1

General Introduction

1.1 Historical Perspectives

Living organisms in nature have evolved over billions of years to produce a variety of unique materials that possess extraordinary abilities or characteristics, such as self-cleaning, self-healing, efficient energy conversion, brilliant structural colors, intelligence, and so on. These biological materials are made by nature using earth-abundant elements at ambient temperature, pressure, and neutral pH. Mimicking these biological materials structures and processing could lead to the development of a new class of advanced engineering materials useful for various applications ranging from transportation (e.g., aircraft and automobiles) to energy production (e.g., turbine blades, artificial photosynthesis), to biomedical products (e.g., implants, drug delivery). Some of these solutions provided by nature have inspired humans to achieve outstanding outcomes. For example, artificial dry adhesives mimicking gecko foot hairs have shown strong adhesion, 10 times higher than what a gecko can achieve,\(^1\) and the strength and stiffness of the hexagonal honeycomb have led to its adoption for use in lightweight structures in airplane and other applications.\(^2\)

The idea of mimicking nature’s materials design has been around for thousands of years. Since the Chinese attempted to make artificial silk over 3000 years ago\(^2\) there have been many examples of humans learning from nature to design new materials and related products. One of history’s great inventors, Leonardo da Vinci, is well known for his studies of living forms and for his inventions, which were often based on ideas derived from nature.\(^3\) Although the lessons learned by da Vinci and others were not always successful, as seen in the countless efforts throughout the ages by humans to fly like a bird, these explorations provided some clue for the Wright brothers, who designed a successful airplane after realizing that birds do not flap their wings continuously, rather they glide on air currents.\(^4\) Perhaps the most common and successful product developed based on bioinspiration is Velcro, a fastener. In the 1940s a Swiss engineer, George de Mestral, noticed how
the seeds of an Alpine plant called burdock stuck to his dog’s fur. Under a microscope, he saw that the seeds had hundreds of tiny hooks that caught on the hairs. This unique biological material structure inspired him to invent the nylon-based fastener that is now commonly used.

Although the idea of learning from nature has been around for a long time, the science of biomimetics has gained popularity relatively recently. This approach, which uses nature’s blueprints to design and fabricate materials, dates back to the 1950s, when the term “biomimetics” was first introduced by Schmitt in 1957. Biomimetics is derived from bios, meaning life (Greek), and mimesis, meaning to imitate. The term “bionics” was introduced by Steele as “the science of systems, which has some function copied from nature, or which represents characteristics of natural systems or their analogues”. The term “biomimicry”, or imitation of nature, coined by Janine Benyus in 1997, refers to “copying or adaptation or derivation from biology”. From a materials science and engineering perspective, the science of biomimetic materials is thus the application of biological methods and principles found in nature to the study and design of engineering materials. This “new” science is based on the fundamentals of materials science and engineering, but takes ideas and concepts from nature and implements them in a field of technology. While the term “biomimetic” is frequently used in this book to describe mimicking the microstructure of biological materials, “bioinspired” is also employed to describe more general inspiration from nature.

The variety of life is huge; many things fascinate us. Leaves use sunlight, water, and carbon dioxide to produce fuel and oxygen. Geckos keep their sticky feet clean while running on dusty walls and ceilings. Some kinds of bacteria thrive in harmful environments by producing enzymes that break down toxic substances. Materials scientists are increasingly interested in how these phenomena work, and applying this knowledge to create new materials for clean energy conversion and storage, reusable self-cleaning adhesives, cleaning up pollution, and much more. Once the biomimicking succeeds, the impact is enormous.

1.2 Biomimetic Materials Science and Engineering

1.2.1 Biomimetic Materials from Biology to Engineering

Applying materials design principles taken from nature’s design to engineering materials can create a new paradigm in materials science and engineering. The term “biomimetic materials science and engineering” is defined here as the study and imitation of nature’s methods, mechanisms, and processes for the design and engineering of materials. Materials science, also commonly known as materials engineering, is a vibrant field creating various materials with specific properties and functions, and applying the materials to various areas of science and engineering. The knowledge, including physics and chemistry, is applied to the process, structure, properties, and performance of complex materials for technological applications. Many of the most pressing scientific problems that are currently faced today are due to the limitations of the materials that are currently available. As a result, breakthroughs in this field are likely to have a significant impact on the future of human technology. While humans make great efforts to look for better materials for technological applications, nature has already provided a vast reservoir of solutions to engineering problems, ready for us to exploit. Thus, it is necessary to extend materials science into biomimetic fields where scientists and engineers create materials with properties and performance beyond those of existing materials by mimicking nature-designed structures, and discover new routes for manufacturing materials.
by imitating biological processes. The integration of biology, material sciences, chemistry, and physics together with nanotechnology and information technology has brought the subject of biomimetic materials to the science and engineering frontier (Figure 1.1); it represents a major international competitive sector of research for this new century.

1.2.2 Two Aspects of Biomimetic Materials Science and Engineering

Biomimetic materials science and engineering advocates looking at nature in new ways to fully appreciate and understand how it can be used to help solve problems related to materials design and processing. This is achieved by considering nature as model, measure, and mentor in two ways (Figure 1.2). The most obvious and common type of biomimetic materials is the emulation of natural material structures or functions. In this aspect, artificial materials that mimic both the structural form and function of natural materials are designed and fabricated using modern technology. With better understanding of the microstructure, chemistry, and function of biological systems, artificial materials with more precisely controlled microstructure and better function can be designed and produced by following biomimetic principles. With advances in nanotechnologies, biological materials can now be characterized at the level of atoms and molecules, and the biomimetic design of materials can be carried out on the same atomic and molecular scale. Computer modeling and simulations can further optimize the biomimetic design and even create new materials based on biological prototypes.

Emulating nature in the process is another aspect of the biomimetic design of engineering materials, which involves learning from the way nature produces things or evolves. Traditionally biomimetics has involved making artificial materials that replicate biological systems by conventional methods, but now it is possible to utilize biomolecules (nucleic acids, proteins, glycoproteins, etc.) and microbes (archaea, bacteria, fungi, protista, viruses, and symbionts) to actually fabricate artificial materials. This development has the potential to

Figure 1.1 Scope of biomimetic materials science and engineering, and its relationship with other disciplines.
Biomimetic Principles and Design of Advanced Engineering Materials

revolucionize materials processing because biosystems synthesize inorganic materials like apatites, calcium carbonate, and silica with nanoscale dimensions. Unlike the traditional materials processes that involve high temperature and high pressure with emission of toxic substances, biological systems produce materials under ecofriendly environments. Beyond the synthesis of nanomaterials, biological systems possess the ability to assemble nanoparticles into larger structures (e.g., bones and shells), effectively performing large-scale integration of nanoparticles. As opposed to the traditional engineering approach, biological materials are grown without final design specifications, using the recipes and recursive algorithms contained in their genetic code. This provides new approaches for materials scientists and engineers to scale up nanoparticles into bulk materials or large structures with desired properties or functions, although this is more challenging than making nanoparticles. Mimicking these bio-assembly processes promises to be an enormously fruitful area of biomimetic manufacturing for advanced engineering materials.

1.2.3 Why Use Biomimetic Design of Advanced Engineering Materials?

Although tremendous progress has been made in the field of advanced materials beyond traditional materials, there still remain technological challenges, including the development of more sophisticated and specialized materials, as well as the impact of materials production on the environment. Many scientists and engineers, whether mechanical, civil, chemical, or electrical, will be looking for new and better designs involving materials. Over some 150 million years, nature has created and tested materials structures from nano and micro to macro and
mega, using the principles of physics, chemistry, mechanics, materials science, and many other fields that we recognize as science and engineering. These materials, or “products”, have been ruthlessly prototyped, market-tested, upgraded, refined, and otherwise improved as the world around them changed. Each of these fragile specimens is a package of innovation waiting to be understood and adapted as a biological prototype for advanced engineering materials. This evolution produced sophisticated materials and structures which rarely overlap with the methods and products made by humans.

In addition to new materials that could be fabricated based on biological design principles, biomimetic materials could be created that are better than the biological prototypes themselves in some aspects since the bioprotoypes are optimized based on the elements available in their environments. Compared to nature, a multitude of synthetic materials with diverse properties are available for selection. Nature has achieved various functions or performances via microstructures restricted to limited kinds of biological materials, mainly collagen and minerals. In contrast, there are abundant artificial materials, including metals, ceramics, and polymers, with various properties facilitating the design and fabrication of microstructures. For example, artificial materials can provide refractive indexes of up to 2.0 and higher for building optical structures while most biomaterials are restricted to an index below 1.5.\textsuperscript{10}

Besides refractive index contrast, metamaterials with properties that do not exist in nature can be employed to create unique optical effects. To transfer the sophisticated design in nature, materials scientists need to design a broad range of fabrication approaches and adopt various artificial materials to fabricate microstructures with desirable features based on biological design principles.

Many biological materials have remarkable properties that cannot be achieved by conventional engineering methods, for example a spider can produce huge amounts (comparing with the linear size of his body) of silk fiber, which is stronger than steel, without access to high temperatures and pressures. Through biomimetics, it is possible to produce synthetic fibers with properties similar to those of natural fibers. These properties are achieved by mimicking the composite structure and hierarchical multiscale organization of the natural fibers.\textsuperscript{11}

Biological materials are different from traditional engineering materials in a number of interrelated ways (Table 1.1). These differences may provide excellent opportunities for biomimetic materials science and engineering to create advanced engineering materials for various engineering applications. In terms of structures, the differences include the following:\textsuperscript{12}

1. \textit{Hierarchy}. Biological materials with different organized scale levels (nano to macro) exhibit distinct and translatable properties from one level to the next. A systematic and quantitative understanding of this hierarchy could provide a new route to building more complex synthetic materials with desirable properties and functions.
2. \textit{Multi-functionality}. While many synthetic materials are designed for one function, most biological materials serve more than one purpose. For example, feathers provide flight capability, camouflage, and insulation, whereas the coating on moth eyes provides anti-reflection, self-cleaning, and protection functions.
3. \textit{Self-healing capability}. Unlike synthetic materials in which damage and failure occur in an irreversible manner, biological materials often have the capability to heal damage or injury because of the vascular systems embedded in the structure.
Evolution. Biological structures are not necessarily optimized for all properties but are the result of an evolutionary process leading to satisfactory and robust solutions. “Living” materials (e.g., bone) have evolved in response to their environments during their lifetime.

Environmental constraints. Biological materials are limited in the elements they are composed of (e.g., C, H, O, N, Fe, etc.) and the availability of these elements dictates the morphology, properties, and functions of the materials.

The differences in processing between biological materials and traditional engineering materials could include the following:

1. Self-assembly. In contrast to many synthetic processes, most biosystems assemble structures from the bottom up, rather than from the top down.

2. Mild synthesis conditions. The majority of biological materials are synthesized at ambient temperature and pressure as well as in an aqueous environment, a notable difference from synthetic materials fabrication.

3. Macromolecule-mediated processes. Most biological processes involve macromolecules as templates, transporters, and catalysts for templating, guiding, and catalyzing the nucleation and growth of biomaterials, especially biominerals.

Biomimetic materials science and engineering also contribute to economy. Some examples found in nature that are of commercial interest include self-cleaning materials, drag reduction in fluid flow, energy conversion and conservation, high and reversible adhesion, materials and fibers with high mechanical strength, biological self-assembly, and antireflection. The applications of these biomimetic materials could generate an enormous market for new products. It is estimated that activity in the field of innovation based on nature increased

<table>
<thead>
<tr>
<th>Materials</th>
<th>Biological materials</th>
<th>Engineering materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical compositions</td>
<td>Mostly earth-abundant elements: C, H, O, N, Ca, P, S, Si, etc.</td>
<td>Large variety of elements: Fe, Cr, Ni, Al, Si, C, N, O, etc.</td>
</tr>
<tr>
<td>Formation/fabrication</td>
<td>Growth by genetically guided self-assembly (approximate design)</td>
<td>Fabrication from melts, powders, solutions, etc. (exact design)</td>
</tr>
<tr>
<td>Processing</td>
<td>Ambient temperature, pressure, neutral pH</td>
<td>Involve high temperature, high pressure, strong acid/base</td>
</tr>
<tr>
<td>Microstructure</td>
<td>Hierarchical structures at all length scales</td>
<td>Mostly microstructures at single length scale</td>
</tr>
<tr>
<td>Functions</td>
<td>Adaption of form and structure to the function, multifunctionality</td>
<td>Selection of materials according to function</td>
</tr>
<tr>
<td>Design criteria</td>
<td>Modeling and remodeling capability of adaption to changing environmental conditions</td>
<td>Secure design (consider large safety factor)</td>
</tr>
<tr>
<td>Failure prevention</td>
<td>Healing: capability of self-healing</td>
<td>Component replacement</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Biodegradable</td>
<td>Biodegradable/ non-biodegradable</td>
</tr>
</tbody>
</table>
seven-fold from 2000 to 2013, and papers published around the field increased eight-fold. Between 2012 and 2013, biomimetic patent issuance increased by 27% and scholarly articles jumped by 28%. By 2030, bioinspiration will generate $425 billion of US GDP and $1.6 trillion of global GDP. Several universities have launched biomimicry disciplines and design courses, and biomimicry design challenges are also gaining popularity.

1.2.4 Classification of Biomimetic Materials

Materials science encompasses various classes of materials, each of which may constitute a separate field. Materials can be classified in several ways, for instance by the type of bonding between the atoms or functions. Traditionally, materials are grouped into ceramics, metals, polymers, and composites based on atomic structure and chemical composition. Although biomimetic materials can also be classified in a traditional way, it is more convenient to divide them into classes according to materials properties, as follows: (1) structural materials, (2) functional materials, and (3) process (or procedure). This book follows this classification for biomimetic materials. The typical biomimetic materials described in this book are summarized in Table 1.2.

Structural materials are materials whose primary purpose is to transmit or support a force. The key properties of materials related to bearing load are elastic modulus, yield strength, ultimate tensile strength, hardness, ductility, fracture toughness, fatigue, and creep resistance. Unlike traditional structural materials, biomimetic materials could simultaneously have high strength and high toughness. On the basis of nature’s design, for example gecko footpads with strong adhesion and controllable friction, biomimetic materials could be fabricated to have the ability to generate controllable friction and reversible adhesion. In addition, these materials could possess adaptive capabilities that could change their mechanical properties and/or self-shaping under external stimuli, or have self-healing capabilities that can recover their mechanical properties upon damaged.

Functional materials display particular native physical properties and functions of their own. There is a huge range of functional materials, including optical (e.g., structural color and antireflection), stimuli-responsive (e.g., electromechanical, photomechanical, mechanical induced and photomechanical materials), self-cleaning (wet, dry, and under water), catalytic (oxygen reduction, oxygen evolution, hydrogen evolution and artificial photosynthesis), tissue engineering materials, etc.

1.3 Strategies, Methods, and Approaches for the Biomimetic Design of Engineering Materials

Materials scientists and engineers usually take biological materials with remarkable properties or functions as a source of inspiration for the design of advanced engineering materials. While in most cases it is not possible to directly borrow solutions from living nature and to apply them in engineering, it is often possible to take biological systems as a starting point and a source of inspiration for engineering design. Biomimetic engineering materials do not result from the observations of natural structures alone but require a thorough investigation of structure–property relationships in biological materials, and the application of these relationships to engineering materials.
Table 1.2  Typical biomimetic materials, their prototypes, properties, and applications.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Properties/functions</th>
<th>Biological prototypes</th>
<th>Biomimetic materials</th>
<th>Potential applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural biomimetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>materials</td>
<td>Strength, toughness</td>
<td>Spider silk, abalone shell, bone</td>
<td>Strong and tough materials</td>
<td>Super-tough CNT yarns, tough ceramic composites</td>
</tr>
<tr>
<td>Hardness, wear resistance</td>
<td>Enamel, DEJ</td>
<td>Tough ceramic composites</td>
<td></td>
<td>Cutting tools, wear-resistant coatings</td>
</tr>
<tr>
<td>Impact</td>
<td>Horns, hoof</td>
<td>Damage-tolerant composites</td>
<td></td>
<td>Impact resistance</td>
</tr>
<tr>
<td>Adaptive (stiffness, shape)</td>
<td>Sea cucumber dermis, squid beak</td>
<td>Adaptive nanocomposites with reversible stiffness change capability</td>
<td></td>
<td>Self-shaping, morphing structures</td>
</tr>
<tr>
<td>Self-healing</td>
<td>Soft tissue, bone, plants</td>
<td>Self-healing composites, concretes</td>
<td></td>
<td>Self-healing composites, roads</td>
</tr>
<tr>
<td>Friction and adhesion</td>
<td>Gecko, tree frogs, pitcher plant, shark skin</td>
<td>Dry adhesive, low friction surface</td>
<td></td>
<td>Surface friction control, drag reduction</td>
</tr>
<tr>
<td>Functional biomimetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>materials</td>
<td>Stimuli-responsive</td>
<td>Muscle, nastic action, sun-tracking plants</td>
<td>Artificial muscle, smart materials</td>
<td>Actuator, control, sensing</td>
</tr>
<tr>
<td>Self-cleaning</td>
<td>Lotus leaf, gecko feet, pitcher plant, shark skin</td>
<td>Self-cleaning materials, anti-fouling coating</td>
<td></td>
<td>Self-cleaning and anti-fouling coating</td>
</tr>
<tr>
<td>Photonics</td>
<td>Beetle, butterfly, moth eye, feather</td>
<td>Structural color materials, anti-reflective materials</td>
<td></td>
<td>Monitoring, sensing, anti-reflectivity</td>
</tr>
<tr>
<td>Catalysis</td>
<td>Leaf, hydrogenase enzyme, blood cells</td>
<td>Catalyst for oxygen, hydrogen evolution, oxygen evolution</td>
<td>Fuel cells, metal–air batteries, water splitting</td>
<td></td>
</tr>
<tr>
<td>Biomimetic materials</td>
<td>Protein-mediated mineralization</td>
<td>Processing at ambient temperature and neutral pH</td>
<td>Formation of ceramic, metal nanoparticles</td>
<td></td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
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</tbody>
</table>
1.3.1 General Approaches for Biomimetic Engineering Materials

A successful biomimetic transfer of technology from nature to actual engineering materials can be broken down into four steps, as schematically shown in Figure 1.3. Each step must be brought to a reasonable level of completion to ensure a successful technology transfer.14

1. Identify a high-performance natural model. At this initial stage, the structure and function of biological systems are studied as prototypes for the design and engineering of materials and structures, but it is not always obvious which should serve as models for manmade designs. In fact, the most successful biomimetic designs have a similar function in nature and in the engineering application. To identify an appropriate model from a great variety of natural materials, one must keep in mind structure–performance–function relationships, in particular multifunctionality.

2. Abstract key mechanisms, structures, and design principles. At this stage, the principles and abstract ideas of natural phenomena and model systems are extracted. Mimicking is not copying. The intrinsic relationship between the features of natural materials and their attractive properties should be identified, understood, and abstracted from the natural model so they can be successfully implemented into engineering designs. However, this process is not always straightforward: natural materials are usually extremely complex and hierarchical over several length scales.

![Figure 1.3](image)

**Figure 1.3** From interesting observation to advanced engineering materials and devices. Examples of transfer routes. (a) From abalone shell to super-tough engineering ceramics.15,16 Source: Barthelat *et al.* (2007)15 and Launey *et al.* (2010).16 Reproduced with permission of Elsevier. (b) From butterfly to structural color-based flat panels. Source: Vukusic & Sambles (2003).15 Reproduced with permission of Nature Publishing.
3. **Transfer and design biomimetic materials structures.** The principles and abstract ideas of natural phenomena and model systems are applied to technical applications and design. This technology implementation includes the choice of proper synthetic materials for the biomimetic structures and often computer modeling is useful to determine and optimize the synthetic systems based on the biomimetic design principles.

4. **Fabricate and implement biomimetic materials.** Once the previous three steps are achieved to a reasonable degree, an actual biomimetic material can be fabricated. However, there is a reason that nature is always one step ahead: we often find that cost or resources limit our ability to exactly replicate nature’s efficiency. Nevertheless we are able to come close enough to produce some very interesting things.

As an example, scientists developed super-tough ceramics, drawing their inspiration from abalone shells, which are composed of 95% mineral calcium carbonate (CaCO₃), but are a thousand times tougher than their components. They followed the process delineated in Figure 1.3a. After recognizing the shell’s outstanding toughness, in step 2 above, the scientists took a closer look at the chemical compositions and structures at micro/nanoscale, learning how they integrate hierarchically. They uncovered how these different features in the shell interacted with one another to produce its unique toughness. This included looking at how the thin mineral layers pile up and the role of organic molecules in the mineral tablets, and how these hard and soft materials work together to resist brittle crack growth and increase energy assumption. This understanding of how the structure properties of shells work allowed the scientists to form a basis from which to design a synthetic version. It was the interplay of these complex structures that inspired the scientists to formulate super-tough ceramics. In step 3, synthetic ceramic (Al₂O₃) thin tablets and polymers were used to fabricate the brick-like structures. In the end, the scientists were able to develop biomimetic ceramics that leverage the super-tough and super-strong capabilities borrowed from the abalone shells.

Similar approaches have been taken for functional materials. Structural color butterfly wings are one example of a biological structural design that has been successfully transferred into products (Figure 1.3b). Brilliant iridescent coloring in male butterflies enables long-range conspecific communication and it has long been accepted that microstructures, rather than pigments, are responsible for this coloration. Although the final products are not a “material”, rather a structure (display), the principles used in creating high-performance electronic color displays are the same: actively varying the interspatial distances of light-interacting layers (e.g., for cell phones), which can change colors rapidly. These flat panels show vivid colors even under low-light conditions, and require less energy than other electronic display methods.

### 1.3.2 Special Approaches for Biomimetic Engineering Materials

In practice, the biomaterials (steps 1 and 2 in the previous section) and synthetic materials fabrication and characterization (steps 3 and 4) are usually done by biologists and materials scientists, respectively. A systematic approach of biomimetics is to store the biomimetic solutions, once they have been uncovered in the analysis of biological materials (steps 1 and 2), in large databases, from where they can be retrieved by engineers in search of technical solutions. Similar to the selection of engineering materials and processes, initial attempts have been made to establish a system into which all known biomimetic solutions can be
placed, classified in terms of function. Such tools would be extremely valuable for the development of bioinspired materials and processes. With the documentation, the biological mechanisms can be verified by following biomimetic manufacture and characterization. This will lead to an iterative process between biology and engineering in which the understanding gained from engineering may be fed back into biology. This mostly unexplored pathway offers the possibility that engineers can also contribute to biological sciences.

Finally, computational methods could play an important role in developing biomimetic materials. Biological materials usually have distinct hierarchical levels in their structure, which leads to an increased diversification in microstructures and multifunctionalities, and enhancement in material properties. A highly controllable assembly strategy can be applied using relatively simple building blocks to create complex structures. It is therefore possible to tailor functional materials to match relevant requirements by designing the hierarchical structures using the basic blocks. Computational techniques have been developed to allow us to simulate the material structures and properties at the length scale from nano to micro and macro scales. At each level of hierarchy, computational methods can be applied to simulate the structure–property relationship, while multiscale modeling approaches can be used to link the properties at the macroscale to the phenomena at the nanoscale, outlining an overall picture over whole levels of hierarchy. In addition, computational concept generation is an effective route to generate several conceptual design variants to optimize biomimetic structures. With computer-based design tools such as interactive evolutionary algorithms based on the de novo design concept in drag design, it is possible to carry out, based on biomimetic prototypes, a full search of the chemical space and fine optimization of biomimetic molecular structures with targeted properties/functions.

Bioinspired materials can also be designed for specific applications by fine tuning multiple design variables in materials synthesis and processing that pertain to the functional outcomes required. With the aid of computer design and simulation, such an approach would produce a more rationally directed design based on model predictions. More cost- and time-efficient design processes could be achieved by controlling structural features on multiple hierarchical levels via integrated computational modeling and processing in the early stages of the material design.

References


