Daniel Robert

Inspiration from Nature: The Emerging Science of Biomimetics[1]

The biomimetics group, working within the framework of the project group *Theoretical Biology*, had the opportunity to organise a symposium on the theme "Inspiration from Nature: The Emerging Science of Biomimetics". For this occasion, scientists considered leaders in their respective fields were invited to present and discuss their work. The first goal of this symposium was to promote a broadly-based discussion on the history, present state, and future developments of biomimetics. In addition, a book is being produced that gathers the multiplicity of studies and approaches presented during the symposium. Although well under way, the edition of the book will require further – and significant – efforts. The efficient organization and logistical support provided by the Wissenschaftskolleg contributed to making this symposium very interactive and informative. Participants regarded it as a resounding success. The symposium was the subject of a News and Views article in the weekly scientific journal *Nature* (Vol. 100, 5 August 1999, pp. 507–509)

Admittedly, the idea of looking at nature to inspire human manufacturing endeavours is not new. As a classic, but outstanding, example dating from the 16th century, Leonardo da Vinci's work depicts the design of flying devices inspired by the bird's wing and other airborne biological entities. Abstracting the structural and functional logic from the forms and processes of the living world and implementing it in human-made devices seems to have long figured in human technological development. Lots of examples come to mind when engineered artefacts are compared to natural processes, also fuelling the question; how can one initially – or does one at all – discover a process in nature and then adapt it, or copy it, with the explicit purpose of improving upon current technology? And how often has this actually happened? It is rather clear that human engineering creativity has regularly converged on technological solutions that have their counterparts in natural technology. How many examples like that of the Velcro fastener have actually made the successful transfer from nature to technology? How much of a bird can be seen in a modern aeroplane? Considering some of the recent developments in biomimetic research is

[1] Seminar under the auspices of the Otto and Martha Fischbeck Foundation held at the Wissenschaftskolleg from June 9–11, 1999.

not to say that future jetliners will look like albatrosses or penguins. The idea – and indeed the fact – remains that the design of more efficient transportation vehicles may benefit from a large array of research in the aerodynamics of birds, the hydrodynamics of penguins, sharks and dolphins, the flapping wings of insects.

Rather than evaluating countless examples with the somewhat useless query in mind: Did nature or technology get the solution first?, the question of main interest in the symposium was to attempt to identify a general scientific methodology that has allowed the documentation, investigation and elucidation of some elegant, efficient and useful mechanisms in nature. It has become increasingly clear in the past years that very divergent fields of fundamental research such as molecular dynamics, composite material, aerodynamics and new robotics have converged on the idea of looking more closely at natural systems. Maybe the first and harder conceptual step has already been taken; the recognition that very valuable knowledge is embedded in the forms and structures of biological species and ecosystems. What the biological world has implemented in the course of evolution can be regarded as an array of sometimes very efficient and clever solutions to very general problems. Since it is still true that there is room for improvement in human technology in terms of efficiency, recyclability and sustainability, we may be well advised to look at nature's solutions. As Werner Nachtigall, a forefather of modern bionics and former Fellow at the Wissenschaftskolleg put it during the symposium: It is not necessary to look at biology for inspiration, but it may simply be wise to do so.

Admittedly, learning from natural structures and functions can potentially take place on all levels of life's complexity, from the susceptibility of ecosystems to natural or man-made toxic agents, to the atomic design of smart materials. The exercise of conceptually zooming in and out of the multiple levels of biological complexity is likely to act to reveal where research has already been inspired by the biomimetic approach and possibly where it has provided valuable results and insights.

Themes presented and discussed during the symposium[2]

Nanofabrication and molecular design are rapidly expanding fields of research in which nature's tool kit of basic building blocks – the molecules and the atoms – are used to design new materials. Seeking a deeper understanding of how materials properties emerge from the – still vastly

[2] The thematic structure of the symposium reflects the current content of the book in preparation.

unknown – interactions between these building blocks, Philip Ball invited us to explore natural molecular constructions and their structural hierarchies. The sophistication and diversity in the fabrication methods that nature employs reveal sophisticated catalytic methods. It was suggested that this knowledge can contribute to the synthetic design of advanced technological materials.

At the next level of the structural hierarchy lies the arrangement between long molecular chains, the properties of crystals, the phase and interface between different materials and their arrangement in fibres, layers and laminates. Fritz Vollrath presented an overview of biophysical investigations on the proteinic constituents of spider’s silk and the current knowledge on their biological synthesis. The remarkable mechanical properties of spider's and moth’s silk (high tensile resistance, and both tougher than steel at equal mass and geometry) has been proposed to result from particular multiproteinic macromolecular arrangements that remains mostly unknown. As more research is evidently needed on such biological macromolecules, it has been acknowledged that learning about the spider’s way of spinning its silk is very likely to contribute a great deal to the development of biological cables and textiles with exceptional mechanical properties.

Fibrous composites found in natural materials can be very useful for the construction of mechanically robust yet light and cheap materials. Addressing the particular importance of mechanical resistance around holes, George Jeronimidis documented the way wood grows and organizes fibres to minimize susceptibility to delamination and fractures around knots. Such knowledge is applied to embed holes during the manufacturing process of synthetic composites, preventing the need to drill holes subsequently, a process that alters the resistance to cracking and delamination. It was suggested that learning how to organically grow materials would, in the long run, provide the technological knowledge on how to elegantly manufacture tough materials with complex geometries. Julian Vincent highlighted the potential benefits of learning more about the organic synthesis of complex materials as a complement to structural research in natural materials. The promised benefits derive from the multiple advantages of reduced toxicity of synthesis in aqueous solutions as opposed to using organic solvents, efficient and adapted catalytic processes that allow synthesis at ambient temperature, high efficiency, little waste products, and recyclability. Another cost besides the need for much more research in this direction is the relatively low rate of growth. Adaptive growth in the presence of optimizing constraints is the subject of Dietmar Reuschel’s contribution. Computer-aided techniques of structure selection was presented as a valuable guidance in the process of design to optimize load distribution. Inspired by the adaptive growth of trees, bones and tiger claws, it was shown that optimal fibres-alignment in composites can be achieved by computer-aided estimates of mechanical stress.

The diversity of natural materials and fibres and their remarkable mechanical properties were presented by Ulrike Wegst, who carries out investigations on their performances in comparison to synthetic fibres, metals and other human-generated materials. A historical analysis was also presented that emphasized the importance of integrating materials and production methods into biological recycling. The advantages and drawbacks of natural fibres were critically considered in terms of their potential for improving not only the mechanical properties of human-made structures, but also in regard to their long-term compatibility with ecological systems.

Biruta Kresling's message articulated itself around the concept that choosing the materials, their shape, compliance and foldability is an essential and urgently early step in the process of design. Weight and stability often constitute opposing constraints, and the functional success of a design depends on understanding the role of shape by itself in conjunction with material distribution and compliance. The study of geometry in natural structures may be very valuable in architectural design. For example, the geometry of unfolding emerging tree leaves has provided valuable insight for the development of a new generation of expandable solar panels for space technology. Appropriately placed folds and bends can provide ultralight structures with high rigidity and economy in material.

In the following series of contributions, materials and their properties are embedded in mechanical functions and dynamical processes. Cornelius Schilling reported on his work on the development of actuators inspired by muscles. Very small – millimeter range – low-energy actuating devices are developed that are capable of generating high forces and momentum. The silicon-based actuators are structurally inspired by the highly efficient intertwined actin-myosin filaments found in biological actuators such as muscles.

Form and function are intimately related in the living world. Antarctic penguins have been shown to swim for more than 100 kilometres a day – in a quite demanding environment – with very low metabolic investment. Among other examples, Rudolph Bannasch reported on his discovery that the minute details shape of the penguin's body also provides a spectacular reduction in hydrodynamical drag. Dietrich Bechert's research is also aimed at developing new energy-saving transportation technology. His studies on the drag-reduction mechanisms used by sharks have revealed that the microstructural adaptations involved are arrays of riblets on the shark's scales. Merging microstructural properties with fluid-dynamical performance, Dr. Bechert's discovery has been demonstrated to significantly reduce fuel consumption in jet liners and is currently being considered for broader applications.

Michael Dickinson investigates sensory motor flight control systems in insects. High-performance flight requires a high degree of sensory control, mediated by a large number of distributed stress sensors on the body and the wings. Dynamically scaled models of insect wings have provided evidence so far elusive for the efficient aerodynamical mechanism with which flies generate lift and thrust. Knowledge gained from research on the sensory and motor organisation of fast-flying insects provides valuable inspiration for advanced control and actuation systems in aeronautics. Holk Cruse's research provides advances in the understanding of self-organized limb coordination in insect and robotic systems. Using minimal explicit instruction sets, his robotic insects perform highly complex adaptive locomotory tasks on uneven and unknown terrain. The contribution of Rolf Pfeifer pertained to recent conceptual and technical developments in neuroinformatics and situated robotics. Emphasis was given to the importance of the interactions of autonomous agents with the real world and their consequences for their integrated design. In this sense, it was pointed out that agents have to learn from their environment to refine their skills. Closing a logical circle in this series of contributions, it was advocated that technology, at any of the levels of complexity considered, ought to learn from nature, or ought to be designed to learn from nature, something that is at the heart of biomimetics research.

Participants and Contributions

Philip Ball, Senior editor, *Nature*, London, UK: Natural Strategies for the Molecular Engineer

Fritz Vollrath, Oxford University, UK, and Aarhus University, Denmark: Form and Function of Spider Silk

George Jeronimidis, Reading University, UK: Functional Holes in Fibrous Structures: Biomimetic Approach to Integrated Sensors

Ulrike Wegst, Cambridge University, UK: The Mechanical Performance of Natural Materials

Julian Vincent, Reading University, UK: Biomimetic Technology: the Low-Energy Option

Biruta Kresling, Bionics and Experimental Design, Paris, France: Folding Mechanisms in Nature: New Concepts for Lightweight Technology

Werner Nachtigall, University of Saarland, Saarbrücken

Dietmar Reuschel, Forschungszentrum Karlsruhe: Tree Growth and Design Engineering

Cornelius Schilling, Technical University Ilmenau: Biological Motion System and Micromechanical Devices

Dietrich Bechert, Technical University, Berlin: Fluid Mechanics of Biological Surfaces, a Few Examples

Yevgeny V. Romanenko, Russian Academy of Sciences, Moscow: The Kinematics of the Dolphin's Flukes

Rudolph Bannasch, Technical University, Berlin: Fluid Dynamics and Drag-Reduction: an Integrated Approach

Michael Dickinson, University of California, Berkeley, USA: The Aerodynamics of Flapping Flight

Holk Cruse, University of Bielefeld: Control of Six-Legged Walking – an Artificial System Based on Biological Data

Rolf Pfeifer, University of Zürich: Dynamics, Morphology, and Materials in the Emergence of Behavior – Investigations in Biorobotics

Thomas Brodbeck, Producer, Munich

Victor Babenko, Wissenschaftskolleg zu Berlin and Institute for Hydromechanics, Kiev, Ukraine

Caroline Baillie, Wissenschaftskolleg zu Berlin and Imperial College, London

Antonia Kesel, Wissenschaftskolleg zu Berlin and University of Saarland, Saarbrücken

Daniel Robert, Wissenschaftskolleg zu Berlin and University of Zurich