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Nature-Inspired Science and Engineering for a Sustainable Future

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The big challenges of the 21st century, such as global warming, access to freshwater, sustainable production of food and materials, and improving quality of life in ageing societies, require a new approach to science and engineering more closely coupled with nature. Biologically inspired designs offer technologically novel and sustainable solutions to society's problems that may not be provided as quickly or economically by traditional approaches. A deeper understanding of how biological systems work can bring new insights and approaches to energy generation, conversion, storage, transport, and efficiency. It can also inspire advances in healthcare, and introduce a new age of materials with novel properties such as self-repair.

Foreword

We are at the threshold of a new era for science and engineering in which human activities become more closely aligned with the natural world, leading to sustainable innovations that improve quality of life without longer term environmental costs. There is a deepening understanding of nature's potential to help solve the major problems of the 21st century, while also inspiring countless smaller innovations that bring great benefits to individuals.

The research communities suggest that the next generation of engineering systems will be more complex in unprecedented ways. Success of these systems will depend on a rich and challenging research frontier, elements of which are of common interest to many nations. Emerging technological frontiers must focus not only on the "how and where" of technology development but also on the pace at which new technologies affect our lives and the way we live.

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Cover
White beaked dolphin (Lagenorhynchus albirostris) sounds, wavelet graph. This image was produced by converting the frequencies of sounds made by a white beaked dolphin into a graph using a mathematical process known as wavelets. Wavelets reveal structure and detail that are not always visible in standard graphs of frequency over time (known as a spectrogram).
Aguasonic Acoustics/Science Photo Library

Workshop participants

The Opportunities

There is the opportunity now to accelerate the pace of innovation in science and engineering by changing the focus of research towards inspiration from nature. The present approach to biomimetics, which is the study of biological mechanisms as models for new materials or solutions, is too random and risks being left behind by events.

The engineering solutions of the industrial revolution changed the world and achieved great advances in transportation, large scale energy production, and construction.

But these advances came at a high environmental price because they were based on the false assumption that raw materials were abundant and that the planet could forever absorb the byproducts of industrialisation without damage to its fabric. Now there is a great opportunity to engineer a new revolution in which advances in quality of life can be achieved sustainably by drawing inspiration from nature rather than acting counter to it. This will embrace the major environmental challenges of energy and water supply, as well as the important sources of quality of life, including healthcare and novel materials.

Energy

One of the greatest challenges we face is production of clean, sustainable energy that is carbon neutral and does not cause adverse effects such as climate change. While there are now several well proven renewable sources of electrical energy such as wind turbines and solar panels, these cannot on their own generate all the energy needed at a time when demand from developing economies is growing rapidly. Plants and some bacteria are able to harvest light from the sun highly efficiently and convert it into both energy and the organic materials they need by photosynthesis. Demonstrations have already shown that bacteria can be bio-engineered to produce almost 1000 liters of hydrogen gas per hectare, which is five times more efficient in terms of energy conversion than can be achieved with current biomass crops. There is the potential to scale up this process and adapt it to also yield electricity directly, but major international collaborative efforts are required to achieve this within an acceptable time.

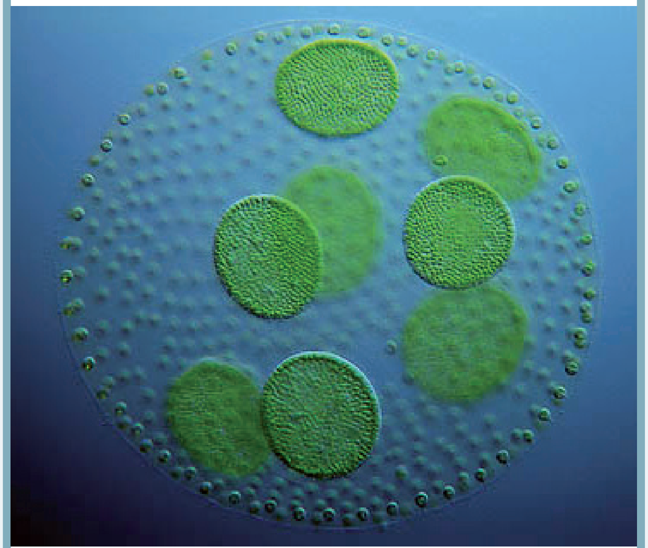


Figure 1.
Biodiesel is now being produced from algae even if it is not yet on a large scale.

• Example

US alternative energy firm PetroSun began operation of a commercial plant producing biodiesel from algae in 2008. This can produce over 4 million gallons of algal oil per year from a series of saltwater ponds spanning 500 hectares.

Water

Many regions face acute shortages of fresh water, both for drinking and irrigating food crops, made worse by rising populations in some of the affected areas. Natural organisms can provide solutions by processing and filtering human wastewater, and by inspiring systems that draw water from great depths and make it available on the surface, as some desert plants are able to do.

Figure 2.
The Epuval system in Belgium treats domestic wastewater from toilets, cleaning activities, and the kitchen.

• Example

The Epuval system developed in Belgium, and exported to Bolivia and Morocco, purifies domestic wastewater, including toilet effluent, to produce drinking water sustainably and affordably without producing unpleasant odours. It comprises a septic tank combined with a vegetal filter in a basin filled with gravel over a plastic bottom, with roots planted on top to attract natural microflora, including bacteria, that remove pollutants such as phosphates. There are 50 Epuval systems in use in Belgium serving small communities from five up to, in principle, 4000 people. As they work under gravity they require no energy and can reduce demand for mains freshwater by up to 90%.

Health/Quality of life

In healthcare reliable early diagnosis of diseases such as cancer would make a huge difference to the effectiveness of existing treatments and quality of life for patients, even without any new drugs or other therapies. One major limitation today in the early detection, screening, and cure of diseases, is the accumulation of drug molecules, and contrast agents for biomedical imaging, at the diseased site. This not only makes it hard to detect signals of disease, but is also a major cause of relapses, and the occurrence of adverse effects.

But new nanoscale technologies, often inspired by nature, can make a huge difference in early diagnosis. Nanoparticles and cell-based therapies offer strong potential for developing novel and more effective therapeutic and imaging systems. In particular, nanoparticles can be designed in different sizes and shapes, with surface and mechanical properties enabling them to recognise specific types of cell. Such particles can be targeted at diseased tissue, and deliver contrast agents, for instance, for imaging.

Such targeted nanoparticles can also be used to deliver new drugs. They can be engineered to evade the immune system, protecting the payload drugs from hostile molecules made by the patient, until they have been delivered to target cells or tissue. Nanoparticles can themselves use tricks perfected by pathogens such as bacteria over hundreds of millions of years of evolution, to evade detection from the host's immune system.

There is also great potential for copying or enhancing natural defenses employed against all forms of disease, including infections, cancer, and various inflammatory conditions such as multiple sclerosis and arthritis.

Figure 3.
Bacteriophages, the viruses that infect bacteria, hold great potential as drug delivery capsules.

• Example

UK firm BigDNA has developed a technology for delivering vaccines and antibiotic drugs by modifying bacteriophages, the viruses that infect bacteria. So far the company has developed candidate vaccines for hepatitis B and also influenza, with big potential savings in manufacturing costs.

Materials

Many organisms have evolved to produce materials with specific properties that support their particular needs, such as spider silk with its extraordinary tensile strength and extensibility. When the materials are integral to the organism, they often exhibit remarkable properties such as self-repair, as in wound healing of skin. Organisms have also evolved exceptional abilities to sense their environment, process information from multiple sources quickly in parallel, and then act accordingly. This ability can be incorporated into engineered stems at various scales ranging from implanted devices that provide assistance to people with neurological impairments, up to city road networks, which could respond to changing levels of congestion or events that might cause it by rerouting traffic and regulating stop lights.

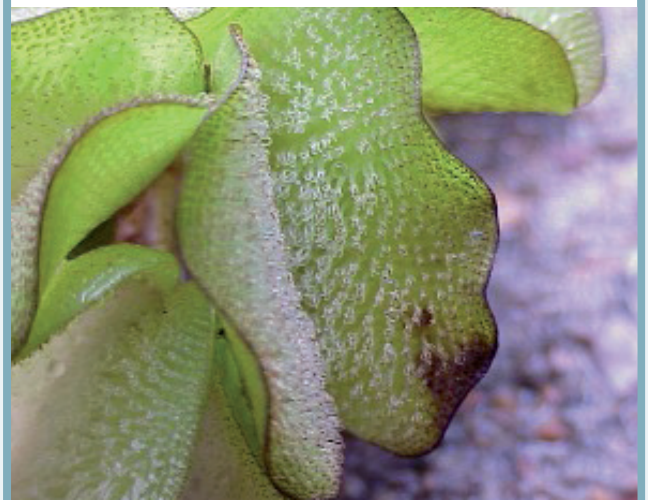


Figure 4.
Hairs on the leaves of the Salvinia fern that trap air under water.

• Example

The ability of the Salvinia fern to trap air under water has potential for building energy efficient ships that move through the water with less friction. The fern's floating leaves are evenly covered with complex hydrophobic hairs that retain a layer of air when submerged under water. The entrapped air is prevented from leaking away by the terminal cells of the hairs, which are hydrophilic, attracting water to form an outer layer held in place by surface tension.

Challenges

The fundamental challenge is to bring scientific and engineering research more closely into line with nature. Research and technological innovation can then be informed by nature, and guided by the requirements of sustainability. Meeting this challenge requires action on three related fronts, education, research collaboration, and fundamental science.

Education

A nature-inspired approach to science will require a new generation of researchers trained in both biology and relevant engineering disciplines before PhD level, with some exposure earlier than that. There will be a need for people with combinations of expertise lacking at present, such as evolutionary biology and robotics, or genetic engineering and nanophysics. Education will need to become increasingly flexible to cope with fast evolving requirements, and continue throughout the working life of researchers. This need could be met partly through intensive workshops and summer schools for both students and post doctoral researchers. New teaching materials will be needed to support the required cross disciplinary education, and enable relevant coursework to be conducted that illuminates the link between nature and the target applications.

Collaboration

Collaboration will be essential at different levels to bring about the desired changes in research and engineering design. At a fundamental level there needs to be greater cross fertilisation between relevant broad disciplines, notably physics, chemistry, biology and engineering, to provide inspiration and ideas for collaborative research. This needs to be followed up by development of the collaborative environments that will enable and encourage people from these disciplines, especially biology and engineering, to work together. This in turn will bring challenges at the funding level, requiring more flexibility for creation of international teams, not constrained by geographical boundaries. Ability to form Networks of biologists and engineers across international boundaries will be crucial for success. This need is in part satisfied by instruments available regionally, e.g., in Europe or the USA, but instruments enabling broad collaboration across continents are not in place and need to be created.

Volker Steger/Science Photo Library

Figure 5.
Artificial hand. Ultralight Anthropomorphic Hand with a human hand. This artificial hand is for use as a prosthetic or as an attachment on a humanoid robot.

Fundamental Science

The scientific challenge is to develop the skills, tools and methodologies needed to obtain inspiration from nature and translate the findings into desirable applications. It is often overseen that the process of innovation begins with fundamental research that develops basic concepts and building blocks for future technologies. New mathematical and physical models are required to understand and simulate natural systems, and to apply the knowledge to design new products or processes. More understanding is required of how biological systems process sensory input, extract knowledge from it, and make decisions based on the complex information obtained. There will be a need for a coherent framework underpinning nature-inspired research, with new systematic methods for bio-inspired creativity and engineering design. Such a framework will help identify how bio-inspired adaptive and evolutionary strategies can be applied to improve future engineering applications.

Policy Implications

Solving the big challenges

Bio-inspired research can tackle the great contemporary challenges of energy production, fresh water availability, health and quality of life, and sustainable materials. But it needs significant changes in science policy around the world, including:

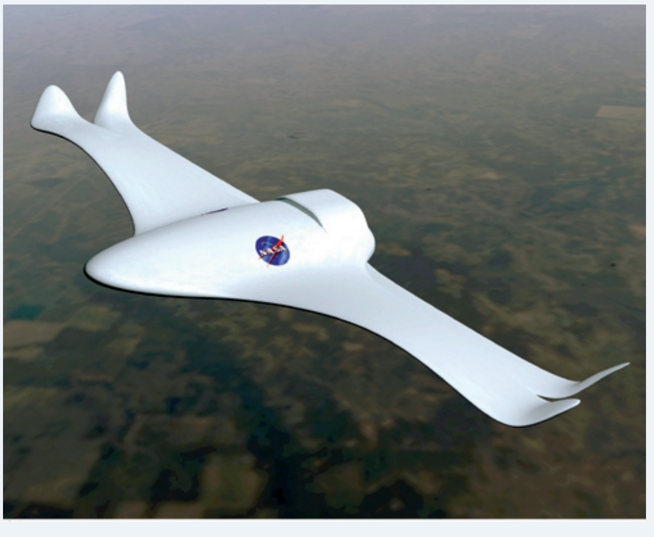
- Better support for multinational projects, with guaranteed funding underwritten by the key research agencies around the world.
- Joint mechanisms for assessing project proposals, including common review across countries.
- Shared centres of excellence.
- Programmes to stimulate exchange of ideas and movement among scientists, as well as students, between countries.
- Steps to encourage greater involvement by industry, which will bring additional sources of funding and vital engineering expertise to translate biologically inspired ideas into applications.

Set up international expert committee to develop policy proposals

These changes require concerted efforts from an international body carrying the authority of key policy makers and research agencies around the world. We therefore recommend establishing an international expert committee that would develop concrete measures stimulating bio-inspired research on a global level.

This committee would be charged with:

- Identifying bottlenecks in the approvals or funding processes.
- Developing strategies for creating the skills needed.
- Consulting widely to identify the opportunities and research priorities in the field of nature-inspired design.
- Recommending specific measures for collaborative research.



NASA/Science Photo Library

Figure 6.
Morphing-wing plane. Engineers developing future aircraft designs are hoping to improve flight performances by mimicking the peregine falcon (biomimetics).

The big message for science policy makers around the world is that the current trickle of nature-inspired innovations in healthcare, energy, and materials can be turned into a powerful and continuous flow without having to make much more money available. This will require further dialogue between scientists and policy makers, as well as platforms to identify concrete proposals that will bring about the required changes.

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