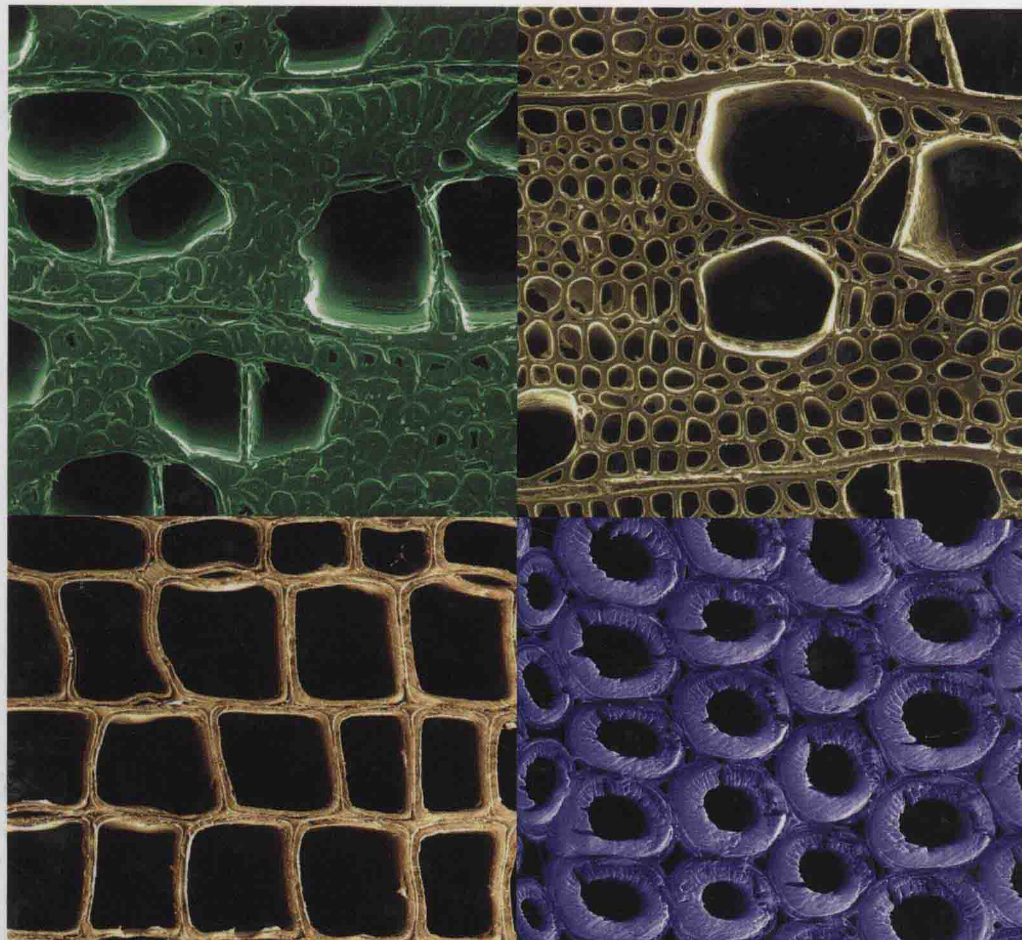
RSC Smart Materials

Edited by Peter Fratzl, John W C Dunlop and Richard Weinkamer

# Materials Design Inspired by Nature

## Function through Inner Architecture



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**RSC Smart Materials**

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# Preface

Biological materials are omnipresent in the bodies of plants, animals and humans. They allow cells to function, eyes to capture and interpret light, plants to stand up to the light, and animals to move or fly. This multitude of solutions has always inspired mankind to make materials and devices which simplify our daily lives. Biological materials have many features which differentiate them from the usual engineering materials. First, they consist of relatively few constituent elements, mainly proteins such as silk or collagen, polysaccharides such as cellulose or chitin, and a few minerals. Nevertheless, nature has evolved – based on comparatively poor base substances – a range of materials with remarkable functional properties. The key is a complex, often hierarchical structuring which results from the growth process of natural materials, where components are synthesized and assembled by the organism according to a recipe stored in the genes. This multi-scale internal architecture offers a number of advantages. It allows, for example, the adaptation to conflicting requirements by separately tuning the properties at different length scales to better meet those requirements. Another feature is an enhanced ability for lightweight construction by an adapted internal architecture (such as struts, plates, fibres) at different length scales.

However, in order to extract useful ideas for the development of bio-inspired engineering, it is not sufficient to describe only the structural hierarchy of natural materials. It is essential to also take into account the full variety of boundary conditions imposed by habitat, food or potential predators, which all influence the adaptation of natural tissues, sometimes in conflicting ways. This makes it improbable that any natural material will be optimized for one function only, given that organisms experience many challenges simultaneously. Moreover, genes carry a long history of evolution and it is not obvious that the adaptation to a particular environmental condition (for example to hard food, to low temperatures, to different levels of oxygen or

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sunlight) will yield an optimal solution, given that the starting point is imposed by the conditions of the past. The consequence is that structures found in an organism may not be optimal for any desired engineering goal but just a compromise between historical baggage and adaptation to conflicting requirements.

Likewise, engineering developments are in most cases nothing else than compromises between other sets of conflicting requirements, such as production cost, consumer acceptance, as well as environmental and health implications. Hence, the difficulty in translating natural solutions to engineering applications is that – even when the same technical problem needs to be solved – the associated conflicting requirements may be radically different.

With this in mind, a group of scientists joined forces in 2009 to explore the possibilities of designing multifunctional materials based on hierarchical structuring. This effort is supported by the German Research Foundation (DFG) in the form of a priority programme (SPP1420; http://spp1420.mpikg.mpg.de/). This programme addresses a variety of challenges, first by characterizing natural hierarchical materials to enlarge the 'idea park' of hierarchical structures and to discover and model new principles for materials design, and then to develop manufacturing technologies for materials solutions based on hierarchical structures. We are explicitly mentioning this priority programme since many of the chapters of this book were contributed by partners and friends of the SPP1420 consortium.

In the first chapter, Yves Bréchet gives an overview over a class of engineering materials which he calls 'architectured materials'. This chapter sets the tone by looking into the rationale of (multi-scale) structuring in order to achieve uncommon property combinations and to eventually fill gaps in material–property space. The chapter considers acoustic absorbers and radiant burners as examples and also analyses the potential of bio-inspiration in developing architectured materials.

Collagen, bone and their hierarchical structure are at the centre of Chapters 2–5. First, Willie, Duda and Weinkamer describe the dynamic structure of living bone (Chapter 2). A particular feature of this material (and as many other tissues in our body) is that bone is continuously renewed by cells that resorb and others that synthesize it. This process is also central for the adaptation of the structure to the applied loads (Wolff's law). Chapter 3 and 4 then introduce modern techniques for the characterization of hierarchical biomaterials. First, Wagermaier and co-authors describe position-resolved X-ray scattering, a powerful tool to studies hierarchical structures in bone and other biological materials. Then Dey and Sommerdijk introduce advanced transmission electron microscopy techniques using the example of bio-inspired mineralization, a process which mimics the mineral deposition in the collagenous bone matrix. Giraud-Guille and co-authors describe natural and artificial materials based on collagen matrices (Chapter 5). Such materials may find applications in tissue engineering and as medical implant materials.

Plants and the plant cell wall are the topic of Chapters 6 and 7. First, the hierarchical structure and its role on the mechanics of plants is introduced by

Ingo Burgert followed by the use of plants in bio-inspired systems. Then, in Chapter 7, Gierlinger and co-authors give an introduction to Raman spectroscopic imaging, which has emerged quite recently as a useful tool for the characterization of biological fibrous materials structured over several length scales. Beside plant tissues, the investigation of collagen and bone is covered.

Chitin-based materials are covered in Chapters 8 and 9, which concentrate on the cuticle of arthropods. Paris and co-authors describe the multi-scale structure and the mechanical properties of the crustacean carapace. Friak and co-authors then introduce the methodology of multi-scale modelling for the theoretical description of this type of materials. The structuring of chitin-based materials in the submicron range also allows light to be manipulated and iridescent colours or light reflectors to be engineered. In Chapter 10, Andrew Parker describes these photonic structures in beetles and butterflies and shows how related concepts can be turned into useful optical devices.

Carillo, Vach and Faivre, in Chapter 11, discuss the structure, arrangement and function of magnetic nanoparticles used by magnetotactic bacteria to navigate in Earth's magnetic field. Silk and other protein materials are reviewed by Smith and Scheibel in Chapter 12.

Hierarchically structured surfaces can be both anti-adhesive or adhesive, depending on the details of the structure and the interactions. These principles are used by plants and insects to regulate their interaction but also by relatively large animals such as the gecko to run on the ceiling. Elena and Stanislav Gorb provide an overview about anti-adhesive surfaces in plants and their effect on insect locomotion in Chapter 13 and how these principles may be used for bio-inspired applications. In Chapter 14, Kroner and Arzt review adhesive surfaces.

Most biological materials are composites, either of different types of macromolecular materials, usually based on protein or carbohydrates or they are polymers reinforced by hard mineral particles. Studart and co-authors introduce bio-inspired structural principles for advanced composites in Chapter 15.

Finally, Chapter 16 is devoted to an interesting biological property: the ability of some organs or biological materials to heal. This occurs with skin and bone in our body but also exists in plants. Speck and co-authors show in this last chapter how concepts of self-healing derived from biological organisms can be understood, developed and pushed all the way to a technical product.

In general, the chapters in this book address the problem of bio-inspired materials in three different ways: first by describing the structure and function of hierarchical biological materials (Chapters 2, 5, 6, 8, 10–12). Then, several chapters introduce state-of-the-art methodology needed for the characterization (Chapters 3, 4, 7) and the theoretical modelling (Chapter 9) of multi-scale structures. Finally, in the remaining chapters (1, 5, 13–16), the focus is on using structural principles recognized in biological materials for their translation into materials for diverse engineering applications.

Bio-inspired materials research is a wide and dynamically evolving field. The present book focuses on a special aspect, namely the use of multi-scale structuring to improve mostly mechanical, but also other properties and to approach a true multi-functionality of these materials, including adhesion, optical and magnetic properties. The authors are biologists, chemists, physicists and engineers and their language varies somewhat according to their fields. Nonetheless, the book should be accessible to readers from all these disciplines.

We hope that this book will enable engineers to become inspired to use multi-scale structuring instead of, or in addition to, changing the composition of their materials. We also hope that biologists will find some pleasure in learning how their science is now starting to influence engineering.

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# Contents



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