the workplace today can be substituted by machines with already-existing technologies. For emerging markets this proportion is even higher.[37] Meanwhile the World Bank estimates that 57 percent of jobs are already automated in Organisation for Economic Co-operation and Development (OECD) countries.[38]

Some argue 4IR technologies will be more disruptive than those triggered by the technologies of the first, second and third industrial revolutions because of the speed of change in frontier technologies and their widespread and systematic impacts on society. Exponential technological change affects all scientific disciplines and economic sectors and blurs differences between them. It also touches all countries, though not in the same way and at the same time. Technology is enhancing human capabilities more than ever before and is changing the nature of work.

The 4IR and Industry 4.0

Today the 4IR is also commonly called "Industry 4.0." This term was introduced for the first time in 2011 during the Hannover trade fair in Germany. At first, it referred to a project pursued in the overall high-tech development strategy of Germany. Later the term was expanded to describe

> "an environment, which includes the strong customization of products under the conditions of high flexibility of mass production (improved automation technology), requiring the introduction of methods of self-organized systems (self-optimization, self-configuration, self-diagnosis, and so on) to get the suitable linkage between the real (machines, workers) and the virtual worlds."[39]

Initially, key technological advancements attributed to Industry 4.0 are internet of things (IoT), industrial internet of things (IIoT), big data, cloud computing, artificial intelligence (AI) and industrial AI, robotics, additive manufacturing of three-dimensional (3D) printing (figure 2.1) and distributed ledger technology (blockchain). Over time, it became widely recognized that the 4IR is not only about connecting smart machines with virtual objects. The scope of the technological advances driving the 4IR forward is much wider and includes nanotechnologies and biotechnologies, cognitive and social sciences, humanities and their convergence. The intersection of the three major domains of technological progress—physical, digital and biological—will form the future reality that we inhabit (figure 2.2).[40]

Internet of things

Internet of things refers to expanding internet connectivity to physical devices used in everyday life. Any device that can communicate with others over the internet, thereby transmitting data, is a part of IoT. IoT devices, embedded with sensors, electronics and internet connectivity permit remote monitoring and control. An IoT system includes the devices themselves, the local network,

FIGURE 2.1

Digital technologies driving the 4IR

Source: Forbes (2018).

the internet and back-end services such as computers and mobile devices (figure 2.3).

Convergence of multiple technologies, real-time analytics, machine learning, commodity sensors, and embedded systems has resulted in the evolution of IoT. When these smart sensors are used to enhance manufacturing experience and production processes, it is termed the industrial internet of things (IIoT).

Big data

Big data describes large sets of digital information, whose relative size or type outstrip traditional methods of data capture, management and processing. The characteristic of big data is high volume, high velocity or high variety, according to the International Business Machines Corporation. The introduction of new technologies has contributed to the growth of big data. By providing new forms and sources for information gathering, artificial intelligence, IoT, social platforms and mobile technologies have driven data management to increasingly complex levels. Big data originates from various activities—information received from sensors, audio-visual media, transactional and log files, web traffic, social media and other general daily occurrences—all instances of very large amounts of data of different sizes and types gathered in real time. Once gathered, these data can be analytically processed to improve data management and gain new insights.[41]

Distributed ledger technology (blockchain)

As commonly understood, blockchain is an open and distributed ledger of recorded transactions between parties that is both verifiable and permanent.[42]

Designed within a system based on incentives and mathematical proofs, blockchain removes the need to place trust in any one central institution or actor and instead continuously exercises fraud prevention and ledger reliability. As the United Nations Department of Economic and Social Affairs puts

FIGURE 2.2

Frontier technologies driving the 4IR

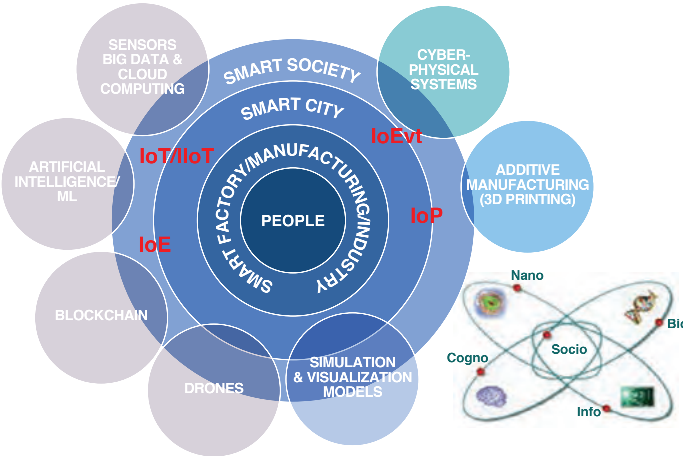
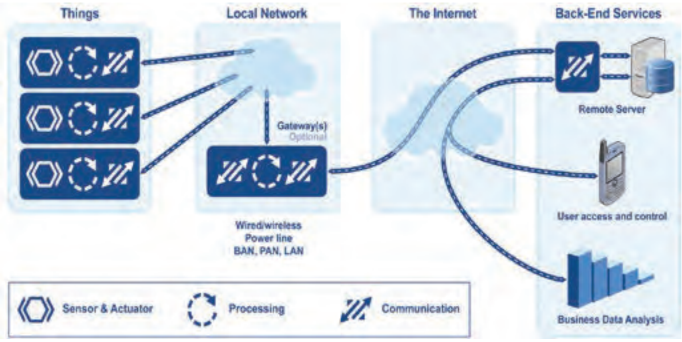


FIGURE 2.3

Four main components of an internet of things system



Source: Micrium (2019).

it, this system and every participant in it "works to build a single public ledger of transactions and constantly verifies its validity," leading to what we call the blockchain.[43] In contrast to the traditional system, which relies on a complex structure of regulatory features and guarantees based on a central authority's reputation, the blockchain technology combines various parts of the transaction system and furthers itself by aligning the interest of participants and their contribution to ensure the security and reliability of systems.

It is considered an improvement over the traditional financial system, where verification of funds ownership and related controls to avoid double spending rely on trust in formal institutions and regulatory systems. The creation of blockchain as an extension of virtual currencies is considered a notable innovation. It has revolutionized payments and logistics, enabling small firms to interact on a trusted basis and transformed decentralized supply chain functions. It is also used for supply chain integration and for traceability, certification and transparency to meet food regulatory requirements during production, shipping, processing and distribution to consumers.

Cloud computing

Cloud computing is derived from a shift in computing processes away from centralized hardware applications. It allows ubiquitous access to data and related services from any internet-connected device anywhere in the world. In the cloud computing environment data are not stored on hard disks in the user's computer but remotely on server farms without direct and active management by the user. Cloud computing also establishes an infrastructure for information technology that allows greater computing power to manage and maintain the growing demand for high capacity networks and their efficient operation.[44]

Artificial intelligence

Artificial intelligence describes different technologies that perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making and translation between languages.[45] It is a cognitive science based on rich research activities in robotics, machine learning, image processing and natural language processing. AI technologies could unlock $9.5–15.4 trillion a year in business value worldwide.[46] The United States is the global market leader, with 40 percent of market share. China and Israel have the next strongest AI ecosystems, followed by the United Kingdom and Canada.[47]

Industrial AI (IAI) is a systematic discipline focused on developing, validating and deploying machine learning algorithms for industrial applications with sustainable performance. The key elements of industrial AI are analytics technology (A), big data technology (B), cloud or cyber technology (C), domain knowhow (D) and evidence (E). Analytics, the core of IAI, can only generate value if other elements are present.[48]

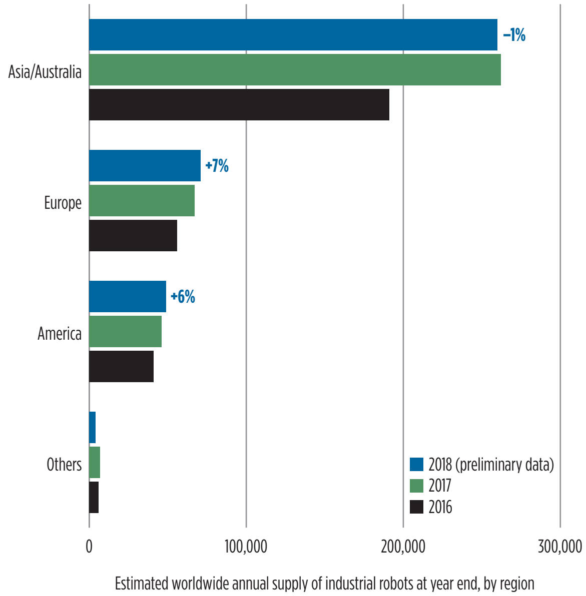
Robotics

Robotics technology is usually divided into industrial and service robots. An industrial robot is defined by the International Federation of Robotics as "an automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes."[49] Collaborative robots ("cobots") working alongside humans in factories will comprise more than 30 percent of all industrial robot sales by 2025.[50] Service robots, in contrast, "perform useful tasks for humans or equipment excluding industrial automation application."[51] Five major country-markets—China, Germany, Japan, Republic of Korea and the United States accounted for 74 percent of robot sales in 2016 and continued as the leaders in 2018.[52]

East Asia (mainly China, Japan and the Republic of Korea) is considered to be the most rapidly developing region in producing, purchasing and implementing robotics technology (figure 2.4). As a region, East Asia buys three times as many robot-units as Europe, the second biggest region-market. In 2016, robot-unit sales in East Asia

FIGURE 2.4

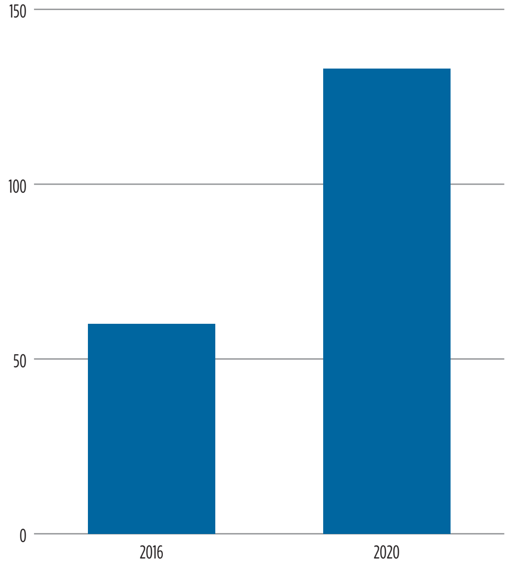
The Asia Pacific region leads the world in using industrial robots



Source: International Federation of Robotics (2019).

FIGURE 2.5

Asia Pacific spending on robotics forecast ($ billions)



Source: UNIDO elaboration based on Statista database (Statista 2019).

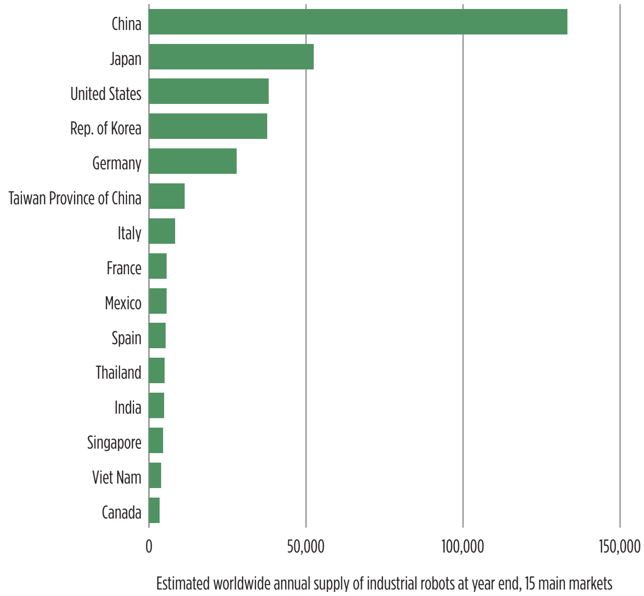
increased by 19 percent to 190,492 units, while in Europe they increased by 12 percent to 56,000 units.[53] Spending on robotics technology in the Asia Pacific is expected to double from $60 billion to $133 billion between 2016 and 2020 (figure 2.5).

Asian economies are leading the implementation of robotics technology in manufacturing, facilitating automation and increasing the number of installed robot-units. China, though the biggest robotics market (figure 2.6), is not yet at the forefront, mainly due to its delayed start. In 2016, the Republic of Korea had an outstanding 631 robots per 10,000 employees installed in industrial settings, followed by Singapore with 488, Germany with 309 and Japan with 303, according to the International Federation of Robotics (figure 2.7).[54]

International Data Corporation (IDC) forecasts that worldwide spending on robotic systems and drones will total $115.7 billion in 2019, an increase of 17.6 percent over 2018. By 2022, IDC expects that spending will reach $210.3 billion with a compound annual growth rate of 20.2 percent.[55]

FIGURE 2.6

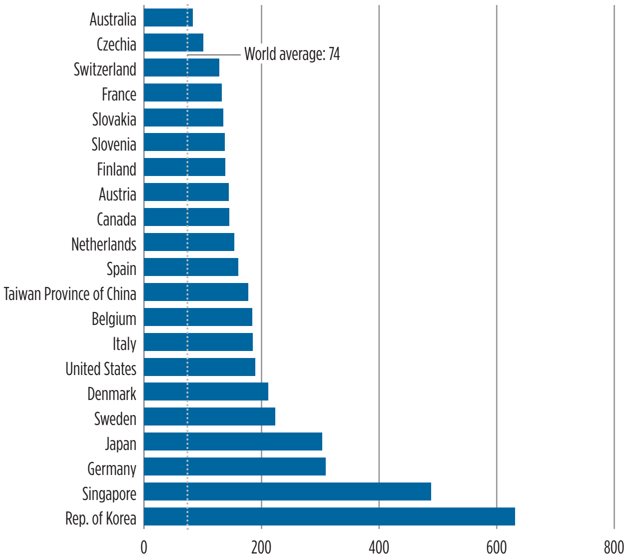
China is the largest market for industrial robots



Source: International Federation of Robotics (2019).

FIGURE 2.7

Number of installed industrial robots in manufacturing per 10,000 employees, by country, 2016



Source: International Federation of Robotics (2017).

Additive manufacturing

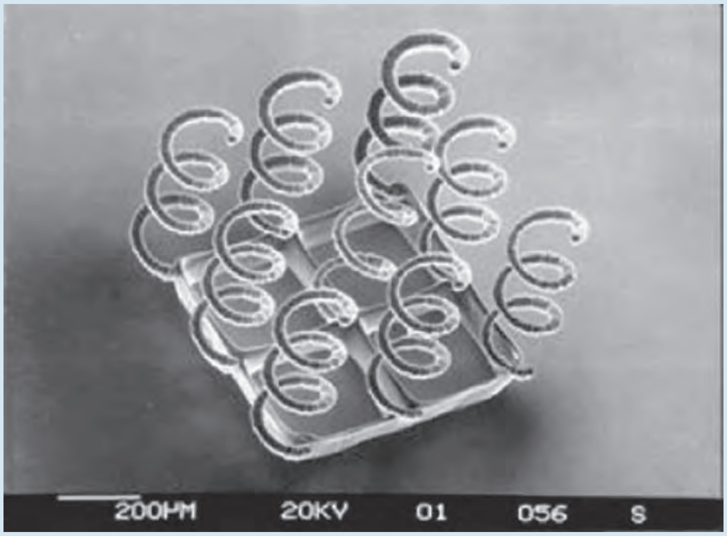
The spread of digital technologies in design (computer-aided design—CAD), modelling and calculations (computer-aided engineering—CAE) and machining (computer-aided manufacturing—CAM) has stimulated development of 3D printing technology. Additive manufacturing in combination with composites—spatial-reinforced, high-strength and high-modulus fibres—is an innovative approach to designing and manufacturing new materials, in place of the traditional methods of casting and machining on machine tools.[56]

The 3D printing of objects made of composite materials with an optimal microstructure will solve problems faced by manufacturers in implementing additive technologies that are unbeaten today in various industries, such as rocket and space technology, aircraft and helicopter engineering and the automotive industry (box 2.1).

BOX 2.1

Additive manufacturing capabilities: Some examples

An Airbus hinge bracket in its original form (*rear*) and in an optimized form (*front)* made by additive manufacturing, which reduced weight by 64 percent.



A 3D micro-spring for microfabrication made by photolithography as a proof-of concept.

Source: Roco et al. 2013.

Projects making consumables through 3D printing are being implemented by the All-Russian Research Institute of Aviation Materials. Enterprises engaged in metallurgy, aviation, the space industry and the arms industry, including NPO Energomash, Tikhvin Carriage Works, Uralvagonzavod, Voronezhselmash, the Tushinsky Machine-Building

Plant and others have expressed great interest in the field. They currently use 3D printing to create prototypes of parts, but not final products. To switch to an Industry 4.0 platform, Kamaz PJSC introduced additive technologies, digitalization of production and, with the assistance of the State Corporation Rostec, made industrial and technological partners at the opening of the Department of Laser and Additive Technologies in the Naberezhnye Chelny branch of the Kazan National Research Technical University of A. N. Tupolev (KNITU-KAI).[57]

The current market leader in selective laser melting (SLM) technology is the German company SLM Solutions Group AG. Major customers are NASA, Airbus Group, SpaceX and GE.[58] The European Space Agency (ESA) has announced the launch of Project AMAZE, whose goal is to print metal parts for spacecraft, aircraft engines and rockets on a 3D printer. The most ambitious goal of the project is to create a space satellite assembled entirely from 15 printed components.[59]

Convergence drives divergence

Convergent technologies or the synergistic combination of five major science and technology fields (nano- bio- info- cogno- socio-), is progressing rapidly and creating opportunities for new activities and hence creating jobs (figure 2.8):

- **Nano**—nanoscience and nanotechnology.
- **Bio**—biotechnology and biomedicine, including genetic engineering.
- **Info**—information technology, including advanced computing and communications.
- **Cogno**—cognitive science, including cognitive neuroscience.
- **Socio**—social sciences and human-centred technologies.

FIGURE 2.8
Converging biotechnology, nanotechnology, information technology and cognitive sciences

Source: http://nbics.org/Eng/Pages/DefaultEng.aspx.

New materials, production processes and products with properties close to those of nature, and hybrid and reproduced nature-like mechanisms can be created by manipulating matter and modifying biological systems. Technological convergence is driving divergence (figure 2.9). Cross-sectoral spillovers and recombined complex technological ecosystems generate new fields of knowledge and technology (figure 2.10), as well as new activities, industries and business models (such as the sharing economy, gig economy and use of platforms). Technological convergence leads to new control systems, expanding human physical capabilities, and to new analytical tools, expanding human cognitive capabilities.

The fusion of technologies is blurring the boundaries between the physical, digital and biological spheres and will fundamentally change how people live and work in the coming decades. The convergence of previously separate scientific and engineering disciplines will require new multidisciplinary skills, enabling the leveraging of specific attributes from different technologies and creating new complementary combinations. These self-reinforcing processes of convergence and divergence propel exponential technological change.

The convergence of technologies and the blurring of boundaries between the digital, production and biological spheres characterize modern scientific trends. New knowledge in nanomaterials and pioneering research penetrate the digital economy and digital technologies.

Science may help develop new technologies for the generation and consumption of energy and for a circular economy based on nature-like technologies. Systems and processes of living nature may take the form of technical systems and technological processes integrated into natural resource turnover. The main idea is to restore consistent natural resource circulation—a kind of metabolism of nature—that has been disrupted by technologies. The term "convergent technologies," which appeared in the early 2000s, implies the integration of nano-, bio-, info- and cognitive technologies to create new results (as discussed in Chapter 1). Emerging high-tech projects employing each convergent science may be realized, which would have not been possible had each science proceeded independently.

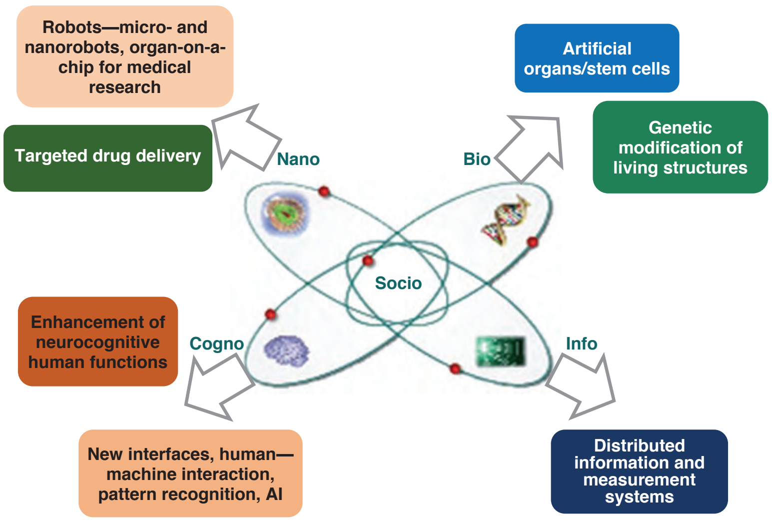
For instance, nanotechnology (figure 2.11), operating with atoms and molecules, creates new substances and materials with specified properties, using the same technological methods as nature itself. Interweaving biotechnology with nanotechnology, along with cognitive and information technology, opens up new opportunities, such as the targeted delivery of drugs with nanocapsules, the synthesis of new drugs using protein crystallography and the creation of new biological materials. Already, with the help of convergent technologies, new human tissues and entire organs are made to extend life, improve its quality and increase human capabilities.

Information technologies allow reproducing natural processes of information sharing in artificial objects. By synthesizing nature-based systems, people will approach the creation of anthropomorphic technical systems with elements of consciousness and the ability to understand.

To benefit from technological progress, it is necessary to change mindsets and attitudes towards civilization, nature and humanity. Adding socio-humanitarian sciences to the formula of NBIC technologies is crucial for turning convergent technologies into a completely new approach that combines natural and social sciences. Such

FIGURE 2.9

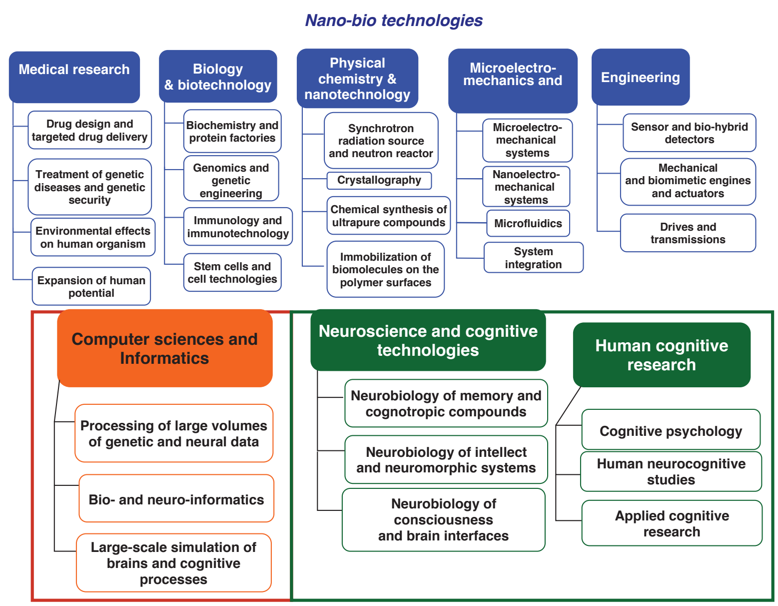
Convergence drives divergence



Source: Kurchatov Institute.

FIGURE 2.10

New fields of knowledge and technology



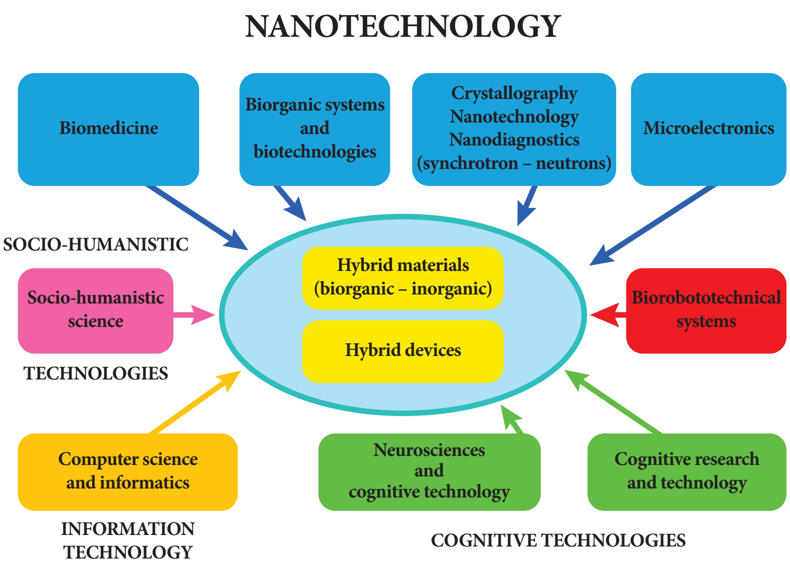
Source: Kurchatov Institute.

scientific integration permits a more complete understanding of nature and its processes.

Convergent sciences create breakthrough technologies that lead to new techno-economic paradigms. They solve global problems, such as the

FIGURE 2.11

Organization chart of the Kurchatov complex of NBICS nature-like technologies



Source: Kurchatov Instituteva.

sustainable functioning of super-large systems—the world's ecosystem—or the realization of the SDGs. Synthesizing nature-like systems and processes creates anthropomorphic technological systems with consciousness and cognitive abilities.

Convergence means not just mutual influence but interpenetration when boundaries are erased. In interdisciplinary work, many interesting results arise precisely at the intersections. The interrelation of nano- and bio- areas of science and technology is complex. For example, when living (biological) structures are considered at the molecular level, their chemical nature becomes apparent. At the macro level, the connection between living and nonliving (for example, a human appendage and a mechanical prosthesis) leads to a mixed nature (a cyborg), while at the micro level the differences between living and non-living structures are not so obvious.

Potential impacts of the 4IR on the Sustainable Development Goals

Achieving sustainability through the Sustainable Development Goals (figure 2.12) is the main global initiative of the next 15 years.[60] Industry 4.0 creates many opportunities to attain the SDGs. The main opportunities are:[61]

- Accelerated upscaling of critical services in health, education, financial services, smart agriculture and low-carbon energy systems.

FIGURE 2.12

Sustainable Development Goals and the UN 2030 Agenda

Source: UNDESA (n.d.).

- Decreased deployment costs for technologies reducing urban and rural disparities.

- Increased innovation, connectivity, productivity and efficiency across many sectors.

- Faster upgrading in the quality of services and jobs.

The frontier technologies of the new industrial revolution can potentially have the greatest impact on SDG 2 (no hunger), SDG 3 (good health and well-being), SDG 4 (quality education), SDG 5 (gender equality), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), and SDG 15 (life on land). The main impact of Industry 4.0 will be on "the allocation of resources, i.e. products, materials, energy and water, which can be realized in a more efficient way on the basis of intelligent cross-linked value creation modules."[62]

Successful businesses are characterized not only by their profitability, but also by their social contributions. New 4IR technologies allow companies to create new solutions that are more environmentally and socially responsible. Access to advanced technologies allows companies to rethink their business models and adjust them to SDG-oriented ones. Sustainable business models can be categorized into eight archetypes:[63]

- Maximize material and energy efficiency.

- Create value from waste.

- Substitute with renewables and natural processes.

- Deliver functionality rather than ownership.

- Adopt a stewardship role.

- Encourage sufficiency.

- Repurpose the business for society/ environment.

- Develop scale-up solutions.

Realizing such models relies on the implementation of 4IR technologies. Two examples are industrial symbioses and circular economy.

Industrial symbiosis

The 4IR technologies have great potential for cross-linking factories and creating closed-loop product lifecycles. They create opportunities for effectively organizing industrial production and consumption in a symbiotic way, mimicking the organization of production and consumption as in natural ecosystems. The interconnection between factories and between machines within factories will allow companies to create sustainable and resource-saving flows of products, water, energy and materials. Those processes in turn enable a closed loop of product usage—"multiple use phases with manufacturing or reuse in between."[64] Such change will greatly influence today's environmental issues, reducing persistent organic pollutants, improving waste management and using energy efficiently.

Circular economy

The 4IR technologies such as industrial IoT (IIoT), big data analytics, robotics and additive manufacturing and business models such as e-commerce and shared economy permit a circular economy, minimizing waste and maximizing resource efficiency. Circular economy activities such as recycling, and remanufacturing and reusing parts and components require data collection and analysis. IIoT allows data collection and manufacturing performance control and analysis. IIoT can be used for products that can be remanufactured after use to return them to their original specifications. Remanufacturing is common for airplane parts, vehicle engines, parts and components of heavy off-road vehicles, medical devices such as magnetic resonance imaging machines, office equipment such as copiers and scanners and even furniture. Advances in robotics allow manufacturers to reduce product and process errors caused by human error and thereby extend product lifetimes. Manufacturers may employ robots for waste management. Additive manufacturing for producing spare parts on demand improves the maintainability of products and equipment and extends their life cycle.

Radio frequency identification of equipment and products expedites maintenance schedules, remotely identifying failures and tracking parts and components that should be returned for remanufacturing. New business models such as shared economy and products-as-a-service (PaaS) also contribute to reusing, reducing waste and recycling. In PaaS models, equipment manufacturers retain ownership and responsibility for flawless operation. The PaaS models allow manufacturers' capacity to be tailored to fluctuating demand and provide them an incentive to produce durable goods and reduce waste.

Car sharing has already influenced the plans of major vehicle manufacturers. Car sharing platforms require data about the whereabouts, the usage and the condition of each car. Heavy off-road equipment can be shared, leased or rented.

In the garment industry, manufacturers are introducing reuse of material from used jeans in the production of new jeans. Key players in global value chains increasingly use secondary raw materials in production of goods and employ take-back schemes to repurpose and recycle products and waste from themselves and others.

The intersection of 4IR technologies and the circular economy can lead to waste reduction. Improved traceability of smart products throughout the supply chain and the lifecycle of products allow manufacturers to continuously optimize the performance of both production and product, leading to a more efficient use of resources.

Biologically inspired engineering for producing a bio-based material from substances derived from living matter or from biotic material originating in living organisms enable moving to a higher level of circular economy, where industries achieve resource effectiveness by eliminating the concept of waste and grow without relying on linear primary raw materials. Products and industrial processes are designed to turn materials into nutrients (resources) that can be perpetually used in industrial systems, producing no waste in an ecologically effective system. In these strategies, recyclability is already considered during product design. The design of healthy and safely recyclable materials and products in circular models enables closed supply systems. The aim is to create a positive footprint with optimised supply cycles.

The circular economy is implemented simultaneously at different levels for chemicals, materials and products, manufacturing processes, services and complete systems. High-performing organizations are developing circular economy strategies to boost competitiveness. They are decoupling growth from scarce or harmful resources and developing new revenue streams that add customer value. Nature-like technologies and converging technologies are enabling all technical and biological processes to be environmentally compatible and products to be beneficial for economic and social development.

Sensors and IoT provide manufacturing equipment the chance for a "second life." Factory equipment is a capital-intensive investment with a life of up to 20 years. But installing sensors and connecting old equipment to a machine network can prolong the equipment's lifetime. Retrofitting old equipment can be a low-cost alternative for companies, contributing to both economic and environmental dimensions of global sustainability. Big data helps companies create smart logistics and adjust their services to the precise needs of customers.

Machine learning and artificial intelligence both allow companies to create self-regulating autonomous systems to shape resource-efficient solutions.[65] They increase resource allocation efficiency within the organizational structure of a company and contribute beyond the company to the sustainability of a country's socio economic system.

For developing countries, 4IR creates momentum to leapfrog in their industrial capabilities and to catch up with the developed world. This accords with the SDGs, stating that global development can only be achieved through inclusive and sustainable industrial development. "Industry is also the most dynamic driver of prosperity and collective well-being, and therefore a global objective that touches upon the economic, social and environmental aspirations of all, and as such is intrinsically woven into the architecture of the 2030 Agenda."[66]

Challenges

Levels of penetration

Around the end of the 19th century, electricity gave what some economists believe to be the biggest boost to productivity ever observed. But it took 40–50 years for a majority of the global population to gain access to electricity, and today 17 percent, nearly 1.3 billion people, still lack it and have yet to fully experience the second industrial revolution. The same pattern holds for the third industrial revolution, with more than half of the world's population, 4 billion people, most of whom live in the developing world, lacking internet access.[67]

Given this, the exponential growth of frontier technologies may widen the technology gap. The penetration of 4IR technologies in developing economies is much lower than in developed countries. Unless these technologies are available for the developing world at optimal costs, they will find it impractical to pursue the governance and business model transformations required of 4IR.

Labour and capital

Another challenge is the demand for diverse skill sets. The demand for highly skilled human capital will increase as will the need for fixed capital, since the new industries will require not only a more qualified labour force but also more infrastructure and equipment. According to Devon M. Herrick,

> "The evolution of technology has certainly increased the need for human skills and competence. But it has also increased the need for buildings, homes, offices, equipment of all kinds, patents, and so on, so that in the end, the total value of all these forms of nonhuman capital (real estate, business capital, industrial capital, financial capital) has increased almost as rapidly as total income from labour."[68]

Compare Detroit in 1990 and Silicon Valley in 2014:

> "The three top companies in Detroit produced revenues of $250bn with 1.2m employees and a combined market capitalization of $36bn. The top three companies in Silicon Valley in 2014 had revenues of $247bn, only 137,000 employees, but a market capitalization of $1.09tn."[69]

The 4IR technologies allow companies to generate more capital by using far fewer human resources due to a substitution of labour-intensive tasks by machine activity. Rising unemployment may become a heavy burden for governments in the medium to long run.

Disruptive potential

The 4IR technologies have enormous disruptive potential. While automation technologies such as IAI and robotics will prove beneficial for diverse customers, businesses and economies through increased production at optimal costs, these technologies will lead to job displacement and mobility across sectors, depending on the pace of their development and adoption and the preparedness of businesses and economies, in terms of skills, management and investments. A 2017 McKinsey analysis estimated that in 60 percent of occupations, at least 30 percent of constituent work activities could be automated.[70]

An estimated 75 million to 375 million workers, that is, 3 to 14 percent of the global workforce, will have to change occupational categories by 2030. To meet that need, new jobs and job categories that do not exist today must be created. And the workers must receive training so that they can guide and adapt to the activity of 4IR technologies. Skills that are hard to automate in current circumstances, such as social and emotional skills, will be of great demand in the coming years, along with technical knowledge to handle the machines. Governments, universities, research centres, international organizations and business firms and associations should take into account the need to inculcate diverse and complementary skill sets in future workers.

Preparedness for 4IR

To respond to 4IR requires countries to develop their own strategies and policies. By now most developed countries and some emerging economies have established frameworks to deal with smooth transformation to 4IR.

Germany was the first country to create a specific strategy to implement technologies of the 4IR. The strategy itself was named "Industry 4.0," coining a term that came to take on a broader meaning. The initiative is included in a framework called "High Tech Strategy 2020," which Germany sees as a "major opportunity to establish itself as an integrated industry lead market and provider."[71] The initiative promotes implementing the new technological solutions in manufacturing in order to increase the sector's competitiveness and efficiency.

The US economy relies heavily on manufacturing, innovating and leveraging the potential of 4IR technologies through numerous industrial policies. Instead of a single holistic 4IR or Industry 4.0–oriented strategy, the United States uses diverse policies to strengthen certain manufacturing sectors in order to capture the benefits of advanced technologies.

Although some EU countries run their own 4IR/Industry 4.0–oriented programmes, the European Union itself has also established an overall innovation framework, Horizon 2020. It seeks to "ensure Europe produces world-class science, removes barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation."[72] In this framework the European Union is allocating $80 billion to innovative research projects and running innovation training programmes at the leading European universities.

Some developing countries have launched national strategies, such as China's "Made in China 2025" to promote 4IR technologies and India's "Make in India" mission to promote manufacturing. Russia has announced a programme called the "Development of the Manufacturing Industry and Improvement of Its Competitiveness for the Period till 2020."[73]

"Made in China 2025" promotes the implementation of 4IR technologies in various sectors by providing financial and legal incentives to companies that restructure their manufacturing processes and create sustainable business models. Addressing the competitiveness of the global market, China is trying to lift its industrial capabilities to a new level to match Germany, Japan and the United States.[74]

The Indian 4IR/Industry 4.0–oriented framework was established in 2014 to "transform India into a global design and manufacturing hub." India is trying to raise awareness of new technologies and advance the technological development of its manufacturing sector. Three main goals of the initiative are to "inspire confidence in India's capabilities amongst local potential partners, the Indian business community and partners abroad; provide a framework for a vast amount of technical information on 25 industry sectors; [and] reach out to a vast local and global audience via social media and constantly keep them updated about opportunities, reforms, and so on."[75]

In Russia the most important 4IR/Industry 4.0 initiatives are the National Technology Initiative of Russia (NTI), and the Strategy of Scientific and Technological Development of the Russian Federation.[76] NTI attempts to form ecosystems based on market-based prioritization (or demand-pull). The Strategy sets out the goal and main objectives of Russia's scientific and technological development, the principles, priorities and main areas and measures for implementing the state policy in this sphere, as well as the expected results of the Strategy's implementation, namely Russia's sustainable, dynamic and balanced scientific and technological development in the long term.[77]

In summer 2017, the Russian government approved the Digital Economy of the Russian Federation programme to run until 2024. It covers the regulation of the digital economy, cybersecurity, education and personnel, the formation of research competencies and information technology infrastructure.[78] The programme has the following priorities:

- Creating regulations for forming a unified, trustworthy digital environment that assures privacy and security of data.
- Circulating civil rights to objects, in a narrow sense as a complex of cases when the civil rights holders change, and in a broad sense as other volitional acts of an administrative nature.[79]
- Ensuring favourable legal conditions for data collection, storage and processing.
- Creating legal conditions for the most efficient use of the results of intellectual activity in the digital economy.
- Creating legal conditions for introducing and using innovative technologies in the financial market.
- Adopting regulations to stimulate the development of the digital economy.
- Implementing measures to improve standardization mechanisms.
- Creating conditions for the digital economy in the legal proceedings and notarial field.
- Creating legal conditions for introducing new rules for collecting reports, including statistical information.
- Determining the position of the Russian Federation on developing the digital economy and harmonizing approaches to it in the Eurasian Economic Union.

The second stage of the programme will create a permanent mechanism for managing change and competence (knowledge) in regulating the digital economy.

The following proposals have also been made:

- Translating laws and regulations into a machine-readable form, automating their execution and developing a language and tools for producing self-fulfilling contracts.
- Forming a single digital space for the legal regulation of the use of artificial intelligence for socioeconomic planning.
- Developing legislation on robotics and cyber-physical systems, including defining the systems and establishing rules and regulations for commissioning them.

The main general digital technologies in the scope of this programme include:

- Big data.
- Neurotechnology and artificial intelligence.
- Distributed registry systems.
- Quantum technologies.
- New production technologies.
- Industrial internet.

- Components of robotics and sensor technology.
- Wireless technology.
- Virtual and augmented reality technology.

The list is expected to change as new technologies emerge and develop and different economic sectors implement them, especially in healthcare, public administration and the creation of smart cities.

Moving towards Industry 5.0 and Society 5.0

Although in many countries Industry 4.0 is only in its initial stages, and the main achievements can be expected no earlier than 2020–2025,[80] some industry and technology experts emphasize moving towards Industry 5.0 with the penetration of AI into people's regular lives, expanding human capabilities and returning people to the centre of the universe (box 2.2).[81] While Industry 4.0 introduces connected devices, data analytics and AI technologies to automate processes further, Industry 5.0 promotes cooperation between people and machines, with human intelligence working in harmony with nature.

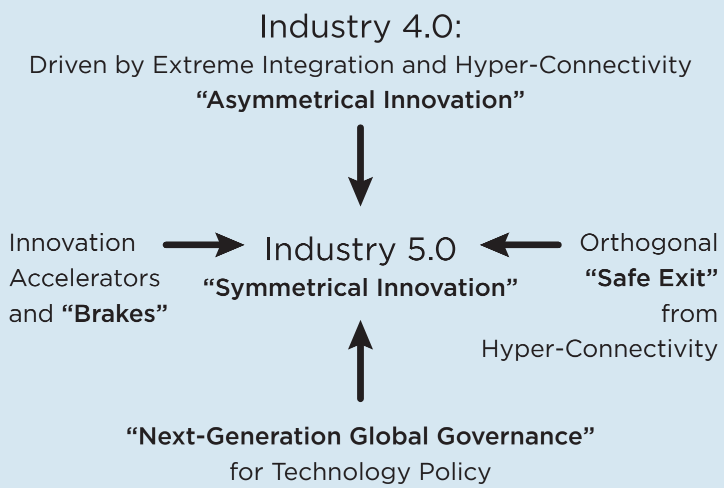
Industry 5.0 harnesses extreme automation and big data with safety and security, innovative technology policy, and responsible implementation science, enabled by 3D symmetry in innovation ecosystem design. The development of nature-like and convergent technologies will promote the transitions to Industry 4.0 and Industry 5.0.

Özdemir and Hekim warn that Industry 4.0 technologies, "if left unchecked might lead to authoritarian governance by one person in total control of network power, directly or through her/his connected surrogates."[82] They favour an Industry 5.0 that democratized knowledge co-production from big data, building on the concept of symmetrical innovation. Industry 5.0 utilizes IoT but differs from predecessor automation systems by having (figure 2.13):

- Equal emphasis on deceleration of innovation as well as acceleration in case diminishing returns become apparent.
- Next-generation social science and humanities research for global governance of emerging technologies. This research considers the technology opportunity costs, ethics, ethics-of-ethics, framings (epistemology), independence, and reflexivity of social science and humanities research in technology policymaking.
- A built-in safe exit strategy in case hyperconnected entrenched digital knowledge networks fail. Such safe exits allow "digital detox" by employing pathways unrelated/unaffected by automated networks, for example, electronic patient records as paper trails on vital medical information as a safe exit strategy.

BOX 2.2
Moving towards Industry 5.0

Industry 5.0 addresses the asymmetry of the Industry 4.0 ecosystem design by (1) innovation brakes, (2) next-generation technology and society research where the opportunity costs and analytical frameworks are made explicit, and (3) orthogonal safe exits that are independent from hyperconnected systems automating manufacturing and production.



Source: Özdemir and Hekim (2018).

The convergence of natural and human sciences—the noospheric path of development

The noosphere is a natural stage of the biosphere's development. Entry into the noospheric path of development presupposes a synthesis of social and natural science images of the world.[83]

The essential movements in the transition to the noospheric path of development are the formation of a person with a moral imperative and the change of public consciousness from a consumer ideology to one of satisfying natural needs and pursuing unlimited growth of spiritual and creative potential. The synthesis of knowledge occupies a central place in the transformation of humanity and public consciousness.

The development of science over the past 400 years has led to the idea of a rapidly changing global information space that is only in the initial stages of its development.

The noospheric path determines the direction and strategy of creating Society 5.0 (SuperSmart Society—figures 2.13, 2.14; box 2.3), where Society 5.0, not limited to the production sector, solves social problems by integrating physical, virtual and social spaces.

FIGURE 2.13

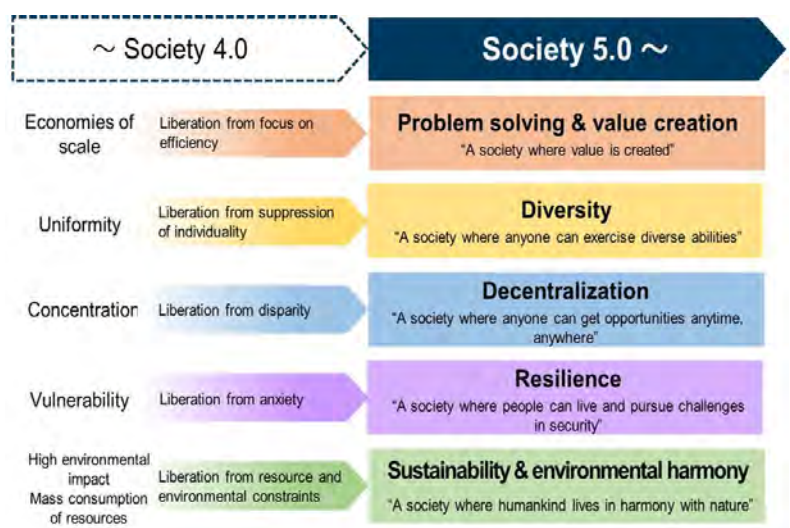
Stages of societal development: From Society 1.0 to Society 5.0 (SuperSmart Society)

The evolutionary aspect of the Society 5.0 concept as introduced in the 5th Science and Technology Basic Plan of Japan

Source: Keidanren (2016).

FIGURE 2.14

Transformation from Society 4.0 to Society 5.0



Source: WEF (2019).

BOX 2.3
Society 5.0

Society 5.0 depicts a "human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space." It was proposed in Japan's Fifth Science and Technology Basic Plan as a future society to aspire to. It follows the hunting society (Society 1.0), agrarian society (2.0), industrial society (3.0), and information society (4.0) (see figure 2.14).

While Industry 4.0 focuses on the digital transformation of manufacturing, the Japanese concept of Society 5.0, in sync with Industry 5.0 and convergence, focuses on a society where anyone can create value anytime, anywhere, in harmony with nature.

Society 5.0 achieves a close convergence between cyberspace (virtual space) and physical space (real space). In Society 4.0, people access a cloud service (databases) in cyberspace via the internet and search for, retrieve and analyse information or data. In Society 5.0, a huge amount of information from sensors in physical space is accumulated in cyberspace. Artificial intelligence analyses that big data—which exceed human capacities—in cyberspace and feeds the results back to humans in physical space in various forms. People, things and systems are all connected in cyberspace. This process brings new value to industry and society in ways not previously possible.

In Society 5.0, innovation will create new value that bypasses regional, age, gender, and language gaps and provides products and services finely tailored to diverse individual needs, some not yet known. Society can thus promote economic development and solve social problems.

In its latest report, Keidanren (the Japan Business Federation) redefined Society 5.0 as the "imagination society." People will be expected to exercise imagination to identify needs and challenges scattered across society, sketch the scenarios to solve them and creatively realize such solutions by using data and digital technologies. In the imagination society, digital transformation combines with diverse people's creativity for problem solving and value creation that lead to sustainable development. The concept can contribute to the achievement of the Sustainable Development Goals.

Reaching such a condition will have its difficulties, and Japan intends to face them head-on to become the first country in the world presenting such a model future society.

Source: Council for Science, Technology and Innovation, Japan (n.d.).

3

MEGASCIENCE AND INTERNATIONAL COLLABORATION AS A BASIS FOR THE DEVELOPMENT OF NATURE-LIKE TECHNOLOGIES

Speakers

Ulf Karlsson, Professor, KTH Royal Institute of Technology, Stockholm

Pavel Logachev, Director, Nuclear Physics Institute, Siberian Branch of the Russian Academy of Sciences

Niki Naska, Director for Relations with European and International Organizations, EUREKA

Vladislav Panchenko, Chairman of the Board, Russian Foundation for Basic Research

Mikhail Rychev, Special Representative in European research organizations of the National Research Centre (Kurchatov Institute)

Aleksandr Tkachev, Director, Centre for Innovative Technologies and Engineering of the Russian Technological University

Grigory Trubnikov, Deputy Minister of Science and Higher Education of the Russian Federation

Megascience was first defined as "big money, big machines," referring mainly to unique experimental apparatuses such as particle accelerators, ground or space telescopes such as the Hubble Space Telescope, and space exploration (European Space Agency and the International Space Station). But the definition has evolved to apply to complex research needing not only very large sums of money—necessitating partnerships between different countries—but also large teams of competent researchers—necessitating cross-border cooperation between countries and participating institutes, often over long periods of time. According to Raniwala et al. 2018, scientific research carried out collectively by a large number of people across geographical and cultural boundaries in pursuit of a common goal is termed *megascience,* and the projects planned and executed in its pursuit are called megascience projects.[84] Consequently, efficient technical coordination and streamlined resource management become mandatory throughout the project. Cross-disciplinary competence is a natural outcome over the course of a mega project. Mega projects of an international scope are means to curtail costs, share risk and augment scientific expertise.

Megascience involves large, complex and expensive facilities. Many countries view them as an important element that helps them demonstrate their technological development and ambitions. Many countries that strive for technological development immediately go for a megascience facility. It shows that this country is on the path of technological development and can afford to maintain it. Megascience facilities should be available for large-scale research, as well as be the infrastructure for industrial and practical needs.—Mikhail Kovalchuk, President, National Research Centre (Kurchatov Institute).

At this point, development of such physico-chemical or physico-technological fields as catalysis and synergetics, medicine and bioindustry, chemical technologies and materials science is not possible without megascience, without experiments, research and results obtained through megascience facilities.—Valerii Bukhtiyarov, Director, Federal Research Centre, Boreskov Institute of Catalysis.

As of today, basically there are no organisms that would consume gas-phase substrates and produce useful substances. We need to use methods of synthetic biology and metabolic engineering to understand how ferments that turn carbon dioxide into useful substances work. Megascience facilities can tell us how those ferments work, and most importantly how to improve them to make this process more efficient.—Aleksandr Yanenko, Director, State Research Institute of Genetics and Selection of Industrial Microorganisms of the National Research Centre (Kurchatov Institute).

Any megascience facility takes some 10–15 years to build, which means it will be today's postgraduate students, or next young specialists, or even today's high school graduates who will get to work with it. It has been several years since we started annual synchrotron and neutron research schools that bring together 100 people representing Russia, Germany and Sweden, above all, to listen to lectures on latest results in this field.[85]—Mikhail Rychev, Distinguished Advisor to the Administrative Director, European X-Ray Free-Electron Laser Facility GmbH (European XFEL GmbH).

A mega project provides opportunities to use sophisticated research facilities and permits interaction between colleagues at all levels, thus filling gaps in know-how and knowledge and accelerating development. But several barriers hinder the effective implementation of international megascience projects, mainly due to the degree of engagement required. Present coordination mechanisms and agreement frameworks are insufficient. The mobility of scientific personnel and equipment is a key issue obstructing the efficient implementation of such projects. New mechanisms that go well beyond current memoranda of understanding are required to increase the mobility of scientific personnel through eased visa issuance and relaxed customs for moving scientific equipment.

There are several megascience projects worldwide in diverse scientific disciplines. Examples are found in weather forecasting, oceanographic studies, and studies of the human genome and biodiversity. The Facility for Antiproton and Ion Research (FAIR), European Laboratory for Particle Physics (CERN), International Thermo Nuclear Experiment Reactor (ITER) and Relativistic Heavy Ion Collider (RHIC), among other institutions, house megascience and mega projects. Figure 3.1 shows the megascience projects located in the European Union.

Intergovernmental initiatives to promote megascience projects include EUREKA, an organization for international research development and innovation (box 3.1).

The Russian Federation is a leading player in several international megascience projects, some of which are listed in figure 3.2. One is the ICNR PIK (International Centre for Neutron Research PIK) which is a Russian–German noncommercial partnership with possible further accession by other countries. Agreements have been signed with Helmholtz Association of German Research Centres, Institut Laue–Langevin (ILL) (France)

FIGURE 3.1
Megascience projects in the EU

Source: Kurchatov Institute.

BOX 3.1
EUREKA and international collaboration

- EUREKA is an intergovernmental network established in 1985 for pan-European research and development funding and coordination.
- It is a leading facilitator of innovation, providing an open platform for international research, development and innovation (R&D&I).
- As of March 2018, EUREKA had 41 full members, including all 28 European Union (EU) member states, the EU itself (represented by the European Commission), 1 partner country (South Korea) and 3 associated members (Canada, Chile and South Africa).
- EUREKA promotes and supports market-oriented international R&D&I project generation. It facilitates access to finance for companies participating in its projects.
- EUREKA and the research activities of the EU proper, notably Horizon 2020 and the European Research Area, seek cooperation and synergy.
- Objectives:
  - To raise the productivity and competitiveness of European businesses through technology.
  - To boost national economies in the international market and strengthen the basis for sustainable prosperity and employment.
- Features:
  - EUREKA Clusters are long-term, strategically significant industrial initiatives. They usually have a large number of participants, and aim to develop inclusive technologies of key importance for European competitiveness, mainly in information and communication technologies, energy and, more recently, automation and biotechnology.
  - EUREKA Clusters have improved the ability of the European microelectronics sector to compete with those on other continents. Some EUREKA Clusters include CATRENE for microelectronics and nanoelectronics and EURIPIDES for electronic packaging and smart systems.

Source: EUREKA. www.eurekanetwork.org

and Jülich Research Centre (Germany), and one is underway with the Budapest Neutron Centre (BNC), for general use and joint development of the experimental base of the PIK reactor.

The ICNR scientific programme in neutron research has been developed in collaboration with the Helmholtz Association of German Research Centres and the Budapest Neutron Centre, with the support of ILL, PIK (commissioned at Petersburg Nuclear Physics Institute) and the European Spallation Source (ESS).

Creating the ICNR on the basis of the PIK reactor aims to provide the Russian Federation and the international community with methods using neutron radiation for fundamental and applied research in priority areas of science, including such critical technologies as industry of nanosystems and materials, cellular biotechnology, hydroenergetics and many others. The National Research

FIGURE 3.2
Megascience projects in the Russian Federation

Source: Kurchatov Institute.

Centre (Kurchatov Institute) led the ICNR scientific program and the experimental ICNR PIK stations, in which 11 working groups were created, including more than 50 scientists from the St. Petersburg Nuclear Physics Institute (part of the

National Research Centre—Kurchatov Institute), Joint Institute for Nuclear Research (JINR), HFZ (Germany), ILL (France), ESS (Sweden) and BNC (Hungary).

Another Russian megascience project is the Specialized Synchrotron Radiation Source of the fourth generation (SSRS-4). This project proposes to develop a new, specialized fourth generation synchrotron radiation source with extremely high spatial coherence, corresponding to laser radiation, record brightness and temporal structure. The current status of the SSRS-4 project is the preparation of the technical proposal with a preliminary design. The SSRS-4 project is important to create a Russian scientific community in synchrotron radiation research in order to develop a national scientific programme with expertise on photon science.

The SSRS-4 project will be implemented under the auspices of the Russian–German Ioffe-Röntgen Institute (established by the Kurchatov Institute and the Deutsches Elektronen-Synchrotron DESY), within the framework of the cooperation platform of the National Research Centre (Kurchatov Institute) and European Synchrotron Radiation Facility (France), as well as the framework agreement between the National Research Centre (Kurchatov Institute) and the National Institute for Nuclear Physics (Italy). On 23 May 2011, Minister of Education and Science of Russia A. A. Fursenko and Minister of Education and Research of Germany A. Schavan signed an agreement to establish the joint Ioffe-Röntgen Institute. The agreement for the establishment of the Ioffe-Röntgen Institute between the National Research Centre (Kurchatov Institute) and DESY was signed in Moscow on 17 April 2012 by M. V. Kovalchuk and H. Dosch.

Ioffe-Röntgen Institute was founded within the cooperation framework between DESY and National Research Centre (Kurchatov Institute) as a common platform for strengthening cooperation in science, education and technological development. It plans to develop new large-scale research infrastructure, including a fourth-generation synchrotron radiation source (SSRS-4) on the territory of Russian Federation, as well as using existing large-scale research infrastructure in both countries for experimental stations.

Another major Russian megascience initiative is CREMLIN (Connecting Russian and European Measures for Large-scale Research Infrastructure). CREMLIN's main purpose is developing scientific cooperation between the Russian Federation and the European Union for large-scale research infrastructure in the framework of the Horizon 2020 program. In May 2015, the National Research Centre (Kurchatov Institute) signed the consortium agreement and grant agreement for the CREMLIN project, and it was finished on 31 August 2018. A follow-up CREMLIN+ project application is in preparation for six megascience projects in the Russian Federation, including three National Research Centre (Kurchatov Institute) projects: PIK, SSRS-4 and the Russian–Italian IGNITOR project.[86]

The CREMLIN project is a Coordination and Support Action (CSA) that received funding from the European Union's Horizon 2020 programme between 2015 and 2018. CREMLIN is designed to foster scientific cooperation between the Russian Federation and the European Union in developing and using large-scale research infrastructure. The six proposed Russian megascience facilities have enormous potential for the international scientific community and represent a unique opportunity for the EU to engage in a strong collaborative framework with the Russian Federation. The CREMLIN project is a first pathfinding step to identify, build and enhance scientific cooperation and strong enduring networks of European research infrastructure and the corresponding Russian megascience facilities to maximize scientific returns.

The project follows the specific recommendations of an international expert group convened by the European Commission's director general for research. It devises concrete coordination and support measures for each megascience facility and develops common best practices and policies on internationalization and access.[87]

The six Russian megascience projects are:

- Scientific and Research Reactor Complex PIK at St. Petersburg Nuclear Research Institute B.P. Konstantinov Gatchina at the National Research Centre (Kurchatov Institute).
- Nuclotron-based Ion Collider Facility NICA at Joint Institute for Nuclear Research, Dubna.
- Fourth Generation Specialized Synchrotron Radiation Source SSRS-4 at the National Research Centre (Kurchatov Institute), Moscow.
- Exawatt Centre for Extreme Light Studies XCELS at Institute of Applied Physics, Russian Academy of Sciences, Nizhniy Novgorod.
- Super Charm-Tau Factory at Budker Institute of Nuclear Physics, Novosibirsk.
- IGNITOR Fusion Project at National Research Centre (Kurchatov Institute), Moscow.

There are many examples of US participation in large international projects. In addition to the International Space Station (ISS), the Large Hadron Collider (LHC) project at the European Laboratory for Particle Physics (CERN) and the International Thermonuclear Experimental Reactor (ITER), such involvement includes the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Global Network of Gravitational Wave Detectors; the Human Genome Project; the Global BRAIN Initiative; and the Thirty Metre Telescope.[88]

Developing countries such as India have also been active participants of megascience projects. Indian participation in CERN represents many educational institutes, including universities, Indian Institutes of Technology (IITs) and research institutes, and is funded by the Department of Science and Technology and the Department of Atomic Energy. The Facility for Antiproton and Ion Research (FAIR) in Germany is another major megascience project in the field of particle physics, with a large Indian contribution—India currently holds 3.5 percent of the shares in the FAIR GmbH, the company that coordinates construction at FAIR. Indian scientists, under the guidance of the Department of Science and Technology and the Department of Atomic Energy have been engaged in three major experimental programmes of FAIR: Nuclear Structure, Astrophysics and Reactions (NUSTAR), Compressed Baryonic Matter (CBM) and Antiproton Annihilation at Darmstadt (PANDA).[89] India participates in building equipment to be used at the heart of the FAIR accelerator. Moreover, as part of Indian contribution, an advanced LIGO detector will be installed and integrated in the network of other detectors in the United States and Italy.

4

READINESS TO DEVELOP AND IMPLEMENT CONVERGENT TECHNOLOGIES—NBICS

Speakers

Yury Abramov, Acting General Director, Agency for Technological Development

Maria Borovskaya, Deputy Minister of Science and Higher Education of the Russian Federation

Ivan Bortnik, owner, FASIE

Andrey Fursenko, Russian presidential aide

Victor Haefeli, consultant, Swiss Ministry of Environment, founder and owner of Smart Resources GmbH

Alexander Khlunov, General Director, Russian Science Foundation

Andrey Klepach, Deputy Chairman (Chief Economist)—Member of the Board, Bank for Development and Foreign Economic Affairs

Vladislav Panchenko, Chairman of the Board, Russian Foundation for Basic Research

Vladimir Raspopov, Deputy Director General, Industrial Development Fund

Wilma Rethage, Director, Russian Office of the German Research Foundation

Grigoriy Senchenya, Adviser to the Head, Federal Service for Intellectual Property (Rospatent)

Mohammad Shaban, Strategy Director, Global Manufacturing and Industrialization Summit

During this Global Forum, a survey was conducted among representatives of research institutions, universities, development companies and development organizations from the Russian Federation to identify their positions on the readiness and barriers to developing and implementing convergent technologies.[90]

The survey revealed that despite government efforts to support research and innovation, there are significant gaps in the innovation chain. Problems and challenges occur in identifying promising topics, commercializing new technologies, increasing scientific research efficiency, fostering the willingness of the real sector to invest in domestic innovations, and finding personnel with the competencies required at different stages of the technology life cycle.

Legislative, social and other barriers to developing and implementing new technologies were defined for the survey by the priorities of the Russian Federation's strategy for scientific and technological development. They addressed the possibility of Russian society responding effectively to challenges in social institutions and in interactions between people and nature, and between people and technology.[91]

The study had four stages:

1. Analysis of the global agenda to identify main types and groups of barriers to developing new technologies.

2. The survey of Russian experts to evaluate those barriers in relation to the situation in the Russian Federation.

3. A strategic session for Russian experts to validate the most significant legislative, social and

other barriers to different stages of technology readiness.[92]

4. Scientometric analysis to identify the leaders of scientific and technological areas who should play a key role in minimizing and removing barriers.

Identified barriers, by type, are provided in figure 4.1 in a matrix by stages of the technology life cycle, and in figure 4.2 by nano-, bio-, and cogno-technologies.

- Legislative barriers: Inefficient management tools for research, development and innovation at the state level, including problems in developing a legal framework, and systems of incentives such as subsidies, tax incentives and protection of intellectual property.

- Social barriers: Social rejection of new technologies due to the lack of information on their consequences; codes of practice describing the problems that can be solved with their help, and special knowledge and skills for their use.

- Competence barriers: The lack of personnel who can create interdisciplinary teams, evaluate interdisciplinary projects, manage research and development projects and implement and promote research and development results.

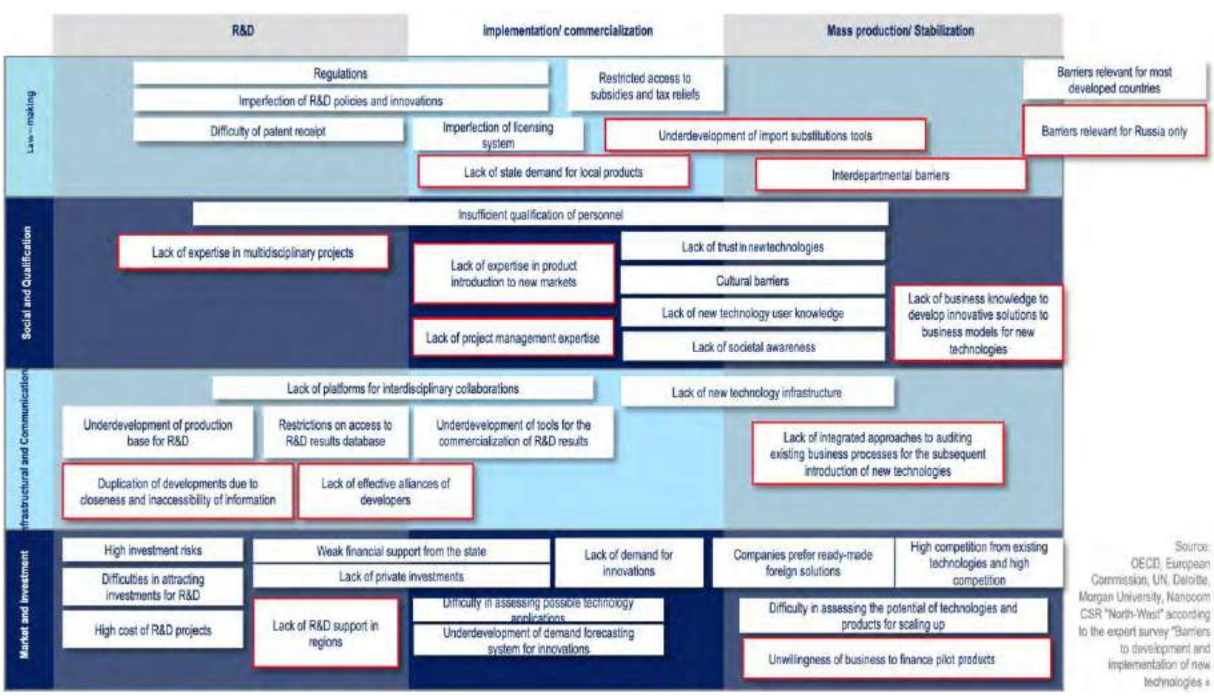
- Infrastructure barriers: An inadequate technical base for research and development, limited access to the data necessary for research and the unavailability of existing infrastructure to absorb new technologies.

- Communication barriers: Underdeveloped communication networks of researchers and developers and underdeveloped formats and platforms for their interaction.

- Investment and market barriers: Investment barriers include the problems of financing research and development projects by the state and by private business investment—largely due to costs, unawareness of the effects of technology, unwillingness to invest in domestic development and the availability of ready-made solutions from abroad. Market barriers

FIGURE 4.1

Barriers to the development of new markets of goods, services and technologies



Source: OECD, European Commission, UN, Deloitte, Morgan University, Nanocom CSR "North-West" according to the expert survey "Barriers to development and implementation of new technologies »

FIGURE 4.2
Barriers to bio-, nano- and cogno- technologies

Source: CSR "North-West" according to the results of the expert survey "Barriers for the development and implementation of new technologies" and strategic session "Barriers to the development of new markets of goods, services and technologies" 01.11.2018

include competition from existing technologies and products, low demand for new developments, difficulties in assessing commercial applications and the potential for scaling and an underdeveloped system of forecasting demand.

The study showed barriers in different technological areas of the complex of convergent technologies. According to Russian experts, the most significant limitations are the high uncertainty of research and development projects, resulting in high risks for investors and difficulties in attracting financing; the bureaucratic hurdles for introducing new incentives; and high competition from existing technologies.

Potential negative side effects

Scientific breakthroughs and the subsequent development of new technologies can have unintended side effects.

For instance, CRISPR, the tool that has facilitated gene editing, can have immense benefits in medical research but could also be used effectively to produce a weapon of mass destruction. As the potential for bioterrorism grows and competition in technology intensifies, the risk becomes high that rivalries could escalate into major conflicts.[93]

The trend of making complex technologies available, with all their potential negative side effects to average users, is growing.

Artificial intelligence (AI) changes the relationship between consumers and producers significantly. Data analysis could be used by companies to manipulate unaware people. AI and related technologies could be used by countries trying to influence other countries. It can be weaponized, and regulation in the United States and other countries did not exist when these technological revolutions began. Over the past five years, however, a huge backlash has occurred on multiple levels.

The spread of digital technologies can entail rising demands for scarce resources, such as certain metals, and can increase energy consumption. Additive manufacturing reduces large inventories, since it manufactures (prints) parts at the time of actual demand, increasing efficiency and reducing waste, but it can increase consumption in some industries.

Recommendations on potential mechanisms for minimizing and removing barriers

The study identified potential mechanisms to minimize and remove barriers at different stages of technological readiness (table 4.1).

Awareness building and access to information

Nature-like and convergent technologies face a market access problem related to the low awareness of financial institutions about the risks of such projects and information on how to minimize them. One of the panel sessions of the Global Forum was devoted to "The Development of Nature-Like Technologies and the Objectives of Development Institutions." The speakers recommended developing mechanisms supporting entry into the market of environmentally friendly technologies and creating a register or website where technologies and support mechanisms could be shared.

TABLE 4.1
Potential mechanisms for minimizing and removing barriers

	Research and development	Implementation and commercialization	Mass production and stabilization
Legislative	• Forming an effective legal system for scientific, technological and innovative development • Strengthening intellectual property rights laws • Simplifying the procedure for obtaining a patent • Developing state programmes to support research and development • Ensuring compliance with national and regional research and development support programmes	• Forming an effective mechanism for regulatory enforcement • Providing policy incentives such as tax rebates and subsidies • Improving the licensing system; simplifying licensing procedures • Improving the management of research and development and innovation at the state level, including tools for long-term planning, monitoring and evaluation of innovative development • Developing public–private partnerships	• Promoting local developers through public procurement
Technical and vocational education and training (TVET) **Capacity building**	• Developing a system for scientific personnel training—both special educational programmes and incorporation of new training into existing programmes. These include programmes for developing competence in working with investors and promoting research results • Developing competence in evaluating interdisciplinary projects	• Developing project manager competencies in research and development and innovation management • Developing competences in marketing and advocacy • Improving public education, spreading knowledge about the results of research and development, new technologies and products, practice codes formation • In higher education, integration of STEM with arts (STEAM) and humanities to enable students to comprehend the impacts of new technologies on people, culture and society is required. STEAM is challenging perceptions that learning areas are separate and creates a new way of thinking that is more engaging, interdisciplinary and inclusive of diverse representation and thought. It helps to move beyond established stereotypes associated with STEM and to stimulate the creation of new generations of interdisciplinary innovators	• Developing competences in marketing and promoting new products • Developing competences in creating business models based on new technologies • Mainstreaming public education, spreading knowledge about the results of research and development, frontier technologies and products, practice codes formation

(continued)

TABLE 4.1 *(continued)*

Potential mechanisms for minimizing and removing barriers

	Research and development	Implementation and commercialization	Mass production and stabilization
Business infrastructure **Innovation and ecosystem building** **Networking and international cooperation** **Collaborative platforms**	• Fostering international scientific and technical cooperation, including increased academic mobility and new platforms for networking • Creating effective alliances of research institutes, universities and business • Creating expertise and innovation centres for developing and implementing new technologies based on leading Russian scientific and technological work • Developing an advanced scientific instrumentation industry • Introducing new tools and approaches to work with scientific information, including using research databases to prioritize research activities based on global trends	• Developing business infrastructure to facilitate commercialization of research and development results • Creating frontier technology platforms as a foundation for effective multilateral cooperation • Conducting hackathons gathering the expert community and industry to form a common vision of the demand for technological solutions by industry and so simplifying developers' task of implementation • Creating expertise centres for developing and implementing new frontier technologies based on leading scientific and technological work	• Developing new tools and approaches to auditing existing business processes in industrial enterprises to ensure the introduction of new frontier technologies
Investment and policy supporting and augmenting markets	• Developing financial support instruments for basic research at the state level • Improving the research grant system • Searching for alternative financing instruments for research and development	• Developing mechanisms for targeted financing • Developing and disseminating new practices of interaction between developers and industry to attract investment (for example, introducing competitions for teams to solve customer needs and implement real projects with a clear result quickly) • Adopting principles of prioritizing research based on forecasting the potential demand for development • Developing new tools and approaches to assess the potential for implementing new technologies and products	• Developing and disseminating new practices of interaction between developers and the industry to attract investment (for example, introducing competitions for teams to solve customer needs and quickly implement real projects with a clear result) • Searching for new commercial applications for technologies and products in different industries • Developing new tools and approaches to forecasting the demand for innovation • Developing new tools and approaches for assessing the potential for uptake of new technologies and products

Some countries lack awareness of technological inventions based on nature-like and convergent technologies. While an English-language portal forms a database of developed technologies, it is not exhaustive or available in other languages.[94]

Creating and developing international channels for disseminating information among representatives of the business community, public authorities, financial institutions and scientific centres and organizations would be an effective mechanism. These channels promote the interests of the wider international community through objective and informative approaches. They can be developed as an international resource from which representatives of scientific, business and other communities from different countries could have access to relevant information and projects.

The following actions can be implemented at the country level as priorities for developing nature-like and convergent technologies:

- Creating a definition, methodology, requirements and terminological and conceptual apparatus for nature-like and convergent technologies.

- Creating a register of such technologies as an international resource for the exchange of information.

- Revising the regulatory and legal framework regulating tax and commission benefits for manufacturers and consumers of technologies.

- Creating research and development clusters and collaborative platforms for convergent technologies, including specialized tools for forming research alliances and innovative "agglomerations" (figure 4.3).

- Supporting the formation of new industries and businesses based on the business ecosystem and innovation system approach, including infrastructure for commercializing innovative developments.

- Instituting financial incentives, such as discounts and incentives on research and development, incubation programmes for startups working in convergent technologies and innovative coupons for small and medium-sized enterprises (SMEs).

- Developing budget items, justifications, goals and indicators for programmes to stimulate the introduction of nature-like technologies.

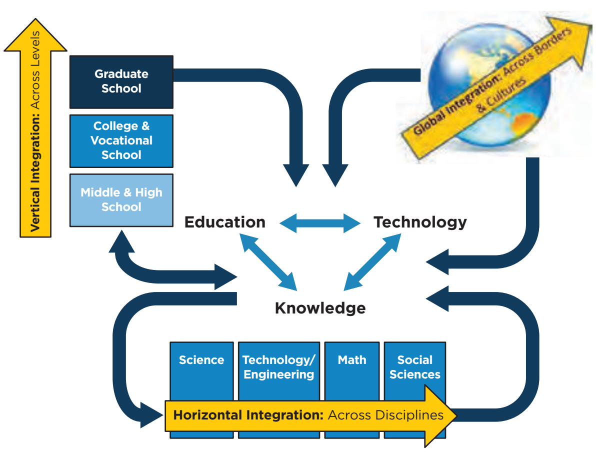
- Developing advertising and educational materials based on the specifics of the country to familiarize people with technologies. Among them could be trainings for accelerators, venture investors, representatives of industrial companies and other stakeholders supporting the implementation and application of such technologies.

- Reform the STEM curriculum to focus on convergent, nature-like technologies and humanities in order to develop a workforce capable of developing new applications and products, and of reasoning ethically by interpreting the effects of these technologies on society and ensuring sustainable and ethical use of science and technology (figures 4.3 and 4.4).

Innovation system building

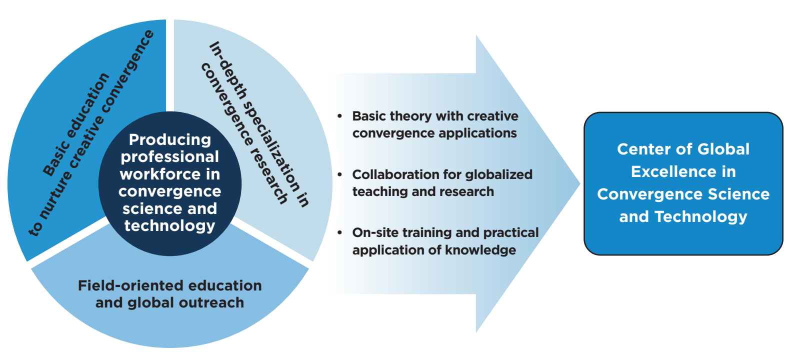
In supporting the development of new technologies, designated geographical areas hosting various science, industry and technology parks—with universities, research institutes, vocational training bodies, technology labs, and other intermediary organizations and institutions providing technical support—can be hubs to stimulate innovation, technological learning and development. Networking among science parks, technopolises, industry clusters, engineering centres, university business incubators, accelerators and local

FIGURE 4.3
NBIC platform



Source: Roco et al. 2013.

FIGURE 4.4
Seoul National University's Graduate School of Convergence Science and Technology



Source: Roco et al. 2013. http://convergence.snu.ac.kr/main/about-2?lang=en.

governments, academia and civil society can result in systemic collaborations and interactive learning processes, forming an innovation ecosystem that links the results of scientific research to the market, the state, the business sector, environment and society. Innovation systems can network with other innovation systems nationally and internationally.

The research programmes of many countries show great prospects for developing nature-like and convergent technologies. Examples include biomimicry accelerator programmes, which provide grants for replicating and marketing inventions based on nature-like and convergent technologies, and the European network for responsible innovation and technology transfer, which links the scientific community, businesses, national institutions and European organizations in an exchange of information with the wider community of interested countries.

Research institutions

In Russia, research institutions have several major structural tasks that include:

- Studying the role of leading countries state policies in overcoming barriers to scientific and technological development.
- Forming interdisciplinary teams together with leading world organizations for research activities that provide academic mobility to strengthen the competence of Russian technology developers.
- Creating centres of competence to create research teams and undertake activities to reduce barriers to developing and implementing new technologies.

There is also a global network of research institutions for scientific and technological research (figure 4.5).

Nature-like and convergent technologies are developing rapidly and are the focus of many research centres (table 4.2).

Science parks and technopolises

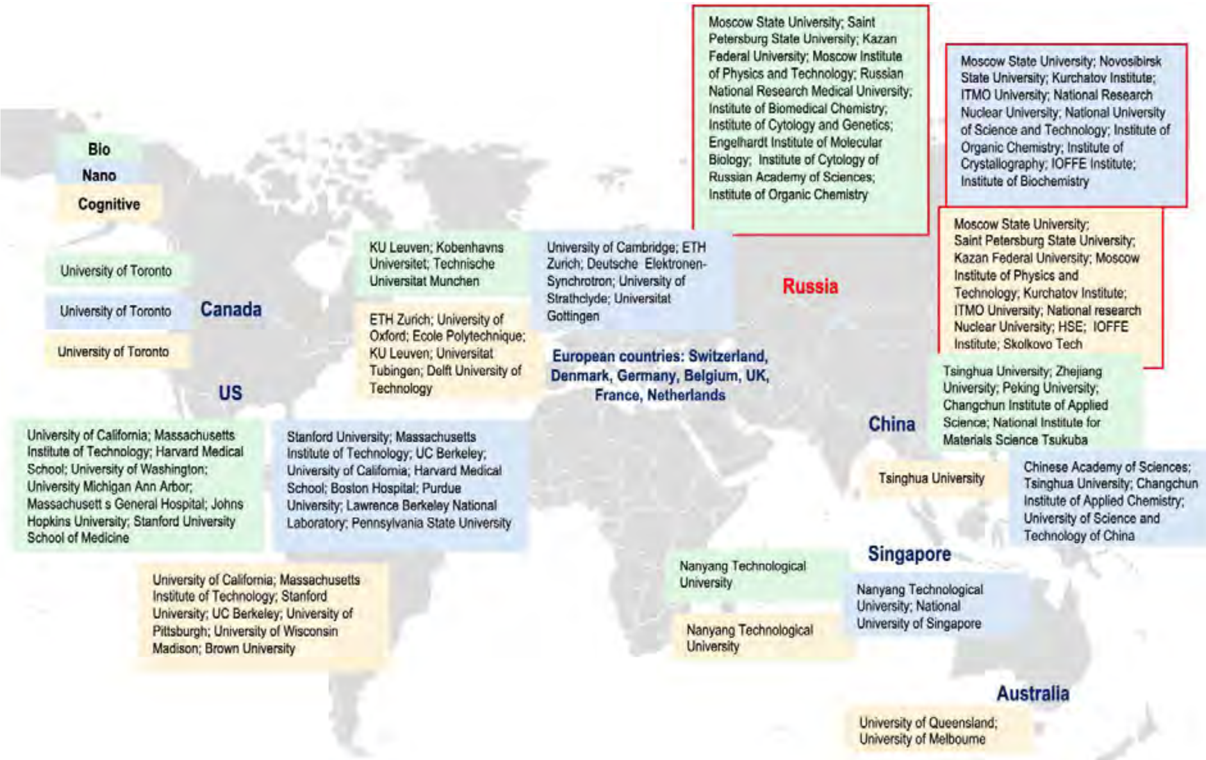
Science parks and technopolises are highly specialized territories that play a key role in economic development through quality space and facilities, high value-added services and dynamic and innovative policies and programmes. They set strict requirements for resident companies, which are high-tech innovative enterprises specialized in robotics, medical technology, infotechnology, nanotechnology, microelectronics and other fields.

Science parks and technopolises, widespread around the world, perform tasks such as:

- Stimulating and managing the flow of knowledge and technology between universities and companies.
- Facilitating communication between companies, entrepreneurs and technicians.
- Providing environments that enhance a culture of innovation, creativity and quality.
- Focusing on companies, research institutions, and people—entrepreneurs and knowledge workers.
- Facilitating the creation of new businesses through incubation and spinoff mechanisms, and accelerating the growth of small and medium-sized companies.
- Working in a global network that gathers thousands of innovative companies and research institutions throughout the world, facilitating the internationalization of their resident companies.

Russian science parks follow the development strategy of foreign science parks. Residents improve the standards of industrial activity, contribute to creating new environmentally friendly enterprises and modernize old production systems. Russian science parks had 3,137 registered residents in 2018.

FIGURE 4.5
Universities conducting scientific and technological research on convergent technologies worldwide



In the following examples of science parks, residents pursue nature-like and convergent technologies.

Science and Technology Park Berlin Adlershof.[95] A striking representative of the German network of science parks, this is one of the most successful high-technology sites in Germany. It is home to 1,072 companies and scientific institutions, with 18,000 workers and 6,700 students. The companies focus on:

- Photonics and optics.
- Renewable energy and photovoltaics.
- Microsystems and materials.
- Information technology and media.
- Biotechnology and the environment.

TABLE 4.2
World's leading research centres and their contributions to the study of nature-like technologies

Scientific centre	Country	Number of publications
Chinese Academy of Sciences	China	71
Centre National de la Recherche Scientifique	France	49
Helmholtz Association	Germany	25
Institut de Recherche pour le Développement	France	25
Pennsylvania Commonwealth System of Higher Education	USA	23
University of California System	USA	22
State University System of Florida	USA	20
Indian Institute of Technology New Delhi	India	19
Institut National de la Recherche Agronomique	France	19
Ohio State University	USA	19
Université Paris-Saclay	France	19
Helmholtz Centre for Environmental Research	Germany	17

The renewable energy and photovoltaics field spans the entire supply chain, from research and development to production and sales. Companies such as Heliocentris, Silicor Materials and Sentech Instruments benefit from the unique blend of innovative technology, top-level research and economic promotion.

Science Park TusPark Beijing.[96] Through more than 20 years of exploration and practice, TusPark has become a world-class university science park. It has gathered over 1,000 technological enterprises and research and development institutions and become a gathering place for innovative startups, the research and development headquarters of multinationals and the headquarters of Chinese technology enterprises. TusPark has developed a special innovation ecosystem and unique culture for boosting innovation and entrepreneurship. It has incubated startups, promoted the transfer of high-tech achievements, and established an industry–academy–research cooperation platform. Both Chinese and foreign companies are located there. Among business incubators in different specializations are:

- TusStar Nanometre. This professional incubator aggregates nanotechnology results, establishes entrepreneurship incubation platforms and connects to industrialization channels.

- TusStar Energy-conservation and Environment-protection. A professional incubator for hi-tech enterprises in the environmental protection industry, it owns more than 30 enterprises engaged in environmental protection, including Tsinghua Solar and Yadu. It is an ideal park for environmental protection business projects.

Hong Kong Science Park. Eco-settings in a science park refers to an eco-friendly relationship between the organization and the environment. It commonly develops and evolves under a green park or green tenant model, where science park management prioritizes environmentally friendly arrangements according to local environmental standards. In addition, management can improve the environment through such proactive measures as using cleaner and renewable energy sources. Hong Kong Science Park[97] is a perfect example, supporting solar energy and green building initiatives. The park has roof gardens to "green" the environment, electronically controlled water taps, an integrated photovoltaic system that converts solar energy into electricity, flushing sensors and weather stations for controlling the irrigation system, and compact treatment of recyclable and non-recyclable waste.

Canon Eco Technology Park.[98] In Japan, Tokyo Canon Inc. and Canon Ecology Industry Inc. opened the park as a focal point for Canon Group environmental activities. The park comprises a showroom and a cutting-edge plant. It aims to reduce waste and maximize resource efficiency through such initiatives as the repeated reuse of used products.

Port of Rotterdam.[99] In this outstanding industrial park, about 80 industrial enterprises (in oil refining, petrochemical and industrial gases), located in the largest port of the Netherlands, took the initiative to capture carbon dioxide emissions, to install wind turbines and biomass power plants, and to burn waste and supply the heat gained to the city.

Science Park MSU.[100] This is one of the oldest science parks in Russia. Residents include companies such as Rusens, Ecoterra, Mitochondrion, Biotech-Innovations and Vivarno-Experimentalnyi Complex. They work in the following areas:

- Developing measures to optimize environmental management.

- Creating new types of drugs and biotechnological preparations.

- Developing new biosensors and analytical systems for environmental purposes.

- Performing clinical diagnosis and quality control of agricultural raw materials and food.

- Developing and commercializing reagents for molecular biology, medicine and diagnostics.

- Biotechnology.

Technopolis Moscow: This is another Russian institute for developing innovative technologies.[101] Schneider Electric, a world expert in energy management and industrial automation, located in the technopolis, offers integrated energy-efficient solutions for energy, infrastructure, various industries, civil and housing construction, and data centres. Another resident, Technoanalit, develops systems for automatic chemical control of production processes and systems for automatic control of the amount and composition of liquid and gas emissions. The Plazarium Company carries out applied research and experimental development aimed at environmental, energy and special technological applications of gas-discharge plasma.

Kurchatov NBICS Centre. The National Research Centre (Kurchatov Institute) is a unique centre of convergent science and technologies in Russia. It conducts research and development in the full range of convergent NBICS-sciences and technologies. A substantial part of Russia's nuclear physics facilities has been consolidated in the NRC. It pursues R&D in a wide range of fields of modern science using unique research and technology facilities including:

- Accelerator complexes.

- Research nuclear reactors.

- Plasma facilities.

- Nuclear medicine complex.

- Data processing centre (supercomputer).

- Complex of NBICS technologies.

The NBICS centre, established in Moscow under the Kurchatov Institute, is one of the first sites in the world focusing on interdisciplinary research in the fields of physics, chemistry, biotechnology, cell and molecular biology, nanotechnology, information technology and cognitive science.[102] The world's first faculty of nano-, bio-, info- and cognitive technologies, was formed at the Moscow Institute of Physics and Technology (MIPT) in coordination with the Kurchatov Institute. The MIPT has formed an innovative scientific and educational system for interdisciplinary training with the world's first faculty of nano-, bio-, info- and cognitive technologies.

Industry clusters, industrial centres, incubators and accelerators

In addition to science parks, public authorities are actively developing industry clusters. The creation of eco-clusters is a new trend—they should play a major role in solving the problem of recycling municipal waste, a full cycle of sorting and recycling waste and making new products from recycled resources.

Clusters such as the Saint Petersburg Cleantech Cluster for the Urban Environment play a major role in the industrial development of nature-like technologies.[103] The cluster's purpose is to support the clean technology industry. It includes educational institutions, public authorities and the private sector. Cluster members are manufacturers of equipment and clean technology for the urban economy and environment in the following areas:

- Energy conservation.

- Energy efficiency.

- Smart city/smart grids.

- Green building/ecohouses.

- Clean production processes.

- Waste treatment.

- Urban transport.

- Information technology for clean technologies.
- Clean production processes in the urban environment.
- Biofuel.
- Solar and wind energy.

The Centre for Nanotechnology and Nanomaterials (https://cnnrm.ru) was established in the Republic of Mordovia in Russia.[104] This joint project of Rusnano and the government of Mordovia aims to create innovative high-tech enterprises in nano-industry on the basis of advanced Russian developments and the transfer of foreign technologies. The centre supports young scientists and startup companies in developing and implementing ideas in nanotechnology by providing the entire infrastructure, equipment, information and investors' resources.

Creation of regional engineering centres is a new project of the Ministry of Economic Development of Russia. Such a centre is dedicated to form an engineering network infrastructure that contributes the adaptation of scientific inventions for industrial production, commercialization of technologies and knowledge. In 2017, 12 regions of Russia successfully launched engineering centres. They operate in the fields of instrument engineering, chemical and biotechnology, nanoindustry, machining, automotive industry and laser technologies.

Business incubators and accelerators are developing nature-like technologies. These structures create favourable conditions for small and medium-sized enterprises to implement scientific and technical innovative ideas. They help entrepreneurs realize business ideas and commercialize technological inventions. Many companies established in incubators and accelerators are now manufacturers and developers in nano-bio-technologies, the medical industry and energy-efficient technologies.

Ingria of St. Petersburg Science Park, started in 2008 as a pilot project, became one of Russia's most famous and successful business incubators.[105] Residents of the incubator have attracted more than 2.3 billion rubles of investment and collected more than 4.8 billion rubles of revenue. More than 400 young companies have received assistance. In 2018, Ingria's best nature-like technologies were:[106]

- Braille Glove—Communicator for deaf-blind people, which won the GlobalBusinessMatching Event-2108 competition.
- GEOPRIME—Field controller to optimize the work of a surveyor.
- AVT & Co—Smart charging stations for electric vehicles.
- Medal—Implants with the properties of electrets for the treatment of arthrosis.
- Couplings NSK—Connection of pipelines without welding and flanges.
- AGR Software—Automation of exploration.
- Vacuum development—Automated heating systems based on energy-efficient baseboard heaters.
- Innokor—Automated energy efficient LED systems, providing up to 40 percent savings.
- Inviro—Environmentally friendly waste management with heat and electricity.
- iGooods—Smart and eco-friendly product delivery service on electric tricycles.
- North Shrimp aqua network.
- TVELL—Automated system for purification of circulating water from suspended matter.
- The Tyreman Group provides professional service and training system for personnel of enterprises in the correct operation of tires to achieve maximum efficiency in the use of tire resources.

Many of these projects are in Saint-Petersburg Cleantech Cluster for the Urban Environment.

Accelerator programmes are another mechanism for supporting the introduction and application of nature-like and convergent technologies. Biomimicry accelerators issue grants for the replication and marketing of inventions based on nature-like and convergent-technologies.

Unions and associations

International unions and associations play an important role in the development of nature-like technologies.

- *The Association of Green Universities of the Eurasian Economic Union* was established in the framework of the Eurasian Economic Union to strengthen cooperation in environmental technology.

- *The Global Cleantech Cluster Association* was organized in Switzerland.[107] It is a fully independent and open platform to support developing a shared economy and low-carbon prosperity.

- *The Baltic Cleantech Alliance* is a cooperative arrangement of Baltic Sea region clusters. It aims to improve resource management, knowledge sharing and new market exploration and to help companies plug into global value chains. It focuses on sustainable eco-efficiency and water expertise solutions in northwest Russia and Central Asia. CB2East project, funded by the EU INTERREG Central Baltic Programme aims at strengthening the Central Baltic Region's economic competitiveness on the markets of Central Asia and Russia, by creating commercially targeted open innovation platforms between Latvia and Finland.

Innovation hubs

For most people a smart city means hyperloops, self-driving cars, ubiquitous Wi-Fi and countless connections to the internet of things (IoT). But new and exciting technologies are only one part of creating smarter, more sustainable and more liveable cities. The other part is nurturing a local environment of co-innovation, with collaborative innovation hubs as the centrepiece.

Today, innovation centres are popping up around the globe. From Google's North America Tech Hub Network to the National Science Foundation's Big Data Regional Innovation Hubs, these hubs, centres, labs and communities bring together government agencies, enterprises, customers, startups, academics and researchers from local universities to explore and develop disruptive solutions to today's pressing challenges.

Their impact on their communities is impressive. For example, the American Underground startup hub in Durham, North Carolina, has attracted more than $50 million in venture funding to the area, created 1,100 jobs and driven $1.4 million in spending towards local businesses over the past two years.[108] At Cisco, 11 co-innovation centres in major cities worldwide have spawned many dozens of digital solutions for its global customer base while supporting local entrepreneurial communities.[109]

Any company, university, municipality or other organization considering developing a co-innovation hub can learn proven best practices to help ensure success.

Innovators, not innovations

First and foremost, innovators should focus on people, not technologies or even the physical centres themselves. Innovation is not simply about inventing new technologies, and innovation centres must be more than glorified showcases for demonstrating products. Rather, innovation is a discipline and a mindset aimed at driving new advances in business and improvements in the way we live. This does not necessarily mean developing new technologies or products. It could imply improving the delivery of social services in a community or improving the environment. For example, local governments can implement programmes that enable self-driving vehicles or install smart street lights, but these initiatives will not create a truly smart city unless local leaders, businesses and citizens work together to foster a citywide culture that embraces innovation and pursues new ideas.

Linz, Austria, offers an apt example. City officials worked with local and international partners on a connected rail solution originally developed in the IDEA London innovation centre.[110] The goal was to improve public transportation and the environment and provide citizens with more open access to information. By connecting its light rail trams and buses to the internet of things, Linz reduced its carbon dioxide output by more than 490 tons.[111] Every tram and bus now also serves as a public Wi-Fi hotspot, providing more than 24,000 unique monthly users free internet access. City officials view the data generated from all these connections as a public resource and make it available to local startups and developers to use to create smart city solutions that will further benefit citizens.

Financial development institutions

The financial subsystem infrastructure for developing modern high-tech enterprises and stimulating new startups is formed from various institutions. Public and private foundations, such as the Innovation Fund in Canada, the National Investment and Infrastructure Fund Limited in India and the National Science Foundation in the United States, support the creation of new technologies. Almost every country grants organizations assigned resident status in a science park, technology park or industrial park benefits for property and equipment used for research and development, innovation and industrial activity.

Science parks and industrial complexes in Russia are provided with support measures in the form of preferential loans and guarantees, subsidies for reimbursement of interest on loans for purchasing equipment, subsidies for internet connectivity, and export support. Residents of technoparks receive the following tax benefits:

- Profits tax rate on taxes credited to the city budget reduced to 13.5 percent.
- Real estate tax rate for legal entities in the science park at zero.
- Land tax reduced to 0.7 percent.
- Transport tax benefits.

Other support in Russia includes:

- *The Industrial Development Fund* established for modernizing Russian industry, creating new industry sectors and supporting import substitution.[112] It offers preferential conditions for co-financing projects to develop high-tech products, reequip and create competitive industries based on the best available technologies. The Fund provides targeted loans at 1 percent, 3 percent and 5 percent for up to seven years in the amount of 5 to 750 million rubles, stimulating the flow of direct investment into the real sector of the economy.
- *The Foundation for Assistance to Small Innovative Enterprises in Science and Technology.*[113] The fund provides direct financial and information assistance to small innovative enterprises implementing projects developing new types of high-tech products and technologies based on intellectual property owned by the enterprises.
- *Russian Venture Company* is a state-funded development institution in the Russian venture capital market.[114] It operates in the field of creating large-scale platforms for the modern digital economy in biomedicine, energy, advanced production technologies, new materials, and the development of microelectronics and component bases.

Knowledge and information sharing platforms

Financing the release of nature-like and convergent technologies to the market faces further problems due to the low awareness of financial institutions on how to minimize the risks of such projects.

Many countries do not have access to information that would enable them to learn quickly about technological developments based on nature-like and convergent technologies. An English-language portal, asknature.org, is a database of developed nature-like technologies, but it is not exhaustive and not translated into other languages. Financing for projects like asknature.org comes mainly from private and public sectors not impartial or objective about convergent technologies.

Creating and developing international channels for information on nature-like and convergent technologies would be an effective mechanism. They could reach industry and other parts of the business community, research centres and organizations and public authorities and financial institutions, promoting the findings of the international community objectively.

Country-level measures that can be prioritized for systematically collecting information on nature-like and convergent technologies include:

- Creating definitions, terminologies, a methodology, and requirements for nature-like technologies.
- Creating a registry of nature-like technologies for subsequent integration into an international resource for exchanging information.
- Revising and modifying the statutory and legal framework for fiscal and fee benefits, including those for producers and consumers of nature-like technologies.
- Establishing research and development clusters or platforms for convergent technologies, including specialized tools for forming research alliances and innovative agglomerations.
- Supporting the formation of new industries and business types in a modern ecosystem of technology transfer, establishing infrastructure for commercializing and marketing innovations.
- Introducing financial incentives such as research and development cash rebates, an incubation programme for startups in convergent technologies and an innovation coupon for small and medium-sized enterprises.
- Developing budgeting for introducing nature-like technologies, including rationale, targets and indicators of the programme.
- Developing promotional and educational materials recognizing country-specific circumstances to familiarize people with nature-like technologies.
- Organizing training on nature-like technologies for the scientific community, representatives of industrial companies, venture investors and other interested parties.

Standards as instruments of new technology development

The emergence of new technologies results from a paradigm shift in the thinking of business, as well as the state. Both objective market factors and company policies influenced the shift.

For more than 40 years developed countries have been developing soft standards for companies because of their role in developing the economy and its innovations. OECD countries already have mandatory requirements for the responsible behaviour of companies, including those in the high-tech sector. Thus standards of responsible behaviour of companies are becoming, among other things, a tool shaping the development of new technologies.

The OECD adopted Standards for Responsible Business in 1976 by signing a declaration for international investment and multinational enterprises. Initially, 24 states joined the declaration; today there are 48 of them, including Russia's partner in the Eurasian Economic Union but not Russia itself.

Today, the Standards for Responsible Business follow a comprehensive methodology for the conduct of a company, and are based on the standards on corporate governance and anticorruption of five international organizations—the International Labour Organization, the International Organization for Standardization, the Global Reporting Initiative, the United Nations and the G20—as well as the standards of the OECD itself. Each standard improves the efficiency and adaptability of a company integrating it into business processes.

For example, a standard to improve company environmental responsibility will influence the development of new technologies and methods so that the company can comply with the standard. In accordance with the rules, companies must take measures to minimize pollution and protect the environment and the sustainable use of natural resources.

The latest standard in 2011, which supplemented the OECD guidelines for multinational companies, gave rules of conduct for companies in science and technology. According to the rules, companies must contribute to the scientific and technological development of the host country, ensure the introduction and transfer of new technologies, promote the achievement of the Sustainable Development Goals and interact with local communities. The rules are already directly influencing the scientific and technological revolution.

Today, not all Russian companies have implemented standards of responsible behaviour. Yet such standards can contribute to Industry 4.0. For example, developing a bioeconomy in Russia requires constant progress in biotechnology. What mechanisms are effective for introducing the necessary innovations in the companies themselves? Forming sustainable supply chains of biotechnologies, growing capacities among specialists in bioproduction and biomaterials, and standardizing bioproducts can be addressed by introducing the OECD standards of responsible behaviour.

Today Russian companies are subject to the responsible behaviour requirements of other countries if they have business ties with companies from these countries. But Russia's lack of an understandable system for introducing behaviour standards limits companies' participation in international trade and their integration into sustainable supply chains, as well as their development of innovation. Incentives are needed for companies to implement such standards. If they are offered, companies will strive to invent and introduce new technologies.

Strategies, policies and programs

In Russia, to ensure sustainable socioeconomic development and national security, a presidential initiative, Strategy for the Development of Nanoindustry, was launched in 2007.[115] Two stages were successfully implemented in 2007–2015. The third stage (from 2016) aims "to excel in developing fundamentally new areas that ensure the creation of a suprasectoral scientific, educational and production environment for the next 10–20 years."

The main content of the third stage is the development and creation of the following:

- Nanobiotechnologies.
- Hybrid and bionic devices.
- Nanobiosystems and devices, including new hybrid bionic systems.
- Biorobot and technological systems.

The first two stages of the strategy laid the intellectual, human and infrastructural base for developing convergent NBICS sciences and technologies. A national nanotechnology network has been formed to unite hundreds of scientific, educational, design and industrial centres and laboratories, universities and institutes of the Russian Academy of Sciences and other scientific organizations, development and other institutions.

To capture the momentum generated by technology convergence and to foster its further development, the US National Academy of Sciences, Board on Life Sciences Report identifies strategies and practices used by institutions to facilitate convergence endeavours (box 4.1), such as designing educational modules.

Germany has also taken the next big step by formulating research strategies towards convergent and naturally based technologies (box 4.2) and interdisciplinary focus of research initiatives at the university level (box 4.3).

Research on developing nature-like technologies is going on in several countries' scientific centres. In some developed countries, research on NBICS technologies has intensified, primarily on the

BOX 4.1

Strategies and practices used by US institutions to facilitate technology convergence endeavours

- Organizing around a common theme, problem or scientific challenge.
- Implementing management structures tailored to the challenges to convergence in each institution.
- Fostering opportunities to interact formally and informally.
- Changing existing faculty structures and reward systems.
- Working with and across existing departments.
- Embedding support for convergence in the promotion and tenure process.
- Designing facilities and workspaces for convergent research.
- Designing education and training programmes that foster convergence.
- Establishing partnerships across institutions.
- Exploring sources of funding within and beyond government agencies.

Source: The National Academy of Sciences, National Academy of Engineering, Institute of Medicine, National Research Council, Board on Life Sciences, May 2014, Report in Brief; Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond.

BOX 4.2

Bio economy—A German initiative

Germany has established a National Research Strategy Bio Economy 2030 research strategy with five priority fields: global food security, sustainable agricultural production, healthy and safe food, the industrial application of renewable resources, and the development of biomass-based energy carriers. The strategy aims to position Germany as a dynamic research and innovation centre for bio-based products, energy, processes and services. Research is supposed to meet responsibilities for global nutrition, as well as for the protection of the climate, resources and the environment.

Numerous pillars of German bioeconomy research, such as the Helmholtz Association of German Research Centres, which pursue plant, environmental, geological, climate, biotechnology and engineering research; the Max Planck Society in Life Sciences; more than a dozen institutes in the Gottfried Wilhelm Leibniz science community; and institutes within the Fraunhofer Society have pooled their resources to establish a broad research environment. Over 30,000 scientists in Germany are currently pursuing biotechnical topics and issues in more than 200 research facilities, which include 63 universities, 26 technical colleges, 104 non-university research institutes and nine government-affiliated sites.

Source: Sachsenmeier (2016).

BOX 4.3
The German Research Foundation

Deutsche Forschungsgemeinschaft (the German Research Foundation) is a self-governing research funding organization that promotes research at universities. Founded in 1920 as "Notgemeinschaft der deutschen Wissenschaft," it has an annual budget of €3.2 billion (2017). Headquartered in Bonn, with 750 employees, it serves all fields of scientific research.

The foundation's scientific aims include:

- Making research funding open to all disciplines in accordance with scientific standards of quality.
- Ensuring the best possible support for outstanding scientists and young researchers.
- Keeping Germany future-oriented and internationally competitive as a scientific location.

Source: Deutsche Forschungsgemeinschaft. https://www.dfg.de/en/dfg_profile/index.html.

convergence of nanotechnologies, information technology and biotechnologies. Among its aims are the development of supercomputers, quantum computing and biocomputers, which in the future will replace existing technological platforms.

A group of European experts identified five main areas of research related to the development of convergent technologies, along with corresponding devices and promising innovative products.[116] They are:

- Expanding human intellectual and cognitive potential and communication capabilities.
- Improving human health and physical capabilities, including fighting against aging.
- Strengthening the effectiveness of the activities of social groups and society as a whole.
- Strengthening national security and defence.
- Integrating science and education.

5

RESOLUTION OF THE FORUM

Global Forum on Nature-Like and Convergent Technologies

As a result of the international forum under the auspices of the United Nations Industrial Development Organization (UNIDO) "global forum of convergent and nature-like technologies," we, the organizers and participants of the event, adopted the following resolution:

Currently, humanity is on the cusp of the fourth industrial revolution, which brings fundamental changes to everyday life. Experts believe that the world has never experienced change of this magnitude. The international community will need to find a response to the new challenges facing humanity.

The main characteristic of the new industrial revolution (NIR) is the convergence of technologies and the blurring of boundaries between the digital, industrial and biological spheres. At the forum, participants identified key drivers: nurture and develop nature-like technologies, first of all, from the point of view of tapping new sources of energy and the principles of sustainable energy consumption. This will be critical to achieve the 2030 Agenda and its 17 Sustainable Development Goals (SDGs).

Today, exponential technological change has led to resource depletion due to the apparent incompatibility of nature and the artificial technosphere.

Panellists were confident that science will help overcome this technological impasse. Today, it is already possible to develop state-of-the-art technologies for generating and consuming energy based on natural processes—nature-like technologies that reproduce the systems and processes in the form of technical systems and technological processes integrated into the natural resource balance.

The purpose of developing such a nature-like technosphere is to restore this natural resource balance—a "metabolism" of nature, which is not disturbed by technologies, detached from the natural metabolism, through developing new technologies, systems and mechanisms.

The notion of nature-like technologies was first introduced at the highest level by the President of the Russian Federation V. V. Putin on 28 September 2015 at the 70th session of the UN General Assembly. In his speech, he said, "[W]e should talk about the introduction of fundamentally new technologies that resemble natural ones that do not cause damage to the world around them and exist with them in harmony, and will allow restoration of the violated human balance between biosphere and technosphere. It really is a challenge of planetary scale..."

The forum demonstrated that the development of nature-like technologies could result in drastically reducing the impact of humanity on the environment and rethinking how people and economic systems should interact with nature.

The international instrument for the introduction of natural-like technologies in the UN system is the 2030 Agenda for Sustainable Development. It contains a number of goals aimed at eradicating poverty, preserving the planet's resources and ensuring well-being for all. Joint efforts by governments, the private sector and civil society are needed to achieve Sustainable Development Goals.

Nature-like technologies play a key role in achieving these goals. One of the main focuses is the universal access to energy. It is expected that in the near future the convergence of science and technology will lead to transformative achievements in the generation, transformation, storage and distribution of energy.

Achieving the goal of eliminating hunger is closely linked to sustainable access to water and energy. Combining agriculture and food systems into an environmentally sustainable community through an updated distribution of energy is essential for eradicating poverty and hunger.

Mitigating the effects of global climate change is among the most urgent challenges faced by humanity. The development of renewable energy sources is among the most effective means to stabilize earth's climate. The development of technologies that resemble natural processes will enable the development of environmentally benign building blocks and manufacturing processes for the semiconductor, chemical, petroleum and pharmaceutical industries, as well as the use of more effective and cleaner industrial production.

Speakers at the forum agreed that nature-like technologies give humanity a chance to avoid resource collapse and at the same time tackle new global threats and challenges. These threats are related to the character of nature-like technologies, which are built on the possibility of technological reproduction of wildlife systems and processes. This possibility does not exclude purposefully interfering with organisms, especially humans.

Traditionally, mankind followed the model of control over the results of technological activity. In the case of natural-like technologies, control is necessary at the very beginning of this new technological structure's development. This, in turn, requires consolidating all efforts at the international level to form a new system that ensures the safe, regulated development of natural-like technologies.

A special role in promoting the theme of nature-like technologies for the Sustainable Development Goals in the international arena is taken up by the UN system and its specialized agencies, and UNIDO in particular.

In this regard, we believe it is necessary to continue to consolidate all efforts by the political, scientific and business communities to achieve the SDGs through naturally based technologies. Particular attention should be paid to the economics of change and its impact on the formation of value chains in international trade. Achieving the sustainable development goals can only be achieved through voluntary action by the private sector and the gradual change of companies' internal business processes to meet internationally accepted standards of responsible business (OECD) and the promotion of ideas for the formation of new standards. Such companies are sustainable and will be able to gain a competitive advantage in the future.

As a result of the forum, we believe it is possible to create a permanent platform for international dialogue in this area. In particular, the next step in promoting nature-like technologies on the world stage is the Global Manufacturing and Industrialization Summit (GMIS), hosted jointly by the Ministry of Industry and Trade of the Russian Federation, UNIDO and Arab partners. Hosting global forum events made it possible to illustrate the priority of this subject to the international community for scientific and technological cooperation.

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BIOGRAPHIES OF SPEAKERS

Yury Abramov
General Director of the Agency for Technological Development

He has held this position since July 2018. As General Director, he supervises the modernization and diversification of enterprises of the military–industrial complex and their interaction with state corporations.

His other professional experience includes: Higher School of Economics, strategic management, crisis management and financial recovery of enterprises, increasing operational efficiency, financial management, investment management, strategic financial analysis, risk management, M & A transactions, due diligence, financial investigations, integrated automation of financial-economic activity, and ERP implementation systems.

Mikhail Bakradze
Head of the Research Department of the All-Russian Research Institute of Aviation Materials

He was named Russian Engineer of the Year 2007 and awarded the President Scholarships of the Russian Federation in 2010–2012 and 2013–2015.

Deputy Head of the Laboratory High-Temperature Materials for GTE Parts, FSUE "VIAM," Moscow; Moscow State Evening Metallurgical Institute—2007.

Professional activity is related to the development of compositions and technology for the production of high-temperature nickel-based alloys for gas turbine engine (GTE) disks of a new generation, the development of heat treatment modes for high-temperature alloys, and industrial production of gas turbine engine disks. These studies are carried out under state contracts with the Ministry of Industry and Energy of the Russian Federation and the Ministry of Defence of the Russian Federation. He is engaged in the creation of heat-resistant nickel alloys for disks with a higher complex of properties as compared to materials of similar purpose. He is a member of the Council of Young Specialists and Scientists of FSUE "VIAM." He participated in the organization of the international scientific-technical conference "Actual issues of aeronautical materials science." His labour activity is marked by two thanks in the orders for the Institute and the Diploma of Honour of VIAM.

He has nine publications and a patent for an invention.

Christophe Behar
Director of FAYAT Group

Previously he served as Director of the Atomic Energy Commission's Nuclear Energy Division with responsibility for the nuclear energy sector (research and development, and disarmament). He is a member of the Supervisory Board of Areva (now, Orano), a member of the boards of Areva, TA (Technicatome), STMI and Grand Équipement National de Calcul Intensif high-performance technologies. In addition to his professional activities he lectures at École Centrale de Paris and at École Nationale Supérieure des Techniques Avancées. Christophe Behar is a Knight of the Legion of Honour and the National Order of Honour.

Alexander Blagov
Director of the National Research Centre (Kurchatov Institute)

After graduating from the Faculty of Physics of Moscow State University in 2000, he was enrolled in full-time postgraduate studies at the Shubnikov Institute of Crystallography of the Russian Academy of Sciences. In 2006 he defended his thesis for the degree of Candidate of Physical and Mathematical Sciences on the topic "Features of X-ray wave diffraction on crystals modulated by low-frequency ultrasound." Blagov expanded the range of tasks and, together with work in the field of X-ray acousto-optics, actively developed methods of high-resolution X-ray diffractometry, X-ray reflectometry, phase-sensitive X-ray methods, conducted studies of the structural features and processes of self-organization of crystalline and poorly ordered materials. His work in the field of x-ray acousto-optics was supported by grants of the President of the Russian Federation for young scientists–candidates in 2008 and 2010. In 2011, he won the President's Award for young scientists in the field of science and innovations for creating the scientific foundations of tunable X-ray optics for a new class of research instruments. His work also served as the basis for a new direction in the field of crystal physics "controlled X-ray optics based on crystals subjected to ultrasonic vibrations." In 2015 Alexander Blagov was appointed as the First Deputy Director of the Institute, and in 2017 as the Director of the Kurchatov Synchrotron–Neutron Research Complex.

Alexander Blagov is the author of more than 100 publications, including 50 papers in peer-reviewed scientific journals and eight patents.

Marina Borovskaya
Deputy Minister of Science and Higher Education of the Russian Federation

She has held this position since 2018. She is a Russian economist holding a doctorate and a professor. From 2012 to 2018 she was the Rector of the Southern Federal University. She served as Chairman of the Council of Rectors of the Southern Federal University and Vice-President of the Russian Union of Rectors.

Ivan Bortnik
General Director Advisor of the Fund of Assistance for the Development of Small Enterprises in the Scientific–Technical Sphere

He is also a member of the Supervisory Board of the Association of Innovative Regions of Russia and Professor of Innovation Management at the Higher School of Economics. He was awarded the Government Prize in education. He has written more than 100 articles and reports in various technical journals, as well as two books, and has made presentations at Russian and international conferences.

In the 1980s, he was First Deputy Chairman of the USSR State Committee on Science and Technology, then First Deputy Chairman of the USSR State Committee on Science and Technology. From 1992 to 1993, he served as Deputy Minister of Science, High School and Technical Policy of the Russian Federation.

He is the founder of the Foundation for the Promotion of the Development of Small Enterprises in the Scientific and Technical Sphere. From 1994 to 2008 he was the CEO of the Foundation. From 2008 to 2016 he served as the Chairman of the Supervisory Board of the Fund.

He is a doctor of technical sciences, professor and the author of two books and more than a hundred articles and reports published in various technical journals and at national and international conferences. He is the winner of the Prize of the Government of the Russian Federation in the field of science and technology for 2001.

Mathew Burrows
Director of the Strategic Foresight Initiative of the Atlantic Council

He worked for more than 10 years as an adviser and analyst at the National Intelligence Council, where he was Director of the Analysis and Production Staff beginning in 2010. At the council he was the principal drafter for the 2012 publication *Global Trends 2030: Alternative Worlds,* the key futurological material for the White House and the US Department of Defense. In 2005 Burrows was asked to create and head a new unit of the intelligence agencies in the USA working on long-term strategic forecasting. From 1999 to 2001 he was the adviser to Richard Holbrooke as US Ambassador to the United Nations.

Vyacheslav Butin
Deputy General Director of Terra Tech

Previously he worked as Business Development Director of Sovzond Company. He is an author and the head of the project GRADIS. He graduated from the Academy of National Economy, Russian Academy of Public Administration.

Ivan Danilin
Head of the Department of Science and Innovation of the National Research Institute of World Economy and International Relations of Primakov Russian Academy of Sciences

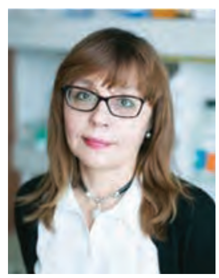
He has held this position since 2010. From 2010 to 2011 he headed the project Energy Foresight of the Russian Federation in the Long Term at Rosatom State Corporation. He has also served as an expert of Skolkovo Foundation since 2011.

Vyacheslav Demin
Director-Coordinator for Nature-like Technologies at the National Research Centre (Kurchatov Institute)

In 2014 he contributed to creating the laboratory of neuromorphic systems, which studies the development of the element base of neuromorphic systems and the hardware of artificial intelligence.

In 2007 he graduated from the Physics Faculty of Moscow State University. In 2008 he received the degree of candidate of physical and mathematical sciences.

His research interests include: artificial intelligence, adaptive neuromorphic networks on memristors, transport of nanoparticles in living organisms, and physics of low-dimensional structures. He is the author of more than 30 scientific publications.



Olga Dontsova
Head of Department of Chemistry of Natural Compounds, Lomonosov Moscow State University

She is the author of more than 170 scientific articles and two books, and holds three patents. She has been a member of the Presidential Council for Science and Education under the President of the Russian Federation since 2017.

Igor Drozdov
Chairman of the Board of the Skolkovo Foundation

He was elected chairman in 2016. From 2005 he was head of the Secretariat of the Chairman of the Supreme Arbitration Court of the Russian Federation, and from 2006 until 2010 he was administrator of the Supreme Arbitration Court of the Russian Federation. At the Skolkovo Foundation he served as Vice President, Director of Legal Affairs and Senior Vice President for Legal and Administrative Affairs. He is a member of the Council on Intellectual Property of the Federation of the Federal Assembly of the Russian Federation and a member of the Expert Council of the Government of the Russian Federation. He is the author of more than 30 scholarly publications on civil law.

Aleksandr Dynkin
President of the Primakov National Research Institute of World Economy and International Relations, Russian Academy of Sciences

He is also an academician of the Russian Academy of Sciences, Chairman of Scientific Council and a member of the Board of Trustees of the Russian International Affairs Council. He leads development in a number of areas of Russian economic development: industrial policy for increasing competitiveness, the contribution of large and small companies to the modernization of the economy, and pros and cons of the formation of the national innovation system. He has published more than 400 papers in Germany, the Republic of Korea, Russia, the United States and other countries. He is the author or coauthor of 20 monographs, including books published outside Russia.

Andrey Fursenko
Aide to the President of Russian Federation

He served as a Minister of Education and Science of Russian Federation in from 2004 to 2012 and as a member of Board of Trustees of Russian International Affairs Council in 2011. On 12 December 2013, Vladimir Putin appointed Fursenko Chairman of the Board of Trustees of the Russian Science Foundation.

Igor Ganshin
Director, International Cooperation Department, Ministry of Science and Higher Education of the Russian Federation

From 2014 to 2017 he was a Deputy Director in the International Cooperation Department at Ministry of Science and Higher Education. He has also held positions at the Embassy and the General Consulate of Russia in China.

Oleg Gusev
Director of the Russian–Japanese division of RIKEN

After several years of work at the National Institute of Agrobiological Sciences, he was invited to work at the Space Agency of Japan, where he supervised joint Russian–Japanese space research in the life sciences. His scientific interests include comparative genomics and analysis of RNA transcription with a variety of adaptive applications in biology and biomedicine.

Victor Haefeli
Director General and Owner of Smart Resources

He is also a Consultant at Swiss Ministry of Environment, Vice-President of the Swiss Association for Environmental Technology and President of the International Congress of Electronics Processors. He has been working in the sphere of ecology for more than 30 years.

Olgun Hayati
Professor of Solar Energy Institute, Ege University

He is the author of more than 15 scientific articles.

Kuniyoshi Hiroshi
Deputy Director General of the United Nations Industrial Development Organization

In August 2006, he was appointed Professor at the Tokyo Institute of Technology, where he conducted research and training on industrial, technology and innovation policy issues. In September 2012, he was appointed Executive Director of the New Energy and Industrial Technology Development Organization (NEDO), a public management organization in Japan. At NEDO, he was responsible for global international projects for developing low-carbon technologies such as renewable energy, batteries and smart grids. He was also the vice president of the Global Federation of Intelligent Networks. He became Deputy Director General of UNIDO in 2017.

Victor Ilgisonis
Director of Scientific and Technical Research and Development, Rosatom

He has held this position since 2015. In 2013, he was appointed as Chief Scientific Secretary of the National Research Centre (Kurchatov Institute); in 2014 he also became Deputy Director for Scientific Research at the Centre. He is currently the Director of Scientific and Technical Research and Development of Rosatom State Corporation. Since 2007 he has been the Head of the Department of Experimental Physics at the People's Friendship University of Russia and lectures at National Research Nuclear University–Moscow Engineering Physics Institute.

Andrey Klepach
Deputy Chairman (Chief Economist) and member of the Board of the State Corporation Bank for Development and Foreign Economic Activity

He has held this position since 2014. Previously he worked as Deputy Head of the Ministry of Economic Development and Trade of the Russian Federation, Director of Department of the Ministry of Economic Development and Trade (2004–2008) and Executive Director of the Centre of Development Foundation for Economic Research (1999–2004).

Sergey Korotkov
Director of the United Nations Industrial Development Organization Centre for International Industrial Cooperation in the Russian Federation

He has held this position since 2005. In 1990, he began to work as an expert of the Ministry of Foreign Trade of the USSR, undertaking long-term assignments in Jamaica and Brazil, where he was in charge of trade and economic cooperation. In 2003, he became project coordinator at UNIDO, working on technology transfer in airborne geophysical surveys of natural resources in the Parnaiba Basin, Brazil. He is a graduate of Bauman Moscow State Technical University (1981) and the All-Russian Academy of Foreign Trade (1990).

Mikhail Kotyukov
Minister of Science and Higher Education of the Russian Federation

He has been serving in this position since May 2018. Previously, he served as Minister of Finance and Deputy Prime Minister of the Krasnoyarsk Territory (2008–2010), Deputy Minister of Finance of the Russian Federation (2012–2013) and

Head of the Federal Agency of Scientific Organizations (2013–2018). He is a member of the Supreme Council of the political party United Russia.

Mikhail Kovalchuk
President of the National Research Centre (Kurchatov Institute)

He has held this position since 2015; from 2005 to 2015 he was its Director. He was Director of the Institute of Crystallography at the Russian Academy of Sciences from 1998 to 2013 and has been a corresponding member of the academy since 2000. He has also served as President of the all-Russian Society of Inventors and Innovators and as Dean of the Physics Faculty at Saint Petersburg University. He was an academic Secretary of the Presidential Council for Science, Technology and Education in from 2001 to 2012; after its transformation into the Presidential Council for Science and Education in 2012 he was a member of the Presidium. He is a full Chevalier of the Order for Merit to the Fatherland.

Vladimir Kuznetsov
Director, United Nations Information Centre in Moscow

He has held this position since 2015. From 2008 to 2015 he worked as the Deputy Permanent Representative of Russia at the UN Food and Agriculture Organization and World Food Programme in Rome, as well as the adviser-envoy of the Russian Embassy in Italy.

Pavel Logachev
Director of the Institute of Nuclear Physics of the Siberian Department of the Russian Academy of Sciences

Since 2017 he has been a member of the Presidential Council for Science and Education. In February 2018 he joined the Expert Council of the United Russia party.

Olga Memedovic
Deputy Director, Department of Trade, Investment and Innovation, United Nations Industrial Development Organization, Chief, Business Environment, Clusters and Innovation Division

She holds a PhD degree in economics from Erasmus University Rotterdam and joined UNIDO in 2000. With UNIDO, she managed and led research projects in international trade, international economics, public economics, industrial and economic development, industrial organization, regional development, energy, environment and global governance. She has produced more than 50 publications, including several flagship reports and policy documents. She has contributed to UNIDO policy advice work, formulating and designing industrial strategies, policies and development programmes for various countries in Africa, the EU and the Middle East. Currently she is project leader and manager for several UNIDO technical cooperation projects addressing business environment reforms, industrial modernization and upgrading, development of systems of innovations, development science, industry and technology parks and transformation to the new industrial revolution.

Pawel Miller
Owner and CEO of NordStar Capital

He has been owner and CEO since 2009. He was CEO and Managing Director of Deutsche Capital Management in 2012–2013. He is currently the Deputy CEO of Bioelectra Group SA in Poland, and since 2017, CEO of Bioelectra SE in Slovak Republic.

Anton Moskvin

Vice President for Marketing and Business Development, Rusatom Overseas

He has held this position since 2011 and is an experienced C Level executive with a demonstrated history of working in the high-tech energy industry. He has a successful track-record in international business development, sales, marketing, multi-billion dollar deals, and project structuring and negotiation. His professional interests extend from venture capital investment to high-tech start-ups and disruptive technologies.

Shaban Muhammad

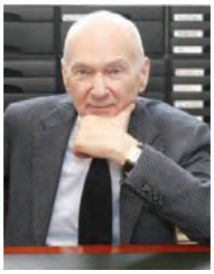
Director of the Strategy of the Global Manufacturing and Industrialization Summit

Niki Naska

With 10 years of experience in stakeholder management and policy analysis in RDI, she is responsible for EUREKA Association's international cooperation, strategic partnerships and institutional relations.

Oleg Naraykin

Vice-President of the National Research Centre (Kurchatov Institute)



He is a member of the Scientific and Technical Council of Rosnanotech, the International Informatization Academy and the International Academy of Sciences of Higher School. He is the Chairman of the Scientific and Methodological Council on Mechanics of the Ministry of Education and Science, a member of the Bureau of the Working Group on Nanotechnology and Materials. He is a member of the Interdepartmental Scientific and Technical Council on Nanotechnology and Nanomaterials. In 1996 he became Head of the Department of Applied Mechanics at Moscow State Technical University. He is the author of more than 70 scientific publications. He has received the Presidential Prize of the Russian Federation (2000) and many other state prizes and medals.

Artem Oganov

Professor, Skolkovo Institute of Science and Technology

A crystallographer theorist, mineralogist, chemist and teacher, he is best known for developing methods of computer design using new materials and predicting crystal structures. In 2014 *Russian Reporter* and *Expert* magazines included him in the list of 100 most influential Russians, and *Forbes* saw him among "50 Russians Who Conquered the World." In 2017 he joined the Presidential Council for Science and Education, and he is Professor, Russian Academy of Sciences.

Vladislav Panchenko

Chairman of the Board of the Russian Foundation for Basic Research

A Russian scientist in the field of laser information technology, scientific instrumentation, nonlinear optics and medical physics, he also serves as the Scientific Director of the Institute on Laser and Information Technologies of Russian Academy of Sciences.

Sergey Polyakov
Director General of the Foundation for Assistance to Small Innovative Enterprises in Science and Technology

He received that appointment in 2008. He is a member of the Expert Council on Technical and Innovational Special Economic Zones under the Ministry of Economic Development of the Russian Federation. He is a member of the Supervisory Board of the Fund of Infrastructure and Educational Programs of Rusnano, a member of the Public Council under the Ministry of Economic Development and a member of the Board of Directors of the Russian Venture Company and the RVC Seed Capital Fund.

Anna Popova
Chief State Sanitary Doctor of the Russian Federation

She is also the Head of the Federal Service for Supervision of Consumer Rights Protection and Human Well-Being (Rospotrebnadzor). Previously she was Deputy Head of Rospotrebnadzor in the Moscow region, Head of the HR department, postgraduate education and public hygienic education at Rospotrebnadzor and Deputy Head of Rospotrebnadzor. She is the author or coauthor of more than 70 scientific papers, two monographs and more than 50 normative and methodological documents.

Aleksey Rakhmanov
President of the United Shipbuilding Corporation

He has held this position since 2014. Beginning in 1996 he was Manager of the Corporate Finance Department at the Moscow office of Ernst & Young. From 2002 to 2008 he was Director of Strategy and Business Development at Severstal-Auto. From 2008 to 2012 he served as Director of the Department of Automotive Industry and Agricultural Machinery in the Ministry of Industry and Trade of Russia. In 2012 he was appointed as Deputy Minister of Industry and Trade of the Russian Federation.

Wilma Rethage
Head of the Russian Office of the German Research Foundation

Previously she managed community relations with scientific organizations in the Czech Republic, Hungary and Poland.

Mikhail Rychev
Special representative of the National Research Centre (Kurchatov Institute) to European research organizations

Since 1995, he worked on the creation of science and technology parks and innovation centres in a number of Eastern European and Commonwealth of Independent States countries as an expert of UNIDO and the World Bank. He is the author of more than 40 scientific publications in Russian and international journals and three monographs. His work laid the foundation for a new scientific direction in the nonlinear optical spectroscopy of low-temperature plasma.

Grigoriy Senchenya
Adviser to the Head of the Russian Federal Service for Intellectual Property (Rospatent)

From 2013 ton2015 he was Deputy Head of the Department of Science, Industrial Policy and Entrepreneurship of Moscow. In 2012–2013 he was Secretary of the Interministerial Commission for the Implementation of the Strategy of Innovative Development of the Russian Federation for up to

2020 of the Presidium of the Presidential Council for Economic Modernization and Innovative Development of Russia.

Alexander Sergeev
President of the Russian Academy of Sciences

He has been President of the Russian Academy of Sciences since 2017. A specialist in plasma physics, femtosecond optics, nonlinear dynamics of optical systems and highly sensitive optical measurements, he is a Doctor and Professor of Physical and Mathematical Sciences (2000). He was Director of the Institute of Applied Physics of the Russian Academy of Sciences from 2015 to 2017. He received the State Prize of the Russian Federation in 1999 and the Russian Government Prize in 2012. There are more than 8,000 citations of his works in scientific journals.

Elena Shmeleva
Head of the Talent and Success Educational Fund

She is also a member of the Presidential Council for Science and Education and Co-Chairman of the central staff of the All-Russia People's Front. Previously she was Vice-President of System, a charity fund; Director of Lift to the Future, a nonprofit partnership to promote the development of intellectual and creative potential of youth; and acting Dean of the Higher School of Management and Innovation of Moscow State University.

Yuri Slyusar
President of the United Aircraft Corporation

He has held this position since 2015. He is a former Assistant to Minister of Industry and Trade of the Russian Federation Victor Khristenko. He has also served as the Director of the Department of Aviation Industry of the Ministry of Industry and Trade and Deputy Minister of Industry and Trade. Since 2013 he has been a member of the Board of Directors of the Oboronprom United Industrial Corporation. Since 2014 he has also served as a member of the Board of Directors of Aviation Equipment Holding and a member of the Board of the Military and Industrial Commission of the Russian Federation.

Aleksandr Tkachev
Director of the Centre for Innovative Technologies and Engineering of the Russian Technological University

As director, he also serves as the National Project Coordinator of the European Science and Technology Program Eureka and is responsible for the development of innovative technologies in the following areas: electronics, instrumentation, biomedicine, chemistry, ICT, new materials, transport, aviation and space, and renewable energy in Russia using the advantages of a special economic zone of technology-innovative type created in the city district of Fryazino, Moscow region.

Grigory Trubnikov
First Deputy Minister of Science and Higher Education of the Russian Federation

He has held this position since 2018. He is a physicist and an academician of the Russian Academy of Sciences. He is the author or coauthor of more than 190 scientific papers and reviews. He received the Russian Government prize in science and technology in 2010.

Karlsson Ulf
Professor at the Royal Stockholm Institute of Technology

He conducts research in material physics, microelectronics and applied physics.

Raif Vasilov
Chairman of the Society of Biotechnologists of Russia

He is a leading specialist in the field of biotechnology, a doctor of biological sciences, professor, and the president of the All-Russian public organization Society of Biotechnologists of Russia named after Yu. A. Ovchinnikov (2003), which unites about 4,000 specialists. His goal is to develop the bioindustry and bioeconomics. He also served as the head of the Russian Biotechnology Society. His research interests include: biochemistry, immunology, biotechnology and genetics. He graduated from Kazan State University with a degree in chemistry (1970). He is the author of 130 publications and five copyright certificates. He is also the chief editor of the journal *Bulletin of Biotechnology and Physico-chemical Biology*.

Alexander Yanenko
Director of the State Institute of Genetics and Selection of Industrial Microorganisms of the National Research Centre (Kurchatov Institute)

He is a Doctor of Biological Sciences and a Professor.

Ekaterina Yatsishina
Deputy Director for Scientific Research of the National Research Centre (Kurchatov Institute)

She is also head of the laboratory of natural science methods in the humanities, with a PhD in philosophy.

She is the author or coauthor of a series of scientific publications concerning naturally based convergent technologies, interdisciplinary research and material sciences for history.

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