EDITORIAL

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Biological and Biomimetic Materials

Nature has long served as a source of inspiration for humans in developing technology. In the last few decades there has been an explosion of studies revealing new and ever more interesting biomaterials and structures that show extreme, unexpected properties. Butterfly wings, mollusk shells, bones, spider silk, gecko feet, lotus leaves, plant cell walls, mussel byssi, Venus's Flower Basket, and brittlestar optics are just several inspirational examples that have fueled a recent escalation of interest in "smart" biological structures from materials scientists.[1] These creatures obviously possess skills and attributes beyond conventional engineering.[2] Scientists began to ask an important question: how do we reformulate biological designs in man-made structures and create bioinspired advanced materials that are structurally and functionally optimized, that can build themselves, repair themselves and evolve?[1]

It is widely accepted that natural materials are composites based on polymers and minerals, which can have a variety of properties depending on their structure at many length scales. Today, intriguing materials solutions developed by biological organisms to provide materials with outstanding properties based on comparatively pure components is considered as an invaluable source of inspiration by a rapidly growing community of materials scientists. One reason is that powerful methods of nanoscale fabrication, characterization, and simulation – using tools that were not available as little as decade ago – have created new opportunities for manipulating and mimicking the intrinsically nanostructured biological materials.

However, biomimetic materials research cannot simply rely on observation and structural description of natural materials alone for a transfer of ideas and concepts. A grand challenge in bioinspired materials science is to understand the underlying design principles and physical/chemical mechanisms that determine the optimized structural organization in biological systems at the molecular, cellular, tissue, and organism level, and its relationship to function. Moreover, the optimal solution of an engineering problem may lead to a quite different material than the biological material serving as inspiration, even if underlying physical/chemical principles are the same. This is due to the different boundary conditions and constraints imposed on natural materials by the biological environment and on man-made materials by the current status of engineering and economy, respectively.[3] Healthy biological and biomimetic materials research should, therefore, involve at least three different, complementary research directions (Fig. 1):

1. Biomimetic materials research starts with the elucidation of structure–function relationships in biological materials.
2. A second important step is to extract the physical/chemical principles of this structure–function relationship (using both experiments and theory), in order to make them available as a concept useful in materials science and engineering.
3. The last step is to develop pathways for the synthesis and the manufacturing of biomimetic materials based on these physical/chemical principles, taking into account the existing capabilities and constraints imposed by engineering and by economy.

A very early example of extracting physical principles (Arrow 2 in Fig. 1) from the observation of a structure–function relation in a biological system (Arrow 1 in Fig. 1) is the study of bone shapes by Galileo (Fig. 2).[4] From his observation that bones of smaller animals are more slender than those from heavy animals, he concluded that the strength of a material is the maximum load divided by the material's cross-section – a principle applied in mechanical and civil engineering using structural materials different from their biological original (Arrow 3 in Fig. 1).

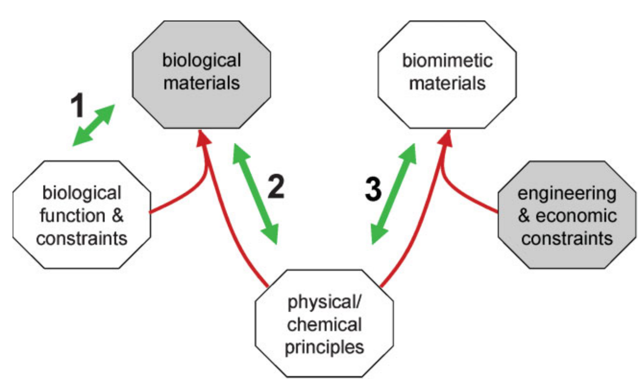

Figure 1. The biomimetic materials paradox. In engineering, one searches for a material fulfilling the desired function, considering a known set of constraints. A known biological material, on the contrary, is the solution to an a priori unknown problem and unclear set of constraints. To use a biological material's concept as a solution to an engineering problem (see the two grey boxes), a number of white boxes have to be filled with information. The first step in biomimetic research is, therefore, to identify structure–function relations in the biological system (Arrow 1). The second step is to extract physical/chemical principles (Arrow 2) and only then this knowledge may be used to actually develop pathways for the synthesis of an artificial material (Arrow 3).

EDITORIAL

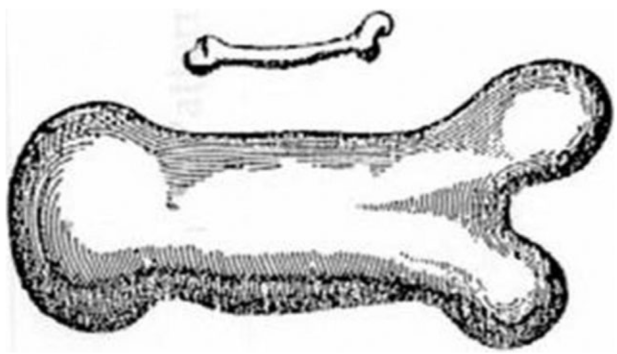

Figure 2. Galileo's observation of the aspect ratios of bones from animals with different weight [4].

The search for fundamental mechanisms and common biological solutions in design, synthesis, and integration of natural structures is the critical requirement in our quest to match their properties in novel, advanced materials and devices.[1–3] Much of the detail is still, however, tantalizingly out of reach. Learning from biology and mastering nature's concepts hold a strong promise to drive a paradigm shift in modern materials science and technology, but may also tell us something about the biological system itself and help us understand the biological function and environmental constraints in more detail. It is important to realize that progress in this emerging field is impossible without cross-fertilization between the materials science, chemistry, physics, biology, nanotechnology, and engineering communities. Fortunately, initial forays into bioinspired materials have been promising and there is every reason to expect many important breakthroughs in the future as this field is explored.

This special issue contains 18 contributions covering various topics across the areas of research on biological and biomimetic materials. Structure–function properties and physical/chemical material design principles are studied and discussed for a variety of biological materials, including tooth, bone, turtle shell, mussel byssi, lobster cuticle, spider silk, and even the sucker rings of squid (see cover). Several papers investigate the interaction of cells with nanoparticles and composites. Inspiration from nature is used to design artificial bone material, actuated nanostructures, friction surfaces, adhesives based on mussel protein or on gecko feet. Hydrogels and polymers are investigated in their ability to control inorganic crystal growth.

The guest editors are most grateful to their colleagues who contributed reports on their work to an exciting volume on biological and biomimetic materials research.

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[1] *Inspired by Biology: From Molecules to Materials to Machines* (committee on Biomolecular Materials and Processes, National Research Counncil of the National Academies), The National Academies Press, Washington, DC, **2008**.
[2] P. Forbes, *The Gecko's Foot: Bioinspiration – Engineered from Nature*, Fourth Estate, London **2005**.
[3] P. Fratzl, *J. R. Soc, Interface* **2007**, *4*, 637.
[4] G. Galilei, Dialogues Concerning Two New Sciences. (original edition 1632), in *On the Shoulders of Giants* (Ed: S. Hawking), Running Press, Philidelphia **2005**.

