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Introduction

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When human ancestors first looked up at the starry sky, they began exploring the laws of nature. It is precisely this exploration and utilization of natural laws that has driven the development of human civilization. The establishment of modern science first originated from curiosity about natural laws, with the discovery, reproduction, and imitation of natural phenomena being the initial paradigm. The use of mathematical and physical methods subsequently constructed the foundation of modern science, from which various methods of utilizing natural laws evolved, leading to multiple scientific and technological revolutions that continuously propelled civilization's development. Entering the twenty-first century, although modern society is highly developed, the relationship between humans and nature is not distant, but rather more closely intertwined. The challenges faced by human society – such as energy crises, environmental challenges, and healthcare – all require finding answers from nature and its fundamental laws.

Surveying the development of chemical science and materials science, one can observe that cutting-edge research follows a certain historical trajectory, developing numerous scientific questions. The value of these scientific questions is increasingly tied to practical social needs, such as solar energy utilization and clean energy, atmospheric water harvesting and water resource management, and CO₂ capture and conversion addressing climate issues. In contrast, research driven purely by curiosity has received less attention – for instance, precise morphological control of nanocrystals, preparation of zeolite-based porous structures, and hydrophobic–hydrophilic interfaces – despite these areas not being fully understood and their potential not yet exhausted. This is certainly not a negative aspect; it indicates that scientific research is progressing steadily, with scientific exploration seeking answers to societal problems and striving to advance social development. However,

this may not necessarily be the most optimal scenario. Some suggest that transformative scientific achievements are gradually decreasing, and the pace of technological development is slowing down [1]. While we cannot predict whether this deceleration will continue, if ongoing research topics become increasingly concentrated on a couple of specific areas, the diversity of research themes will significantly diminish, thereby reducing the likelihood of nurturing new research directions and generating revolutionary breakthroughs.

Addressing this issue, thinking out of the box is crucial. Creatively combining different things can bring forth new scientific questions and directions. A viable approach is to directly utilize or mimic bio-based materials found in nature. Many bio-based materials are characterized by widespread availability and low cost, with wood being a representative example. It can be directly used in human activities, and further functionalizing or transforming such materials can not only create social and economic value but also potentially provide solutions to other scientific problems related to social needs. Moreover, under the challenge of survival pressures, nature has evolved over millions of years numerous efficient means of energy and material utilization, for example, photosynthesis, respiration, branching fractal structures, hierarchical structures, etc. These methods have been proven effective by time itself, capable of maximizing material properties under limited resources. These are also the ultimate goal of artificial material design. Therefore, mimicking these structures and functions can also bring breakthroughs in materials science and scientific thinking approaches.

Currently, we have not fully understood the material design principles of nature. Taking mechanical properties as an example, natural materials are generally organic–inorganic composite materials with multilevel structures [2]. In nacre structure, aragonite calcium carbonate and chitin form a layered, ordered “brick-and-mortar” structure reminiscent of modern architecture [3], where the inorganic components support the overall structure, and organic components regulate the interactions between inorganic components. This organic–inorganic composite structure exhibits strength and toughness far exceeding pure calcium carbonate or chitin, while remaining lightweight and possessing high practical value. However, we are still unable to fully understand the growth mechanism of such materials in nature and can only reproduce these structures through alternative methods [4, 5]. Moreover, we remain uncertain about why nature selected these specific two materials to construct such structures. An intriguing question remains: If chitin were replaced with chemically similar cellulose or hemicellulose, and aragonite phase with calcite phase, would similar structures and properties still be achievable? Natural materials demonstrate numerous types of multilevel structures, such as coral structure, sea urchin-like structure, nacre, and others [6–8]. The building blocks in these multilevel structures are arranged in an extremely orderly manner, with the overall structure presenting diffraction patterns similar to single crystals. Some structures have building blocks with slight rotational dislocations, while others have no such restrictions. We are yet to fully comprehend the material science benefits arising from these characteristics. In the field of bio-based materials, numerous unknowns await exploration. These investigations hold promise for generating new insights into material preparation and design, potentially providing feasibility for developing next-generation lightweight, high-strength, and tough composites with versatile functionalities.

Research on biomimetic materials has a long history and has achieved numerous advancements. We can scarcely determine the earliest origins of biomimetic practices. The design of wooden boats might have mimicked fish body forms and used wooden paddles imitating fins; bone needles might have been inspired by fish spines; even the invention of saws could potentially have been a reproduction of leaves with sharp teeth on both sides. In modern technology, there are also many examples of biomimetic research. Taking the regulation of hydrophobic and hydrophilic properties as a representative case, researchers have carefully observed structures in the biological world exhibiting different wettability characteristics and created various functional materials. Lotus leaves demonstrate an extremely pronounced hydrophobic nature, with raindrops rapidly sliding off their surface – a phenomenon attributed to their rough micro- and nano-surface structures [9]. Building upon this observation, multiple superhydrophobic interface designs have emerged, applicable in areas such as material self-cleaning, surface defogging, frost prevention, etc. [10–12]. Spiders in desert environments can extract water from the air, thanks to their ability to produce superhydrophilic spider silk [13]. Water from the air condenses on these silk strands, and their super-wetting properties enable rapid water droplet collection. Extending from these principles, researchers subsequently designed hedgehog-like structures exhibiting unique amphiphilic properties [14, 15]. These studies have driven attention and contemplation regarding interface structures and properties. Numerous other examples exist. The sharkskin swimsuit was once a widely discussed example among the public. The rough, V-shaped wrinkles on sharkskin surfaces can significantly reduce water flow friction, enabling more efficient water flow around the body and allowing sharks to swim rapidly. By applying the same principle to swimsuit design, swimmers' performance improved obviously.

Beyond directly mimicking the structures of natural substances to optimize functionality, there is another biomimetic approach that focuses on the principles of functional implementation – imitating operational methods without being constrained by specific chemical compositions or structures, also known as function mimicking [16–19]. The most representative example of this approach is mimicking neural structures to achieve computation. Although we are still unclear about how thought and consciousness are realized in the brain, this does not prevent us from attempting high-performance computation by simulating neural operational modes. At the end of an axon, a neuron presents as a synaptic body that can connect with the cell body or dendrites of other neurons, forming a synapse – a small gap through which the axon transmits neurotransmitters or electrical signals. Each neuron receives signals from other neurons through synapses, and when input reaches a certain threshold, it generates an output signal, with both input and output represented by voltage. This operational pattern has been applied in computations, where each node mimics a neuron, with interconnections that mutually influence each other and can exist in resting or activated states. Artificial neural networks have two structures: recurrent and backpropagation [20–22]. In recurrent networks, each node's state is determined by the states of other nodes, allowing feedback, so that each node's state serves simultaneously as output and input, with connections potentially forming circuits. Backpropagation networks, by contrast, have input and output layers, and may also include hidden layers. These are the

basis of today's popular machine learning methods. It is worth noting that machine learning has now been proven highly effective in discovering unknown relationships between material structures and properties, thereby guiding and promoting materials science development. Moreover, current computer architectures still differ significantly from brain structures – in computers, storage and computation are separated, whereas in the brain, they are likely integrated. To achieve storage and computation integration at the physical level, memristors have consequently garnered widespread attention and are considered more suitable for implementing machine learning than current computer architectures [23–25]. There are again much more examples in functional biomimetics.

The field of biomimetic materials is extremely vast, with research currently flourishing across multiple frontiers and breakthrough achievements continuously emerging in different advanced areas. Numerous professional monographs and review papers have already summarized and reviewed various domains [26–36]. This book cannot encompass all content, and to avoid excessive overlap with existing works and considering the rapid development of the discipline, we can only attempt to select some emerging fields for simple presentation, aiming to provide readers with foundational insights that might spark new ideas. We also follow the two categories of mimicking bio-based materials. As for mimicking the structures of bio-based materials, the discussion is further divided into inorganic material systems and organic material systems. Therefore, the content of the book can be broadly divided into three parts:

Part 1: Biomimetic Inorganic Nanostructures

This part primarily covers inorganic nanomaterials that mimic biogenic structures, such as biominerals or biomorphs. It spans from Chapters 2 to 5. Chapters 2–4 delve into biominerals and related topics, while Chapter 5 discusses a unique subject named “Biomimetic Chiral Nanoparticles.” Here, the focus is on emerging chiral inorganic nanoparticles, such as calcite, quantum dots, and gold nanoparticles. The synthesis of these chiral structures often involves the use of amino acids or peptides. Additionally, the resulting chiral nanoparticles can act as mimics of proteins or other biomacromolecules, offering a novel perspective on biomimetic strategies.

Part 2: Biomacromolecules and Structural Mimics

This part explores some of the latest hot topics in material science related to biomacromolecule-based or mimicking nanomaterials. Chapter 6 discusses biomacromolecular mimics, primarily focusing on molecules that mimic proteins. Chapter 7 is on wood-based materials, emphasizing the modification of natural wood to achieve specified mechanical or chemical properties. Chapter 8 addresses cellulose, concentrating on its application in functional materials for mechanics, optics, sensors, etc. Chapter 9 explores a wider range of biomass types that can be utilized for a circular economy. Chapter 10 discusses aerogels, which mimic

the structure of plant leaves or animal fur to produce functional materials for thermal insulation, fire retardancy, water transport, and more. Chapter 11 looks at mechanical materials with biomimetic hierarchical structures.

Part 3: Nanomaterials Mimicking Biocatalytic Processes

This part looks at some exemplary biocatalytic processes and introduces the strategies and principles used to mimic these biosystems for high efficiency. Detailed topics include enzymes (Chapter 12, nanozymes), photosynthesis (Chapter 13, photosynthesis and photocatalytic water splitting; Chapter 14, CO₂ conversion), and N₂ fixation (Chapter 15, artificial N₂ fixation).

Again, the field of biomimetic materials is too vast for this book to comprehensively showcase all its content. We can only select some representative emerging fields for presentation. However, it is equally important to note that current research paradigms are primarily based on traditional methods, simplifying and modeling complex systems, and studying static processes. Biological materials generally utilize both order and disorder structures, generating rich functionality on this basis, and often a single material possesses multiple functionalities – a realm that current materials science research has yet to approach. It can be anticipated that future research will comprehensively consider complex systems, examining the synergistic interactions between different components, order and disorder, and exploring the collaborative realization of material functionalization and multifunctionality. Future studies will also focus on the dynamic processes involved in material function implementation. Future research can leverage achievements from systems science to shape shared scientific language and research thinking, examining existing material systems from entirely new perspectives. This approach may generate new research growth points and innovative breakthroughs, forming an entirely novel scientific value system. While we cannot precisely predict where biomimetic science will lead us, we can foresee that the continuous exploration of nature will persistently propel the advancement of civilization.

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