A gaze into the crystal ball: biomimetics in the year 2059

I C Gebeshuber[1,2,3,*], **P Gruber**[4], and **M Drack**[5]
[1]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[2]Institute of Applied Physics & TU BIONIK, Vienna University of Technology, Vienna, Austria
[3]AC^{2}T Austrian Center of Competence for Tribology, Wiener Neustadt, Austria
[4]Transarch, Vienna, Austria
[5]Department of Theoretical Biology, University of Vienna, Vienna, Austria

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Abstract: Biomimetics is a field that has the potential to drive major technical advances. It might substantially support successful mastering of major global challenges. In the first part of the article, the current state of biomimetics is reviewed, and goals and visions of biomimetics are presented. Subsequently, possible biomimetic scenarios to overcome the major global challenges, as indicated by the Millennium Project, are envisaged. Those of the 15 challenges (sustainable development, water, population and resources, democratization, long-term perspectives, information technology, the rich–poor gap, health, capacity to decide, peace and conflict, status of women, transnational crime, energy, science and technology, and global ethics) where biomimetics might provide relevant contributions are considered in more detail. The year 2059 will mark the 100th anniversary of Part C of the *Proceedings of the Institution of Mechanical Engineers*, the *Journal of Mechanical Engineering Science*. By this time, some of these challenges will hopefully have been successfully dealt with, possibly with major contribution from biomimetics. A new Leitwissenschaft and a new type of 'biological technology' are emerging, and in biology more and more causation and natural laws are being uncovered. In order to estimate the fields of biology from which technical innovations are likely to appear, the amount of causal knowledge is estimated by comparing it with correlational knowledge in the respective fields. In some fields of biology, such as biochemistry and physiology, the amount of causal laws is high, whereas in fields such as developmental biology and ecology, we are just at the beginning. However, sometimes ideas and inspirations can also stem from nature when the causations are not known. The biomimetic approach might change the research landscape and the engineering culture dramatically, by the blending of disciplines (interdisciplinarity). The term 'technoscience' denotes the field where science and technology are inseparably interconnected, the trend goes from papers to patents, and the scientific 'search for truth' is increasingly replaced by search for applications with a potential economic value. Although the trend in many scientific fields goes towards applications for the market, a lot of disciplines will stick to the traditional picture of science. An open question left to the future is whether the one development or the other (technoscience or pure science) is an advantage for the future of humans. In the subsequent section, the article gives information about organizations active in biomimetics. It shows the relevance of biomimetics on a global scale, and gives reasons for promoting transdisciplinary learning. Increasing interdisciplinarity calls for novel ways to educate the young. Brian Cambourne's 'Conditions of Learning' theory is recommended in this respect. This dynamic and evolving model for literacy learning comprises the concepts immersion, demonstration, engagement, expectations, responsibility, employment, approximation, and response. Each of these conditions supports both the student and the teacher in their discovery of learning, helps provide a context within which to learn,

Corresponding author: Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, Salangor, Darul, Ehsan, 43600 UKM, Malaysia.
email: ille.gebeshuber@iap.tuwien.ac.at

and creates an interactive and dynamic experience between the learner and the content. In the year 2059, researchers and developers who routinely think across boundaries shall successfully implement knowledge in solving the major challenges of their time!

Keywords: biomimetics, future studies, emerging fields, physical biology, causation, global challenges

1 INTRODUCTION

Will there be something like biomimetics in 50 years from now? Is biomimetics just a hype of the beginning of the 21st century? The approach of biomimetics is much older than its name. Researchers and scholars, who have used biological role models and have used inspirations from living creatures and systems, can be found very early in history. It is thus quite reasonable to assume that the approach will be used further on, perhaps under the same name, perhaps with another name. But what will it look like? This article tries to give an answer to this question, although reality will look different, that is for sure.

In this article the authors shortly sketch how biomimetics became what it is today and extrapolate therefrom what it might look like in the future.

Questions that arise when gazing into the crystal ball of the future of biomimetics are the following: Should different scenarios be considered? What is the method? What will be the reasoning? Pure science fiction fantasy? The authors decided to use as a measure for what will be possible three different methods: issues biomimeticians always dreamt of (flying, photosynthesis, etc.), global challenges that set aims for biomimetics, and an analysis of causation in biology to see what is likely to become applied. The potentials are examined from a push and a pull perspective. The pushes are what biomimeticians want to achieve by themselves (first method). The pulls are equal to the needs that are mentioned with respect to our futures (second method). Furthermore, another methodical approach is used to estimate what areas within biomimetics have a high potential to develop quickly (third method): it is often acknowledged that biomimetics is not a mere copy of nature. The underlying principle of the natural phenomenon to be biomimetically applied in technology has to be understood. Such an understanding is indicated by the ratio of causal versus correlational knowledge, or the ratio of explanatory versus descriptive knowledge. In other words, especially where the causation is known in biology, serious attempts in biomimetics can be made. In many biological disciplines, however, causal laws are not at hand yet.

In all three cases (methodical approaches) only the limited potential of technology to serve society can be considered. Additionally also issues beyond the feasibility of mere technical applications are discussed. Biomimetics is a programmatic connection of science and technology. If this approach is gaining ground also developments in institutions, teaching, etc. are to be expected.

2 CURRENT STATE OF BIOMIMETICS

Biomimetics is different! It is different from traditional science and traditional engineering. The approaches taken in biomimetics, however, are not new. Already the Renaissance scholar Leonardo da Vinci tried to understand birds' flight with the intention to build a machine that would allow human flight. One would say today that he worked across disciplines. This transdisciplinary work is a basic characteristic of biomimetics, but what distinguishes biomimetics from accidental bioinspiration is the strategic approach.

In a former article Gebeshuber and Drack [**1**] distinguished two methods (not to be confused with the methods used in this article) of biomimetics: biomimetics by analogy and biomimetics by induction, to which the different activities in the field can be assigned (in order to avoid the judgemental terminology of 'bottom up biomimetics' and 'top down biomimetics' described by Harder [**2**] suggesting nature as base and technology as top). In contrast to biomimetics, technical biology investigates organismic entities or systems with methods, models, and tools from engineering. Biomimetics by analogy starts with a problem from technology and tries to find analogous problems in nature with the respective solutions that might also be useful in technology. Biomimetics by induction refers to ideas that stem from basic science with no intention for applications as a motivation in the first place. In German-speaking countries the term 'Bionik' has become widely accepted for the corresponding field to 'Biomimetics'. 'Bionik' – combining biology and technology – is a broader field than 'bionics', which is referring to a combination of biology and electronics.

In the 1980s Werner Nachtigall differentiated the field of 'Bionik' into subfields – three main fields represent a categorization, which seems to be valid until today [**3**]:

(a) structural 'Bionik', nature's constructions, structures, materials;
(b) procedural 'Bionik', nature's procedures or processes;
(c) informational 'Bionik', principles of development, evolution, and information transfer.

Biomimetics is yet another example for the increasing dissolution of disciplines, which is found in science, together with the development of highly specialized domains. Interdisciplinary work with a special focus (for example the functional design of surfaces by means of nanotechnology) requires input from more than one classical discipline (in this example: physics, chemistry, biology, mechanical engineering, and electronics).

Biomimetics is discussed as a method rather than a discipline, and examples of biomimetic design are often controversial.

One of the most popular examples, the 'boxfish car', a Mercedes-Benz concept car, is referred to as 'the bionic car'. The criticism of scientists ranges from naive transfer of morphology to misuse of biomimetics for promotion purposes. The transfer of the morphology may be questionable in terms of flow conditions, but as a matter of fact the construction of the carriage was optimized according to Claus Mattheck's SKO optimization method [**4**, **5**], derived from the natural growth of bones. The discussion about the car illustrates a common problem in the design of complex products: the boxfish car was developed on many different levels, and just for one or two levels a biomimetic approach was used – does this legitimate the attribution of 'bionic' or 'biomimetic' to the whole product? Do we need yet another term for the scientific approach that we want to pursue to differ from a sales argument?

On the other hand, the increasing popularity of biomimetics is also due to a common misunderstanding of biomimetic technologies being directly linked to sustainability and thus 'greener' than any other innovation method. It is beyond controversy that the discussion of nature and natural technologies delivers an increased knowledge and consciousness about ecological interconnections, but as researchers have argued again and again, biomimetics as a sole innovation tool can also deliver unsustainable products and is not a panacea for all global problems. The intention to design environmentally responsible and sustainable products is independent of this design method. The values according to which applications are designed come from outside referring to societal and cultural norms. This will not change in the future, which means biomimetics will still be an innovation method, characterized by the strategic information transfer, independent of a value system.

To characterize the current state of biomimetics, members of the BIONIS network in the UK analysed publication rates of patents in the US and China [**6**], showing rapidly increasing activity in new technologies derived from biological models. The recent development of national and international networks and the increasing publication activity in technical journals are likely to enhance productivity in the field of biomimetics.

There is growing interest in methodology, having led to several techniques to gain information transfer in different disciplines. The Biomimicry group in the USA [**7**] for example has elaborated a refined step-by-step method to integrate biological knowledge and research into industrial research and development processes. Based on Altshullers 'Theory of inventive problem solving' the Biomimetics group in Bath, UK, developed another methodical approach called BioTRIZ [**8**]. A TRIZ-based analysis of problem solutions in nature has shown the profound difference of 'design' in nature to 'design' in technology: while technology solves problems largely by manipulating usage of energy, biology uses information and structure [**9**]. Only recent technologies such as nanotechnology and smart materials work in a more 'biological' way.

The Advanced Systems Team of the European Space Agency is also working with biomimetics. A multi-level database that enables the search for biological phenomena according to specified parameters and keywords is available online [**10**]. In November 2008 the Biomimicry group launched the Ask Nature website, 'How does nature...?' [**11**] offering access to knowledge about outstanding natural phenomena and establishing contacts with the experts. The availability of research findings is crucial for interdisciplinary work in biomimetics, and databases like the ones mentioned could establish themselves as the first step to take when looking for a specific biological role model.

The application fields of biomimetics in industry are diverse, ranging from nanotechnological surface design to the application of communication strategies of insects in the distribution of goods. In 2008 the Department of Foresight and Policy Development of the Austrian Institute of Technology (the former Austrian Research Centers ARC Systems Research) carried out a study on the international research landscape for selected fields in biomimetics focused on transportation technology. More than 80 000 publications containing biomimetic terminology could be identified using DialogWeb [**12**] and FIZ-Technik [**13**] databases. Purely chemical and biomedical databases were then excluded and 1500 articles published between 2004 and 2007 were selected for detailed analysis. The study revealed important fields apart from biomedicine and chemistry: automatization, structural analysis of natural materials, and synthesis of biomimetic materials. FIZ-Technik delivered material sciences as the most important field. Others include bioscience and sensing and actuation technology. The geographic distribution showed China and the US as the most active countries in the field, followed in Europe by Germany, Italy, the United Kingdom, France, Sweden, Austria, and others. According to the attributed classification codes, the articles came from a wide range of disciplines, bioengineering, chemical engineering, and engineering physics being the most important.

In general, there seems to be a strong interest in biology and chemistry to combine both fields with technology [**14**].

3 BIOMIMETICS 50 YEARS FROM NOW

3.1 The goals and visions of biomimetics

Research in the field is pushed forward by outstanding natural phenomena that have always inspired scientists and engineers, some of them still not being transferable. Visions of the future of biomimetics published by representatives of the scientific community as presented in the following include solutions from nature that exceed our technical abilities today.

Steven Vogel is very cautious in pointing out the prospects of the field. Still, he mentions some areas related to mechanical engineering where a biomimetic approach might be fruitful. In general, Vogel states that the smaller the scale the more potential lies in approaches of biomimetics. Materials science and nanotechnology seem to be the most promising fields. In nature forms and materials are built bottom up (i.e. by a combination of material components on the micro- and nanometre scale). Thereby, a broad variety of hierarchically organized materials is available for organisms with a wide span in relevant properties. Mimicking nature in the field of composite materials and smart materials (e.g. for adjustment in response to changes in load) will lead to technical innovations. Moreover, Vogel mentions as promising fields muscle-like devices that directly convert chemical to mechanical energy, robotics, walking vehicles, swimming by bending (in contrast to the predominant stiff engineering materials, in the living nature flexible materials are often used), and prosthesis (with materials and structures similar to the original ones) [**15**]. The prospects of Vogel can be assigned to the fields of materials science, energy conversion technologies, and biomechanics.

The following more detailed visions of Ingo Rechenberg about a biomimetic world in the year 2099 [**16**] can be assigned to materials science, production technologies, energy systems, mobility, sensing technologies, robotics, recycling, computer science, space travels, sports, politics, and management.

In a broad sense, the following examples can be classified into materials science and production technologies: growing structures for engine parts and work pieces are, according to Rechenberg, promising examples for an area where engineers can learn from nature. Mechanisms of molecular self-organization play an important role here. Rechenberg denotes the science of self-replicating structures as 'Replionik' and the science of growing structures as 'Auxonik'. Accordingly, 3D-printers or morpho-printers that mimic the ontogenesis of organisms should be available, working differently from the today known rapid prototyping. As found in nature, materials and structures are not made at once. Rather the structure and composition change over time and according to inner and outer 'driving forces', such as for instance a change in load. Bones and wood are obvious examples. The self-arrangement in its structure that allows bone to adjust to changing external forces should also be implemented in technical constructions like bridges. Self-healing is related to this and could, if understood properly, be used in many technical areas, e.g. in materials for roads. Glues that work under water are found in many organisms and detailed investigation should reveal principles that can be used in new technologies [**17**]. Also the highly elastic protein resilin, as found in insects such as the grasshopper, can serve as a model for technical innovations to produce rubber that gives back the energy stored by compression with high efficiency [**18**]. Also manufacturing of products might look different in the future. Rechenberg proposes a Darwin–Mendel factory. The products of this factory are not all similar but differ in little details, not recognizable by the consumer. The 'best' of which are then used to generate the next generation of products.

With regard to energy systems photosynthesis occurs in many biomimetic visions. This process of converting solar energy is utilized in every plant and is currently focus of many research groups worldwide. Artificial photosynthesis also plays a role in Rechenberg's visions. A paint (e.g. for house facades) should be developed that can easily be put on, and after an initial structural formation the solar paint can serve to convert energy from the sun to electricity. There are many other processes in nature where energy is converted. The direct transformation of chemical energy into mechanical energy, as it occurs in the muscle, is a process that interests biomimeticians. The muscle is also a model for linear engines, i.e. forth and back movements. Related to this is the field of nanotribology [**19–21**] which is gaining importance, as technical devices are becoming smaller and smaller.

Another important topic is mobility. Scientists from aero- and hydrodynamics have been looking at flying and swimming animals for a long time. A considerable cut in fuel consumption (by up to 80 per cent) will be achieved by multi-winglets, as found in birds, micro-structured surfaces, as found in sharks, flexible surfaces, as found in dolphins, and a newly developed integrative drive. With this drive air molecules that are slowed down by friction accelerate again, so that ideally the air behind the plane is standing still. As there are no fast creatures found on the surface of the water, also boats in the future will drive under water. Those submarines will show an up to 85 per cent reduced resistance, compared with today's vehicles. The elastic and flexible dolphin skin, the micro-structured shark-skin, and the veil of bubbles used by penguins will help to reduce the resistance of submarines. An integrative drive, as used in jellyfish, will also help to reduce fuel consumption. Overall, the fuel consumption of boats should be reduced by 90 per cent.

With respect to transportation on land sensing will be an area where technology can use principles from nature. In analogy to mechanisms in animal swarms, automatic control of distances will be used in traffic systems to avoid crashes. The engineering discipline that deals with swarms is denoted by Rechenberg as 'Hesmonik'. Sharks have the ability to detect electrical fields stemming from prey in the seabed. Similar sensing should be used by artificial swarms to detect people who go buried alive, e.g. by an avalanche. Related is the field of artificial 'smelling'. Some animals have the ability to smell or detect single molecules. With sensor technology, based on principles found in nature, it should in the future be possible to reach this limit.

Of course also robotics will play a role in the future scenario of Rechenberg. He has the vision of artificial micro-robots used for cleaning. Micro air vehicles should be realized that can be used for investigating sewers. Miniature robots should circulate in the human body for inspection purposes.

In nature huge amounts of material are recycled. In order to achieve a similar efficiency in the use of materials, Rechenberg suggests producing materials in a way that is analogous to natural production of proteins out of amino acids. Materials with desired properties should be produced by combining different such components to produce macromolecules. When the products consisting of such materials are no longer used, they can be recycled by cutting up the macromolecules in a way that mimics protein recycling. All can be recycled in the same way.

Principles from nature can also be used for computer science. Genetic programming can be used to develop software that generates itself. Options range from a minor self-generated variation in code to the creation of entire programs. Computer viruses represent a common application field of self-replicating code. Evolutionary computation and decentralized information processing are key issues in this fast developing field. An inspiration for such systems is found in natural role models such as the nervous system or insect colonies. According to Rechenberg's vision, a global neural net (GNN) should replace the internet in analogy to neural networks and brains. The GNN should work like a super large brain and should be much more powerful than the internet of today. The personal neural net (PNN) should be linked to sensors to store artificial sense 'impressions'. Experiences from the past can thus be reproduced via a 'second brain' device.

Concerning space travel, Rechenberg considers self-reproducing space ships, terraforming Venus, and the development of systems similar to ecosystems for space travels.

Also for innovations in sports principles from nature can be used. A device that allows people to hop like a kangaroo, or a competition that combines running, swimming, diving, and flying can be thought of – mimicking certain birds. Mimicking the gill on the skin of the axolotl might turn out to be useful for diving.

Biomimetics might also be applied in politics and management. Rechenberg proposes an evolutionary strategy for progress. (All examples are taken from reference [**16**].)

There is a certain interesting overlap in the visions of Vogel and Rechenberg. Both see progress of biomimetics in the fields of material science, energy conversion technologies, and biomechanics. But Rechenberg's visions are not restricted to these areas.

Increase in energy demand shall be met by exploitation of 'free energy'. Increased 'activation' of formerly static and 'dumb' technical elements is observed and described for architecture and the built environment [**22–24**] and also takes place in technology developments in other fields. Classical 'criteria of life' such as movement, sensing, reactivity, and growth are increasingly represented in technology and are most interesting for the current discourse in architecture [**22–24**]. With rapid prototyping, a group around Adrian Bowyer, Senior Lecturer in Mechanical Engineering at the University of Bath in the United Kingdom, already successfully carried out the experimental introduction of self-replication technology [**25**]. Introduction of 'intelligence' and 'aliveness' in technological devices will continue and shall lead to more sustainable interaction between cultural and natural processes and environments.

3.2 The global challenges: issues and opportunities

3.2.1 Introduction: the Millennium Project and the 'state of the future' reports

The Millennium Project [**26**] was formed by the Futures Group International, the American Council for the United Nations University, the Smithsonian Institution, and the United Nations University. Since the beginning of operations in 1996, about 2000 futurists, scholars, decision-makers, and business planners from over 50 countries have contributed with their views to the Millennium Project research.

The project currently has nodes in 30 countries. These are independent entities (composed of both entities and individuals from different institutional categories – government, corporations, NGOs, universities, individuals, and UN or international organizations – which act like trans-institutions) that cooperate with each other and the Millennium Project to provide an international perspective on future research. The Millennium Project is currently directed and coordinated by Jerome C. Glenn.

The Millennium Project publishes the annual state of the future report, now in its 12th edition (2008) and containing almost 100 print pages and around 6000 CD pages of data and analysis [**27**]. The 'state of the future' report summarizes the results of research and studies under the Millennium Project. It deals in detail with 15 major global challenges for humanity.

> 'After 12 years of the Millennium Project's global futures research, it is increasingly clear that the world has the resources to address our common challenges. Coherence and direction are lacking. Ours is the first generation with the means for many to know the world as a whole, identify global improvement systems, and seek to improve such systems. We are the first people to act via Internet with like-minded individuals around the world. We have the ability to connect the right ideas to resources and people to help address our global and local challenges. This is a unique time in history. Mobile phones, the Internet, international trade, language translation, and jet planes are giving birth to an interdependent humanity that can create and implement global strategies to improve the prospects for humanity' [**27**] (executive summary, state of the future 2008: http://www.millennium-project.org/millennium/SOF2008-English.pdf).

Below, a concise review of the current state of affairs of the global challenges is given, including some potential biomimetic contributions in addressing the respective challenge when appropriate. The employed biomimetics comprise current as well as possible future biomimetic approaches, as they might exist in the year 2059, the then 100th anniversary of the *Proc. IMechE, Part C: Journal of Mechanical Engineering Science*. Main information sources for the concise reviews of the current state of affairs ('Issues') are the state of the future reports 1997 and 1998 [**28**, **29**], updated to current day knowledge.

3.2.2 The 15 global challenges

'15 global challenges' have been defined and tracked since 1997 in the state of the future reports. The challenges are updated annually. The 15 global challenges in the 2008 state of the future report [**27**] are

1. *Sustainable development*: How can sustainable development be achieved for all?
2. *Water*: How can everyone have sufficient clean water without conflict?
3. *Population* and *resources*: How can population growth and resources be brought into balance?
4. *Democratization*: How can genuine democracy emerge from authoritarian regimes?
5. *Long-Term Perspectives*: How can policymaking be made more sensitive to global long-term perspectives?
6. *Information Technology*: How can the global convergence of information and communications technologies work for everyone?
7. *Rich–Poor Gap*: How can ethical market economies be encouraged to help reduce the gap between rich and poor?
8. *Health*: How can the threat of new and re-emerging diseases and immune microorganisms be reduced?
9. *Capacity to Decide*: How can the capacity to decide be improved as the nature of work and institutions change?
10. *Peace* and *Conflict*: How can shared values and new security strategies reduce ethnic conflicts, terrorism, and the use of weapons of mass destruction?
11. *Status of Women*: How can the changing status of women help improve the human condition?
12. *Transnational crime*: How can transnational organized crime networks be stopped from becoming more powerful and sophisticated global enterprises?
13. *Energy*: How can growing energy demands be met safely and efficiently?
14. *Science* and *Technology*: How can scientific and technological breakthroughs be accelerated to improve the human condition?
15. *Global Ethics*: How can ethical considerations become more routinely incorporated into global decisions?

Many of the global challenges deal with topics that concern the negotiation between what we still call natural versus cultural landscape (a terminology resulting from the interpretation of the separation of nature and culture, including technology, in Western philosophy), including industrial and production space on earth. However, the view presented is anthropocentric. A systems view of the biosphere should be taken to target ecological and sustainable development. This should also be reflected in the global challenges.

> 'We grasp nature by constructing it according to the role model delivered by our inventions. We explain nature by interpreting it according to the composition of our inventions. In this sense nature is a product of our culture' [**30**].

The manifold interconnections between 'nature' and 'technology' also in terms of space are the underlying topic of many of the 15 global challenges.

With the three methodical approaches applied in this work only the limited potential of technology to serve society can be considered. Other issues on the economic, sociological, or political level – as found in the Millennium Project – cannot be considered here. Challenges No. 3 (population and resources), 4 (democratization), 5 (long-term perspectives), 7 (rich–poor gap), 9 (capacity to decide), 10 (peace and conflict), 11 (status of women), 12 (transnational crime), and 15 (global ethics) fall into this category. Investigations for this outlook have shown that there is very little biomimetics that can contribute to some of them. Therefore, the biomimetic approaches suggested for these challenges can only be rather weak in terms of arguments, examples, and possible technologies. Description/discussion of these challenges is therefore omitted and the work concentrates on challenges 1 (sustainable development), 2 (water), 6 (information technology), 8 (health), 13 (energy), and 14 (science and technology).

3.2.3 Global challenge 1: sustainable development

3.2.3.1 Issues: the world population is growing; food, water, education, housing, medical care must grow apace. Adverse interactions between the growth of population and economic growth with environmental quality and natural resources. The Intergovernmental Panel on Climate Change (IPCC [**31**]) is a scientific intergovernmental body set up by the World Meteorological Organization and by the United Nations Environment Programme. The IPCC reports that CO_2 emissions rose faster than its worst case scenario during 2000–2004 and that without new government actions greenhouse gases will rise 25–90 per cent by 2030 over 2000 levels [**32**]. The current absorption capacity of carbon by oceans and forests is about 3–3.5 billion tons per year; human activities add 7 billion tons annually. Human consumption is 25 per cent larger than nature's capacity to regenerate or to absorb our 'ecological footprint'. A temperature increase greater than 2.54 °C puts 20–30 per cent of plant and animal species at risk of extinction; 60 per cent of ecosystem services are already gone or are being used unsustainably; disturbing changes in the thermohaline circulation in the Atlantic have been measured; ice in the Arctic and in Greenland is melting faster than expected; the eight warmest years in the NASA Goddard Institute for Space Studies record have all occurred since 1998, and the 14 warmest years in the record have all occurred since 1990, 2007 was tied as earth's second-warmest year ([**33**], status January 2008), leading some to warn that climate change has reached the point of no return. As matters get worse, the environmental movement may turn on the fossil fuel industries. The legal foundations are being laid to sue for damages caused by greenhouse gases.

Some scientists have started exploring geo-engineering to combat climate change, such as adding iron powder to the oceans to dramatically increase absorption of CO_2 on a planetary scale [**34**] and using devices to suck CO_2 from the air. Massive seawater agriculture along 24 000 km of coast deserts would be a carbon sink and a source for biofuels, paper products, and food. Laboratory breakthroughs in solar energy promise to cut costs drastically, yet 800–1000 coal plants are planned with 40-year life spans. Carbon trading, including buying carbon offsets, is gaining attention. Carbon capture and storage would help reduce emissions, but even if emissions can be stabilized, heat generated by energy consumption could further the warming.

Environmental security, not just climate change, should be brought to the UN Security Council. Massive urbanization and concentrated livestock production could trigger new global pandemics. Climate change alters insect and disease patterns. Definitions and measurements will be needed for commonly applied tax incentives, along with labels for more environmentally friendly products and green accounting. Developing countries need to leapfrog unsustainable practices to more sustainable ones; the World Bank estimates that adapting to climate change will cost developing countries \$10–40 billion a year. Large reinsurance companies estimate that the annual economic loss due to climate change could reach \$150–300 billion per year within a decade ([**35**], status 2006). The value of intact ecosystems far outweighs the cost of protecting them.

Government subsidies need to switch from fossil fuels to renewable suppliers of energy (it is estimated that industrial countries subsidize fossil fuels with \$200 billion a year). Other suggestions include raising fuel efficiency standards 5 per cent a year relative to GDP; an environmental footprint tax for using more than 1.8 global hectares per person; a 1 per cent tax on the \$1.5–2 trillion of international financial transactions per day; and mandating improved car mileage one mile per year. Taxes on international travel, carbon, and urban congestion should be considered. Such tax income could support an international public/private funding mechanism for high-impact technologies. Massive public educational efforts via film, television, music, games, and contests should stress what individuals and groups can do. The synergy between economic growth and technological innovation has been the most significant engine of change for the last 200 years, but unless we improve our economic, environmental, and social behaviour and close the gap between the rich and the poor, the next 200 years could be difficult. Next to the proliferation of weapons of mass destruction, unsustainable growth may well be the greatest threat to the future of humanity. Yet without sustainable and equitable growth, billions of people will be condemned to poverty and much of civilization will collapse.

Destruction of the environment is one of the five major reasons for the collapse of societies, as historical analyses have proved. Environmental damage, climate change, hostile neighbours, and loss of trade partners can turn out fatal for the development of societies. The fifth major issue, the reaction of a society to their environmental problems, is of great importance [**36**].

ISO environmental standards and guides like the natural step and equator principles should be promoted, 'sustainability report cards' on company practices publicized, and key habitats declared off-limits for human development, a World Environment Organization with powers like the WTO established, an international environmental crimes intelligence and police unit created, and synergy between environmental movements and human rights groups encouraged to make clean air, water, and land a human right [**37**].

3.2.3.2 Opportunity: biomimetics contribution to achieving sustainable development for all. Sustainability in nature can be defined as the ability to maintain ecological processes, functions, biodiversity, and productivity into the future. Currently humanity is living unsustainably. Biomimetics that follows 'Life's principles' (Table 1) as defined by the Biomimicry Guild from Helena, MT, USA [**38**] supposedly yields sustainable products and processes.

Possible biomimetic approaches to achieving sustainable development for all include for example chemical heat production inspired by plants such as the lily and the philodendron.

Heating and *cooling without fossil fuels* is a possible approach to contribute to sustainable development. The increased use and exploitation of solar energy is the only way of harvesting energy directly from a natural source without destruction of the biosphere.

Microbial fuel cells: as bacteria store energy in the form of ATP, they must rid themselves of electrons. In 2005, Derek Lovley and his colleagues reported that metal-reducing bacteria such as *Geobacter sulfurreducens* produce electrically conductive nanowires that apparently can help transfer electrons beyond the cell. The metabolism of *Geobacter sulfurreducens* passes electrons between intermediate electron carriers and the food source via nanoscale pili. The likely function of the pili is to complete the circuit between these various intermediary electron carriers and the Fe(III) oxide [**39**].

Bioinspired products and application ideas include microbial fuel cells generated from electron donors in wastewater (charge transport known as extracellular electron transfer); converting renewable biomass such as compost, human and animal waste into electricity; creating nanowires in small circuits or electronic devices and connecting them to create a microscopic grid; consuming oil-based pollutants and radioactive material with carbon dioxide as waste by-product in environmental cleanup for underground petroleum spills. Further bioinspired products and application ideas are miniaturization of electronic devices, manufacturing of nanowires from bacteria, removal of nitrate, perchlorate, and sulfur from polluted materials. Industrial sectors that might be interested in this strategy are electronics, energy, waste treatment, agriculture, and bioremediation. The uranium-reducing bacterium *Geobacter uraniireducens* might help to concentrate and remove precipitation of uranium out of groundwater [**40**].

Chemical heat production: heat-producing plants [**41**, **42**] shall provide inspiration to novel types of heating without fossil fuels. Examples for thermogenic plants are species of elephant foot, lily, and philodendron. The inflorescence of *Philodendron selloum* temporarily maintains a core temperature of 38–46 °C, despite air temperatures ranging from 4 °C to 39 °C, by means of a variable metabolic rate. The heat is produced primarily by small, sterile male flowers that are capable of consuming oxygen at rates approaching those of flying hummingbirds [**43**] and sphinx moths [**44**].

Table 1 Biomimetic products and processes that are developed along 'Life's principles' are likely to be sustainable

Life's principles	
Build from the bottom up	Embrace diversity
Self-assemble	Adapt and evolve
Optimize rather than maximize	Use life-friendly materials and processes
Use free energy	Engage in symbiotic relationships
Cross-pollinate	Enhance the biosphere

3.2.4 Global challenge 2: water

3.2.4.1 Issue: fresh water is becoming scarce in localized areas of the world. Lack of adequate waste management in most places in the world; excessive consumption and contamination of water aquifers; excessive farming on marginal lands; and trends in population, urbanization, tourism, standard of living, and technical ability to find and deliver more water are affecting the availability – and future expectations of availability – of fresh water. The countries facing scarcity include 11 African countries, nine Middle Eastern countries, northern China (including Beijing and the agricultural lands surrounding it), India (including New Delhi and thousands of rural villages), Mexico (including Mexico City and irrigated farmlands in northern Mexico), and portions of the Western United States. Decreasing availability of water also limits economic activity. For example water is the limiting factor in coal production in Shanxi Province in China.

Although methods exist to purify salt water, these methods are expensive. To further complicate the situation, agricultural uses far exceed other uses of water – as high as 70 per cent of total usage in some regions. With increased demand for food, pressure to use water for agriculture can only increase – unless we come up with novel, perhaps bioinspired methods. Agricultural land is being lost to brackish conditions due to long-term geological trends in some regions. The possibility, speed, and consequences of global warming are only predictable to some extent, but at the very least, changes in rainfall patterns will undermine effectiveness of existing water control, storage and distribution facilities, and widen areas affected by scarcity. Some areas like Northeast China have benefited from the increased average temperatures by increased crop production. Nevertheless, as urbanization, population, and economic growth continue, competition between urban and agricultural uses of water will grow and can become a source of political instability and conflict [**28**].

3.2.4.2 Opportunity: biomimetic contributions to ensure water supply throughout the planet. Water is essential for maintaining life. Living nature excels at accessing, distributing, and 'managing' water resources. Desalination, water collection mechanisms in extreme environments such as deserts or mud lands and water 'management' via high species diversity, shall provide strategies to collect water more efficiently. Below, some examples of organisms and ecosystems excelling at collecting and 'managing' water are given.

Desalination with aquaporins: a lipid bilayer membrane encloses living cells. This bilayer membrane separates the cells from other cells and their extracellular medium. Lipid bilayer membranes are essentially impermeable to water, ions, and other polar molecules; yet, in many instances, such entities need to be rapidly and selectively transported across a membrane, often in response to an extra- or intracellular signal. The water-transporting task is accomplished by aquaporin water channel proteins [**45**, **46**]. Aquaporins are crucial for life in any form and they are found in all organisms, from bacteria via plants to man. Aquaporins facilitate rapid, highly selective water transport, thus allowing the cell to regulate its volume and internal osmotic pressure according to hydrostatic and/or osmotic pressure differences across the cell membrane.

In 2003 Peter Agre received the Nobel Prize in Chemistry for the discovery of the aquaporins, and in 2009, P. H. Jensen from Copenhagen, Denmark, patented a biomimetic water membrane comprising aquaporins used in the production of salinity power.

Desalination via transpiration and filtering through membranes: mangroves desalinate seawater by evaporation energy [**47**]. Mangroves can live on the saline water of the ocean, which destroys other green terrestrial plants. In some species of mangroves the sap is almost salt-free, though the roots are washed by seawater. Mangroves extract the salt by using the transpiration energy in the narrow capillaries of their roots to suck up the sea water and then filtering it through thin membranes in which the salt is detained [**48**].

Water collection via desert plants: the roots of desert plants extract hard to remove water from soil using negative pressure potentials. This 'capillary water' in tiny recesses of soil crumbs has minimized its exposed interface with air [**49**]. For the roots of a plant to extract the water requires making more surface, which appears as an additional (negative) component of the pressure potential in the vessels running up a stem or trunk. The lowest (most negative) pressure potentials known in plants occur in desert shrubs. An extreme value on record is -120 bar [**50**]; that would hold up a column of water over 1200 m high. Hence the pull needed to obtain water free of soil can exceed both the pull that keeps water moving in the vessels and the pull that counteracts gravity [**51**].

Removing water from materials can be expensive and energy consuming, but using a negative-pressure-potential large-surface-area device that mimics the desert roots of plants would enable low-energy water removal. Bioinspired products and application ideas can be therefore envisaged for obtaining water in deserts, as well as for manufacturing housing materials, textiles, and diapers.

Water management in camel nasal surfaces: the nasal surfaces of camels help conserve water by using hygroscopic properties to remove water from air during exhalation. The nasal surfaces of a dromedary camel help conserve water when the camel is dehydrated, by extracting water from exhaled air. During hot desert days, this nasal heat exchange mechanism also helps protect the camel's brain from overheating.

Heat and water exchange takes place primarily along the turbinate structures of the camel's nasal passages. Turbinates are spongy nasal bones, and the camel's turbinates are highly scrolled, providing narrow air passageways and a large surface area for water and heat exchange. Measurements suggest that camels have more than 1000 cm^2 of nasal surface area, whereas the human nasal cavity may have a total surface area of only 160–180 cm^2. Normally, the surface of the turbinates is covered with moist secretions, which help humidify dry desert air as the camel breathes in. However, as the camel becomes dehydrated and the nasal passages dry out, this simple mechanism works in reverse [**52**]. The camel's body temperature may fluctuate several degrees Celsius during one day. Therefore, a dehydrated camel only cools and desaturates exhaled air during cooler night-time temperatures. During hot desert days, protecting the brain from overheating becomes more important than conserving water, and the camel exhales saturated air at approximately body temperature. High blood flow heats the turbinates during the day, cooling the arterial blood flowing to the brain in the process [**52**].

According to a report from the United Nations Environment Programme, severe water shortages will affect 4 billion people by 2050. Looking to the camel's water conservation strategies for inspiration, we could design solutions to limit evaporation from water storage ponds, design more efficient irrigation systems, learn how to best minimize water loss, and recapture both water used in industrial processes as well as graywater in buildings. Further bioinspired products and application ideas can be envisaged in building, water storage, agriculture, and manufacturing.

Catching water from mud: tufts on some species of marsh crab legs, including *Sesarma*, draw water from mud into the body by using hydrophilic setae (stiff hair-like structures) [**53**]. Bioinspired products and application ideas include water collection by drawing water out of mud.

Water catchment basins: current water supply authorities operate at the other extreme of the biodiversity scale showing water catchments that are fully vegetated, whether by native forest, woodland, or plantations. In such cases, the expectation is not that the catchment ecosystem will be unchanging, but that water collected in the reservoir will be so low in nutrients that it will not support significant blooms of algae which would impair water quality and thus render it unfit for human consumption without expensive treatment. The present cases differ because of higher nutrient levels and corresponding greater levels of biological production leading to health risks and aesthetic problems. These observations suggest that there is a case for a wider mimicking of nature at a landscape scale. The naturally or artificially vegetated water catchments that retain natural biodiversity in order to obtain pure water are examples of the systems to be mimicked. Tree lots, wind breaks, and aquatic vegetation fringing watercourses are all mimics of woodland, swamp, marsh, or stream fringing plant communities, which may be effective in stripping excess nutrients from drainage lines, streams, and waterbodies. In cases involving landscape scales, the criterion of enough (referring to biodiversity) is satisfied when the nutrients discharged from one ecosystem are within the assimilative capacity of the receiving system without altering its biodiversity. When biodiversity has been lost, then the functional replacements such as the re-vegetation mentioned above should be designed to satisfy the foregoing criterion, especially as nutrients end up in water bodies, rivers, and estuaries where the resulting algal blooms, loss of biodiversity, and pollution from rotting biomass is legendary [**54**].

Bioinspired products and application ideas comprise wastewater treatment without chemicals in agriculture and water treatment and maintaining systems in agriculture and community water sources that mimic the way that water catchment basins function to remove any excess nutrients.

Forests are further impressive examples of how ecosystems 'manage' water. They help retain water onsite through interaction of many species. Neither maize nor grasses can duplicate the services of the original tropical forest. With its hundreds of plant species, the forest lets virtually none of its soil or water escape and sustains a lush productivity year-round [**55**]. Bioinspired products and application ideas in retaining water onsite are agriculture or land restoration efforts that mimic the diversity of native forests to prevent soil, water, and nutrient loss.

3.2.5 Global challenge 6: information technology

3.2.5.1 Issue: information technology's promise and perils. The internet has grown faster than any information processing device in history. Interactive cyberspace has become an important new and unprecedented medium for civilization. All forms of information technology will spread throughout even the poorest regions of the world as prices for computers, software, and telecommunications continue to fall and their capacity and ease of use continues to improve. Currently, 90 per cent of the information technology market is in the USA, Europe, and Japan, but this is changing. Already by the end of 1994, electronic mail connected all countries together through virtual gateways. AT&T's Africa One Project [**56**] and the Global Information Infrastructure vision of former U.S. Vice President Al Gore accelerated the internet growth in developing countries [**57**]. Between the years 2000 and 2008, internet usage grew by 305 per cent, and by February 2008 21.9 per cent of the world population used the internet [**58**].

The internet represents one of the most powerful agents of change in the world affecting everything from science and religion to politics and medicine. It is becoming the first location for the discussion of new ideas, publishing, advertising, and commerce. For developing countries, the internet possesses the potential means to accelerate economic development, provide greater and faster access to the world's knowledge, and become the medium for participating in the world's economy.

Many people find the internet confusing and unorganized, while others find it exciting and self-organizing. Within the next decade, the internet will be simpler, more accessible, and faster. Automation has begun displacing routine human behaviour, giving rise to the possibility of economic growth with less employment. If new kinds of enterprises and employment are not created to address computer and automation-induced unemployment, the unemployed and underemployed could well create an anti-technology sentiment and political crises.

At the same time, one should expect sabotage through the internet. Credit and bank fraud, computer viruses, other forms of criminal manipulation, and even information warfare by individuals, groups, corporations, and nations are possible. Additionally, pornography and other influences deemed culturally unacceptable are creating hostility towards the free growth of the internet. Privacy and property rights are also issues of concern. Authenticity of information will be difficult to establish. Nonetheless, information technology is creating a planetary 'nervous system' necessary for improving the prospects for humanity [**28**, **29**].

3.2.5.2 Opportunity: biomimetics contribution to utilizing the global convergence of information and communications technologies for everyone. Use of virtual models for decision and optimization processes is needed; in the real world, the speed of change does not allow slow empirical adaptation any longer. Optimization processes in computer models could replace slow trial and error methods. The complexity of models (for example atmospheric models that predict the weather, or models of urban traffic) makes predictions possible that were unthinkable decades ago. The increase in computational capacity will deliver new methods of decision-making, in technology as well as in politics; in general, a relocation of optimization processes into the virtual world can be observed.

Currently, humankind faces the problem of an immense growth of quantitative information – we are approaching the age of self-documenting systems that communicate most unnecessary data to the users (elevators, toasters, mobile phones, hi-fi systems, etc.). Nature, on the other hand, utilizes highly optimized 'expert systems' that work on a minimum of information that is processed highly efficiently. Convergence between information management and communication is possible, but in many cases not necessary, for the information already exists. Not the information management is the issue to look at, but the way to provide information. Nature shows us that selective information acquisition excels over the current way of human information and communication technologies, where increasing amount of data are generated from which the important information then has to be processed.

Many researchers traditionally believed that facial recognition required a large brain, and possibly a specialized area of that organ dedicated to processing face information. Dyer and co-workers reported in 2005 that honeybees can learn to recognize human faces in photos, and remember them for at least 2 days [**59**]. The honeybee brain has less than 0.01 per cent the number of neurons of the human brain [**60**].

A system that is tolerant against mistakes can live with the mistakes. Currently in our western society, making no mistakes is sacrosanct. Nothing wrong may be said anymore. But nature is often resistant against mistakes. Therefore the question in global challenge 6 'How can the global convergence of information and communications technologies work for everyone?' [**27**] is ill-posed: we do not need to worry about information management, we need to worry about how to provide information. An untypical and inspiring example of handling information is the following dialogue from the classical movie Casablanca [**61**]:

> *Captain Renault*: What in heaven's name brought you to Casablanca?
> *Rick*: My health. I came to Casablanca for the waters.
> *Captain Renault*: The waters? What waters? We're in the desert.
> *Rick*: I was misinformed.

3.2.6 Global challenge 8: health

3.2.6.1 Issue: how can the threat of new and re-emerging diseases and immune micro-organisms be reduced? Recent outbreaks of bubonic plague in India, ebola virus in Africa, and drug-resistant tuberculosis in the United States are causing the world to rethink its public health policies. Increasing mass migrations and international travel spread disease more rapidly than in the past; increasing urbanization and population density accelerate and intensify this problem. Furthermore, the widespread use of antibiotics has resulted in the evolution of micro-organisms that are resistant to antibiotic treatment. The threat of biological terrorism is now plausible [**28**, **29**].

> 'Infectious diseases spreading in US hospitals kill more people each year than all Americans killed in Vietnam... The heaviest concentration of pathogens is found in the developing world ... The progress of pathogens to adapt to our arsenal of medicines promises to be the fight of our species... It is a trend that holds the capacity to bring life as we know it to a grinding halt ... A handful of microbes can be stopped at the border but the vast majority can not'. (U.S. Congressional testimony April 25, 1996 by Chuck Woolery, National Council for International Health).

3.2.6.2 Opportunity: biomimetics contribution to increase health. Maintaining health is important to maintain life and to ensure propagation. 'Strategies' of organisms and ecosystems to detect and fight diseases provide numerous biological examples on how to contribute to increased health. Immune systems can inspire novel nanomedical approaches [**62**, **63**]; biomimetic sensors and targeted drug delivery [**64**, **65**] will detect and fight diseases faster and more reliable, with less hassle for the organism. Nanosurgeons directly and independently acting inside the (human) body and minimum invasive surgery are hot topics of research [**63**]. Newly developed pharmaceuticals that use bioinspired devices can cross the blood–brain barrier [**66**], a fact that on the one hand opens up enormous possibilities concerning treatment of psychic diseases, and on the other hand poses enormous dangers to humanity (e.g. psychic manipulation via chemical drugs). Biocompatible implants, re-grown organs, and online-monitoring of health are further applications that might benefit from biomimetic approaches, although here the border between biomimetics and bioengineering becomes blurred. Below, some specific examples illustrate the potential of organisms to contribute to increase health.

Glue for medical applications: the skin of Australian frogs of the genus *Notaden* protects from insect bites via secreted glue, which gums up insect mouthparts, causes them to stick to the frogs' skin, and the frogs can later eat the stuck insects. An interdisciplinary team of biologists and surgeons tested the glue in sheep with torn knee cartilage and found that the glue hardens within seconds and sticks well, even in moist environments. When set, it is flexible and has a porous structure that should make it permeable to gas and nutrients, which would encourage healing. When used on the sheep, it worked well at holding damaged knee cartilage together [**67**].

Bioinspired products and application ideas can be envisaged in medical and manufacturing industries, where glues that work in moist environments are needed. Engineering strong and robust adhesives that are stable in wet environments currently poses a major technical challenge. Most man-made adhesives fail to bond in wet conditions, owing to chemical modification of the adhesive or its substrate [**68**]. Further organisms that already inspired emerging man-made adhesives include the abalone shell and diatoms. In both cases, the adhesives are tough and self-healing [**69**, **70**].

Maintain health: the metabolism of the bacterium *Pseudomonas aeruginosa* produces products that inhibit yeast and fungal growth via the conversion of unsaturated fatty acids. For example growth of *Candida albicans*, a yeast that sometimes causes thrush and other infections in humans, and the rice blast fungus is inhibited, raising the prospect for a biological fungicide against these pathogens. Bioinspired products and application ideas can be envisaged in medicine and agriculture, e.g. in the development of green chemistry processes for production of fungi and yeast inhibiting substances based on the bioconversion reactions of this microorganism [**71**].

3.2.7 Global challenge 13: energy

3.2.7.1 Issue: growing energy demands have to be met safely and efficiently. In the face of increasing CO_2 emissions from gasoline (petrol), and the anticipated scarcity of crude oil, a worldwide effort is underway to find cost-effective alternative fuels.

> 'Vast improvements in efficiencies, conservation, and tele-everything will help, but substitutes for the current energy sources still have to be constructed, and the economic and population growth of the next 50 years will still require increasing energy supplies. Since the major energy sources eventually will run out and threaten future climate stability, massive investments into safe and sustainable sources such as wind, geothermal, ground solar and space solar, and saltwater-based biofuels are essential' [**27**] (executive summary: http://www.millennium-project.org/millennium/SOF2008-English.pdf).

3.2.7.2 Opportunity: biomimetic contributions to developing alternative suppliers of energy. Energy conversion is of paramount importance in nature. Various concepts for primary energy conversion such as photosynthesis, radiosynthesis, oxidation of molecular hydrogen, and sulfur oxidation can be identified. Bioinspired wave and tide power systems have been developed as an energy-supplying source. The convergence of nanoscience and physical and biosciences shall provide more detailed explanations of biological methods of energy conversion and set the ground for novel biomimetic methods [**72**].

Photosynthesis: photosynthesis [**73**] is a biological process whereby the sun's energy is captured and stored by a series of events that convert the pure energy of light into the biochemical energy needed to power life. This remarkable process provides the foundation for essentially all life and has over geological time profoundly altered the Earth itself. It provides all our food and most of our energy resources.

Many of the events crucial to plant photosynthesis are now known in molecular detail and artificial photosynthesis is a hot topic of research [**74**]. The Australian Artificial Photosynthesis Network (AAPN) is a coordinated research effort to develop effective photosynthesis technology.

The aims of the AAPN are to extract CO_2 from the atmosphere and to photoreduce it to synthesize useful products, foods, fuels, and fibres, without the excessive use of water which is characteristic of terrestrial plants; to devise artificial photosynthetic devices to produce electricity; and to diminish CO_2 emissions from fossil fuels by the photoproduction of hydrogen as an alternate energy-supplying source. Work of the AAPN is therefore highly relevant for multiple global challenges.

The structures of the artificial photosynthesis devices shall maximize light absorption by mimicking the thylakoid structures of plants and cyanobacteria that maximize exposure to light by being stacked and cross-linked.

The German biophysicist Helmut Tributsch explores how plants and animals have devised to turn principles of physics and engineering to their advantage in the struggle to adapt and survive. He describes his vision of a city in the future as follows:

> 'A bird's-eye view of a natural metropolis would show nothing but green. No roofs, parking lots, or highways would be visible. All flat surfaces would be covered with woods, parks, and gardens. The vertical structures would be the facades of offices, residential buildings, cafes, and boutiques, all with access to nature. Inside the 'thylakoid structures' would be sufficient space for transportation, parking lots, shopping malls, and factories, which could manage with artificial light' [**75**].

Bioinspired products and application ideas comprise the design of sustainable communities to maximize energy gathering and reduce water runoff. Industrial Sectors such as construction, landscape architecture, city planning, and zoning could benefit from such approaches.

Radiosynthesis: melanin in micro-organisms captures high-energy electromagnetic radiation as a source of supplying metabolic energy. The process is called radiosynthesis (as opposed to photosynthesis in plants). Radiosynthesis might serve as a novel way to convert energy for technological applications. Fungal mats might serve as protective layers for micro-organisms sensitive to ionizing irradiation, e.g. in space or in radioactive waste disposal sites. Further bioinspired products and application ideas comprise radioprotection from nuclear fallout [**76**, **77**].

The melanotic fungus *Cladosporium cladosporioides* manifests radiotropism by growing in the direction of radioactive particles and this organism has become widely distributed in the areas surrounding Chernobyl since the nuclear power plant accident in 1986 [**78**].

Oxidation of molecular hydrogen: the oxidation of molecular hydrogen H_2 directly from the environment is the main source of supplying energy for primary microbial production in the Yellowstone National Park high-temperature (>70 °C) hot springs ecosystem. Bioinspired products and application ideas comprise efficient hydrogen chemistry for fuel cells [**79**].

Bioinspired wave and tidal power systems: inspired by efficient propulsion systems, the Australian company BioPower Systems Pty Ltd (http://www.biopowersystems.com/) has been developing bioinspired wave and tidal power systems: the wave power system, bioWAVE™, is based on the swaying motion of sea plants in the presence of ocean waves. The hydrodynamic interaction of the buoyant blades with the oscillating flow field is designed for maximum energy absorption. In extreme wave conditions, the bioWAVE automatically ceases operating and assumes a safe position lying flat against the seabed. This eliminates exposure to extreme forces, allowing for lighter designs and substantial cost savings. Systems are being developed for 250, 500, 1000 kW capacities to match conditions in various locations. The tidal power conversion system, bioSTREAM™, is based on the highly efficient propulsion of thunniform mode swimming species, such as shark, tuna, and mackerel. The bioSTREAM mimics the shape and motion characteristics of these species but is a fixed device in a moving stream. In this configuration the propulsion mechanism is reversed and the energy in the passing flow is used to drive the device motion against the resisting torque of an electrical generator. Because of the single point of rotation, this device can align with the flow in any direction, and can assume a streamlined configuration to avoid excess loading in extreme conditions.

Radiative cooling of buildings: the method of BioTRIZ has led to the development of a new approach to the cooling of buildings. The central challenge is the coupling of mass to the cool sky while decoupling it from the sun and ambient temperatures. 'Heat-selective' insulation gives a roof mass a cool view of the sky because integrated pathways focus and channel long wave thermal radiation through it. It is biomimetic because it achieves infrared transparency by adding structure to the component – something that is often found in biology – rather than manipulating the properties of the material itself [**80**].

3.2.8 Global challenge 14: science and technology

3.2.8.1 Issue: scientific and technological breakthroughs need to be accelerated to improve the human condition. Information and communications systems are broadening the scope, accelerating the pace, and increasing the synergy of scientific discovery and technological applications. Development of new theoretical principles in science is leading to great improvements in physics, biology, and chemistry that are supposedly leading to great improvements in engineering and medicine. Hardware and software are developing at an unprecedented pace. The computer defeated the previously 'undefeatable' human chess master. Brain-like intelligent systems using neural networks and other simulation technologies will help achieve a more functional understanding of human cognition, intelligence, thought, and self-consciousness.

Nanotechnology promises to lower unit cost, and spread the benefits of technology while lowering the environmental impact of a growing world economy and population. Vaccinology and genetic medicine will eliminate many acquired and inherited diseases. Rather than reducing support of the new frontiers of science and technology, renewed efforts should provide extraordinary tools to improve the human condition [**28**, **29**].

Charles Kleiber, the State Secretary for Science, Berne, Switzerland, clearly illustrates the need for a new kind of science:

> 'What kind of science do we need today and tomorrow? In a game that knows no boundaries, a game that contaminates science, democracy and the market economy, how can we distinguish true needs from simple whims of fashion? How can we distinguish between necessity and fancy? How can we differentiate conviction from opinion? What is the meaning of this all? Where is the civilizing project? Where is the universal outlook of he minds that might be capable of counteracting the global reach of the market? Where is the common ground that links each of us to the other?
>
> We need the kind of science that can live up to this need for university, the kind of science that can answer these questions. We need a new kind of knowledge,

a new awareness that can bring about the creative destruction of certainties. Old ideas, dogmas, and outdated paradigms must be destroyed in order to build new knowledge of a type that is more socially robust, more scientifically reliable, stable and above all able to better express our needs, values and dreams. What is more, this new kind of knowledge, which will be changed in turn by ideas yet to come, will prove its true worth by demonstrating its capacity to dialogue with these ideas and to grow with them.

Why should disciplines be brought together? It is becoming increasingly clear that all three historical forces – the market economy, science and democracy – not only benefit from but more importantly require, working across disciplines. First and foremost, the market economy requires polydisciplinarity. The complexity of today's world demands that any given participant to be able to combine the responsibilities and talents of multiple roles; we are called upon to be a new breed of hybrid professionals, i.e. both economists and lawyers at the same time, as well as engineer-economist or doctor-historian. Second, science itself requires interdisciplinarity. How else can we study the effect of climatic disorder on genomics, if not by adopting a transdisciplinary approach? Finally, democracy requires transdisciplinarity. Indeed, it is a sine qua non condition underpinning the proper functioning of the agora in a complex world' [**81**].

3.2.8.2 Opportunities: biomimetic contributions to the expanding potential for scientific and technological breakthroughs. Science and technology is all what biomimetics is about. In this section no long series of examples for biomimetic inspiration are given, but rather a description of current biomimetics as a method. The end of this section gives an outlook, describing how biomimetics might be applied as a method of working in 2059.

The three gaps theory between the world of ideas, inventors, innovators, and investors. For accelerated scientific and technological breakthroughs to improve the human condition, the authors propose a 'Three-gaps-theory' (Fig. 1): the inventor gap, the innovator gap, and the investor gap have to be bridged. 'Inventor gap' denotes the gap between knowing and not knowing that has to be overcome. The 'innovator gap' denotes the gap between knowledge and application of the knowledge. The 'investor gap' denotes the gap between the application and the creation of the product. To improve conditions, we do not primarily need basic knowledge but we need solutions and products. Since development always takes a path from the primitive over the complex to the simple, effective or efficient solutions can be envisaged, depending on the time frame provided and the acceleration wanted.

To accelerate scientific and technological breakthroughs, we should aim at having a context of knowledge, with the application. To prevent being trapped in the inventor, innovator, or investor gap, a cross dialogue is necessary, a pipeline from 'know-why' to 'know-how' to 'know-what', from the inventor who suggests a scientific or technological breakthrough to the innovator who builds the prototype to the investor who mass produces the product and brings the product to the consumer. Currently, and this is the main problem, at universities worldwide huge amounts of knowledge are piled up with little or no further usage. We know a lot, we can do relatively little. We need a joint language and a joint vision.

There are two ways to bridge the three gaps: 'pull' and 'push'. In the 'push' way an 'evangelist' walks around and prays how wonderful the idea is. The 'push' way is generally applied in times of peace, and is very slow. In the 'pull' way there is a vision and an innovation is urgently needed. Here, no 'evangelists' but 'scouts' are the main actors. 'Scouts' search for technologies, and demand them. People are hired, and allowed to work.

The driving force of the 'evangelist' is the dream; the driving force of the scout is the vision. The main difference between vision and dream is that the dream could become something, and in the vision the outcome is clear, and the path is to be determined. To establish

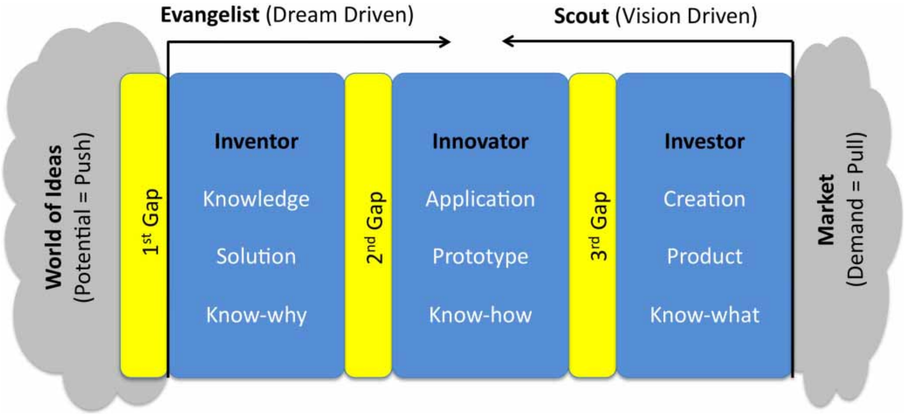

Fig. 1 The three gaps theory between inventors, innovators, and investors

a merging of dreams and visions, 'scouts' and 'evangelists' have to be brought together. In this way, the development starts: the pile of knowledge comes to the drain (vision), the vision assimilates the knowledge, and the knowledge slides off the paper.

The 'evangelist' is always a specialist; the 'scout' is always a generalist. To build a car, to build a locomotive, thousands of ideas are needed; generalists are needed. Somebody who has a specific solution for a flywheel has to be a specialist. To advance our system, more visions and a platform for 'evangelists' are needed. Interdisciplinary working groups with generalists as heads, coordinating the specialists, are needed.

At the moment, we do not have such structures. The problem is insufficient communication between customers of knowledge and its generators, between inventors, innovators, and investors – the three gaps mentioned above. Industry lacks visions, science cannot promote its knowledge, there is no platform. Biomimetics can on one hand help to bridge the gap between the fields in promoting an inter- and transdisciplinary working mode beyond the borders of classical science and industry, and on the other hand contribute to fundamental research that fulfils the old aim of increasing the knowledge without being immediately turned over into an economic asset.

3.3 Causal potential from biology

In former centuries, physics was the Leitwissenschaft and accordingly physics was the basis for many technological applications. Today, biology is often seen as the new Leitwissenschaft and it is very likely that technological innovations in the future are based on research in biology. Now, we can ask what a 'physical technology' was like, and what, in analogy, will a 'biological technology' be like? Technology in the last centuries can be characterized by applications of findings from physics and chemistry. Thereby natural laws revealed by research in physics and chemistry were used to construct or design various constructions and processes. The precondition for being able to proceed in this way was that basic principles, causations, and natural laws were at hand, that could in a subsequent step be applied by engineers.

When applying knowledge from biology in technology, the same precondition must be considered. To not only superficially copy nature, the basic principles, causations, or natural laws have to be uncovered. 'Biological technology' can be seen as analogous to 'physical technology' in this respect. For making predictions on the prosperity of biomimetics, it is thus useful to take a look on biology by raising the question in which fields causalities or laws have been revealed so far, which can be distinguished from mere correlations between some investigated parameters. Lots of biological knowledge is based on correlation, littler on causation. For instance, the causes and effects in the physiology of sense organs are quite well known, although much has to be investigated in the future. In other fields like developmental biology little is known about such causal laws; the knowledge in this field is very much descriptive. Table 2 shows the amount of causal knowledge in different biological fields. This amount is estimated by relating it to the amount of correlational knowledge (i.e. the amount is high if there are many causal laws in the field compared to correlations). In other words, fields in which many explanations have already been revealed (compared to mere descriptions) the amount is high.

The list is not meant to be exhaustive, and the attributions are rather general for larger fields. This does not negate that causal laws are known in the respective fields when it comes to details. The list should only serve as a first tool to evaluate the potentials for biomimetics. Where the amount of causal laws is high, mimicking by technical applications may be more probable and it is reasonable to expect technical innovations that rely on the biological insights in those fields. Estimating the future potential of the development of the fields towards finding causal laws is difficult. However, at the moment it looks as if biochemistry, biophysics, biomechanics, and physiology are the fields from which biomimetic applications are likely to come from in the near future.

There are functions and processes in the living nature of which already a lot is known. Examples are photosynthesis or the biochemical processes in the muscle movement. Mimicking those processes, however, seems to be hard, as technological innovations

Table 2 Causations in biology

Biological field	Amount of causal laws in the field
Biochemistry	High
Biodiversity research	Rather low
Biomathematics	Rather high
Biophysics and biomechanics	High
Cytology	Rather high
Developmental biology	Rather low
Ecology	Rather low
Ethology	Medium
Evolution	Medium
Genetics	Rather high
Microbiology	Rather high
Molecular biology	Rather high
Morphology and anatomy	Medium
Neurobiology	Medium
Physiology	High
Physiology of sense organs	High

The table shows selected biological fields and the amount of causal laws in the respective fields. The biological fields were partly selected from a list of disciplines of the Austrian Science Fund. The amount of causal laws (in relation to rules based on mere correlations) is an educated guess.

in these areas did not have a major impact until today. Those examples show that also the technical realization is difficult even when the basic principles are known. This is a reason for delays. Biological knowledge takes time to be realized in applications.

Nevertheless, ideas or inspirations can also stem from nature although the causations are not known. Technical innovations can be inspired by nature without knowing every detail in nature. But biomimetics that results from such inspirations cannot be predicted and can thus not be treated here.

3.4 The science of biomimetics

In earlier sections, the authors were looking at technical innovations stemming from biomimetics. In this subsection the focus is on the development of biomimetics in a broader sense, that is on how the biomimetic approach will change the research landscape and the engineering culture. First, the probable future position of biomimetics among the sciences and its connections to society is studied. Second, a prediction of the future of organizations related to biomimetics and how they might differ from today's organizations (i.e. research institutions, schools, universities) is made.

The interconnection of science and technology is interesting in itself and discussions about that topic will also be continued in the future. Biomimetics is positioned in this field of tension. The following questions are relevant for the development of biomimetics and the developments in other areas that are influenced by biomimetics: how will the application-driven approach of biomimetics change science? How will the application of principles from biology change technology and engineering cultures in a broader sense?

Biomimetics is an interdisciplinary field. Hence its methods are different from those utilized in single research or technology areas. Today only a small amount of people is working in the field of biomimetics, but if it is gaining importance, the characteristics of biomimetics (its methods, culture of collaboration, etc.) will influence other areas on a larger scale. Some work on such blending of disciplines, which is related to the concept of 'technoscience', has already been performed.

With the term technoscience a field is characterized in which technology and science are inseparably interconnected. This characteristic hybrid form is, for instance, seen in the atomic force microscope – a symbol for both nanoscience and nanotechnology. This tool allows for basic scientific investigations, but also for manipulation and engineering at very small scales. In technoscience there is no clear distinction between investigation and intervention. Even more, by investigation already interventions may be made.

Traditionally, engineers are interested in what works (i.e. what functions and is useful) and are hence rather pragmatic, scientists are interested in explanations, hypotheses, and theories that reflect a rather different stance. Experiments are a means for scientists to try to proof or falsify a hypothesis or theory. The practical aspects of experiments, that is the potential applicability do not belong to science but to technology. 'While traditional conceptions of science foreground the formulation and testing of theories and hypotheses, technoscience is characterized by a qualitative approach that aims to acquire new competencies of action and intervention' [**82**]. Of course, also pure scientific theories are a basis or prerequisite for technology, but it is not necessary to have an application in mind before a scientific investigation, which is a characteristic of technical biology. Living nature is seen from an engineering viewpoint, or even nature itself is thought of as an 'engineer' who is facing technical problems. Nordmann [**82**] asks whether the engineer is learning the construction principles from nature or the construction principles of the engineer deliver explanations for natural appearances.

No doubt, also the investigation of nature from an engineer's perspective will shed light on pure scientific problems. Products must stand the test of 'reality' too. However, it is plausible that the way in which things are done will differ on various levels. The organized scepticism of science is disappearing in technoscience. The cultural self-image (Selbstverständnis) of scientists and techno-scientists is different. The scientific community of equals will (at least in the short run) be replaced by a collaboration of differently situated people. In science publications in scientific journals are important; in engineering patents are important. It is reasonable to consider that in biomimetics the trend will also go from papers to patents and from open discussions to secretiveness. The search for 'truth' will subsequently be replaced by a search for applications with a potential economic value (on the basis of reference [**82**]).

But was not the connection of physics and chemistry with engineering in the past also a sort of technoscience?

Will there be a general trend of a change from a culture of science to culture of technoscience? Probably not. Although the trend in many scientific fields goes towards applications for the market, a lot of disciplines will stick to the traditional picture of science. If the one development or the other (technoscience or pure science) is an advantage or not is an open question left to the future.

However, also in the future disciplines will, although not always easily, be distinguishable from biomimetics. Bioengineering is such a field that is related and sometimes confused with biomimetics, but, although the borders are blurred, it is different. Synthetic biology, artificial life, and artificial intelligence, however, can be seen as part of biomimetics.

3.4.1 Organizations

Education in biomimetics is offered on different levels and embedded in different disciplines. The Universität des Saarlandes in Germany offered a University-level education in Bionik until the retirement of Werner Nachtigall in 2002. Antonia Kesel has established a bachelor and masters education in Bionik in Bremen, which for the past years represented the only such university education in Europe. There is a new Master program in Bionics in Energy Systems in Villach, Austria, starting in Autumn 2009. Several lectures are implemented in different study curricula in Bath and Reading, UK, Vienna, Austria, and several places in Germany (see reference [**83**] for details). A list of university-level education possibilities can be found on the biomimicry website [**84**].

The dual nature of biomimetics seems to be a handicap in terms of education. The allocation to either natural science or engineering schools seems to be difficult to implement in both cases. The increasing number of universities offering the study of biomedical engineering shows that a focus on a specific application field may be advantageous for the future development of biomimetics. With growing popularity, biomimetics is taught in schools and public workshops [**16**].

The curricula of schools and universities will change towards an integration of biology and technology. In integrated courses both fields will be taught. When this is the only way by which natural phenomena are taught (i.e. by merely focusing on the engineering aspects with a potential application in mind) biology will become a different field, different from a scientific field as we know it today.

3.4.2 Technology assessment

Interestingly, Rechenberg says that in his future scenario in 2099 technology assessment will still play a role [**16**]. He compares technology assessment to natural selection. There is no possibility for preventing abortive developments, but they have to undergo a selection process by which they are eliminated.

Predictions with regard to the demands and acceptance of applications (technology assessment) are much harder to make than a mere outlook of what will be technically possible. However, the authors think that technology assessment will and should play an important role in the future. As seen from the above examples there are probably many issues to be dealt with.

4 CONCLUSIONS

The high potential of biomimetics in science and technology is a good reason for intensifying biomimetic research. The public image of biomimetics is positive, and if biomimetics increasingly aims at providing sustainable solutions, this image might not change. As in any powerful technology, also biomimetic technology can be used in dangerous ways. Now that we begin to understand the language and concepts of life itself, careful selection between what is possible, but harmful, and what is possible and useful has to be made. Cyborgs, devices from synthetic biology, bioinspired self-replicating systems and the like do not go through millions of years of natural selection, and therefore might show unforeseeable outcomes. People will have to establish ethical codes of conduct for using novel technologies especially outside of the protected space of the laboratory. In some cases it might be advantageous not to follow some routes at all.

Biomimetics is a means not an end! The ends have to be found outside biomimetics, on another way, elsewhere. Perhaps biomimetics can lead to a new paradigm, but it surely cannot and should not replace any belief.

Successful biomimeticians are inherently transdisciplinary thinkers. Increasing inter- and transdisciplinarity calls for novel ways to educate the young. A common language for biologists and engineers, in which descriptions at different levels of detail are more compatible, is needed. More general principles that can be applied by engineers who are not at all involved in biology have to be identified. Such general principles are, for example, integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality, energy efficiency and development via trial-and-error processes [**1**].

Novel ways of teaching shall promote context knowledge instead of learning by heart, as is still required in many cases, from school to university. Brian Cambourne's 'Conditions of Learning' theory is recommended in this respect [**85**]. This dynamic and evolving model for literacy learning comprises the concepts immersion, demonstration, engagement, expectations, responsibility, employment, approximation, and response. Each of these conditions supports both the student and the teacher in their discovery of learning, helps provide a context within which to learn, and creates an interactive and dynamic experience between the learner and the content.

In the year 2059, researchers and developers who routinely think across boundaries shall successfully implement knowledge in solving the major challenges of their time!

Given the many examples where we can learn from living nature, and the time it will take to apply such things in engineering, it is very likely that biomimetics will still exist as a scientific discipline in the year 2059.

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