Chapter 1
Introduction

Nature always tends to act in the simplest way—Bernoulli
(In nature,) nothing is lacking and nothing is superfluous—Leonardo da Vinci
Look deep into nature and you will understand everything—Albert Einstein

Biomimetics means mimicking biology or nature. Biomimetics allows biologically inspired design, adaptation, or derivation from nature. The word biomimetics was coined by polymath Otto Schmitt in 1957, who, in his doctoral research, developed a physical device that mimicked the electrical action of a nerve. Biomimetics is derived from the Greek word biomimesis. Other words used include bionics (coined in 1960 by Jack Steele of Wright-Patterson Air Force Base in Dayton, OH), biomimicry, and biognosis. The word biomimetics first appeared in Webster's dictionary in 1974 and is defined as "the study of the formation, structure or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones." The field of biomimetics is highly interdisciplinary. It involves the understanding of biological functions, structures, and principles of various objects found in nature by biologists, physicists, chemists, and material scientists and the biologically inspired design and fabrication of various materials and devices of commercial interest by engineers, material scientists, chemists, biologists, and others (Bhushan, 2009).

Nature has gone through evolution over the 3.8 billion years since life is estimated to have appeared on the Earth (Gordon, 1976). Biological materials are highly organized from the molecular to the nano-, micro-, and macroscales, often in a hierarchical manner with intricate nanoarchitecture that ultimately makes up a myriad of different functional elements (Alberts et al., 2008). Nature uses commonly found materials. Properties of materials and surfaces result from a complex interplay between surface structure and morphology and physical and

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chemical properties. Many materials, surfaces, and objects in general provide multifunctionality.

Biomimetics-inspired materials and surfaces are eco-friendly or green which have generated significant interest and are helping to shape green science and technology.

1.1 Lessons from Nature

The understanding of the functions provided by objects and processes found in nature can guide us to design and produce nanomaterials, nanodevices, and processes (Bhushan, 2009). There are a large number of objects, including bacteria, plants, land and aquatic animals, and seashells, with properties of commercial interest. Figure 1.1 provides an overview of various objects from nature and their selected functions (Bhushan, 2009). These include bacteria (Jones and Aizawa, 1991), plants (Koch et al., 2008, 2009), insects/spiders/lizards/frogs (Autumn et al., 2000; Gorb, 2001; Bhushan, 2007, 2010), aquatic animals (Bechert et al., 1997, 2000; Dean and Bhushan, 2010), birds (Jakab, 1990; Bechert et al., 2000), seashells/bones/teeth (Lowenstam and Weiner, 1989; Sarikaya and Aksay, 1995; Mann, 2001; Alexander and Diskin, 2004; Meyers et al., 2008), spiderweb (Jin and Kaplan, 2003; Bar-Cohen, 2011), moth-eye effect (Genzer and Efimenko, 2006; Mueller, 2008) and structure coloration (Parker, 2009), the fur and skin of polar bears (Stegmaier et al., 2009), and biological systems with self-healing capacity (Fratzl and Weinkamer, 2007; Nosonovsky and Bhushan, 2009) and sensory-aid devices (Barth et al., 2003; Bar-Cohen, 2011).

Figure 1.2 shows a montage of some examples from nature (Bhushan, 2009). Some leaves of water-repellent plants, such as *Nelumbo nucifera* (Lotus), are known to be superhydrophobic, self-cleaning, and antifouling due to hierarchical roughness (microbumps superimposed with a nanostructure) and the presence of a hydrophobic wax coating (Neinhuis and Barthlott, 1997; Barthlott and Neinhuis, 1997; Wagner et al., 2003; Burton and Bhushan, 2006; Bhushan and Jung, 2006, 2011; Bhushan, 2009, 2011; Koch et al., 2008, 2009). Water droplets on these surfaces readily sit on the apex of nanostructures because air bubbles fill in the valleys of the structure under the droplet. Therefore, these leaves exhibit considerable superhydrophobicity (Fig. 1.2a). Two strategies used for catching insects by plants for digestion are having sticky surfaces or sliding structures. As an example, for catching insects using sticky surfaces, the glands of the carnivorous plants of the genus *Pinguicula* (butterworts) and *Drosera* (sundew), shown in Fig. 1.2b, secrete adhesives and enzymes to trap and digest small insects, such as mosquitoes and fruit flies (Koch et al., 2009). Water striders (*Gerris remigis*) have the ability to stand and walk upon a water surface without getting wet (Fig. 1.2c). Even the impact of rain droplets with a size greater than the water strider's size does not immerse it in the water. Gao and Jiang (2004) showed that the special hierarchical structure of the water strider's legs, which are covered by large numbers of oriented tiny hairs (microsetae) with fine nanogrooves and covered with cuticle wax, makes the

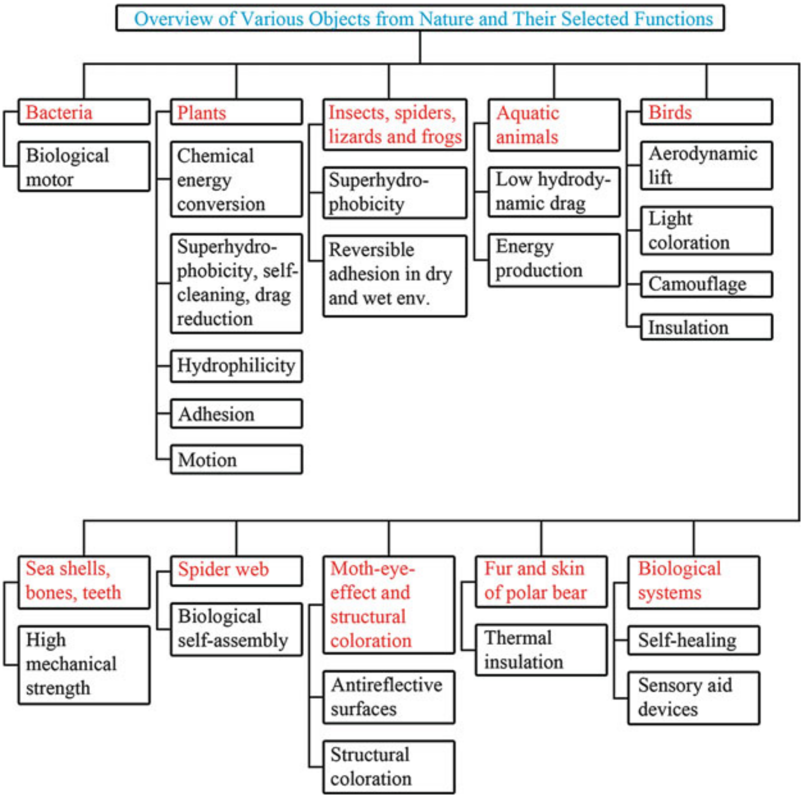

Fig. 1.1 An overview of various objects from nature and their selected function (Bhushan, 2009)

leg surfaces superhydrophobic, is responsible for the water resistance, and enables them to stand and walk quickly on the water surface.

A gecko is the largest animal that can produce high (dry) adhesion to support its weight with a high factor of safety. Gecko skin is comprised of a complex hierarchical structure of lamellae, setae, branches, and spatula (Autumn et al., 2000; Gao et al., 2005; Bhushan, 2007). The attachment pads on two feet of the Tokay gecko have an area of approximately 220 mm^2 (Fig. 1.2d). Approximately 3×10^6 setae on their toes that branch off into about three billion spatula on two feet can produce a clinging ability of approximately 20 N (vertical force required to pull a lizard down a nearly vertical (85°) surface) and allow them to climb vertical surfaces at speeds of over 1 m/s, with the capability to attach or detach their toes in milliseconds (Bhushan, 2007).

Shark skin, which is a model from nature for a low drag surface, is covered by very small individual tooth-like scales called dermal denticles (little skin teeth), ribbed with longitudinal grooves (aligned parallel to the local flow direction of the water). These grooved scales lift vortices to the tips of the scales, resulting

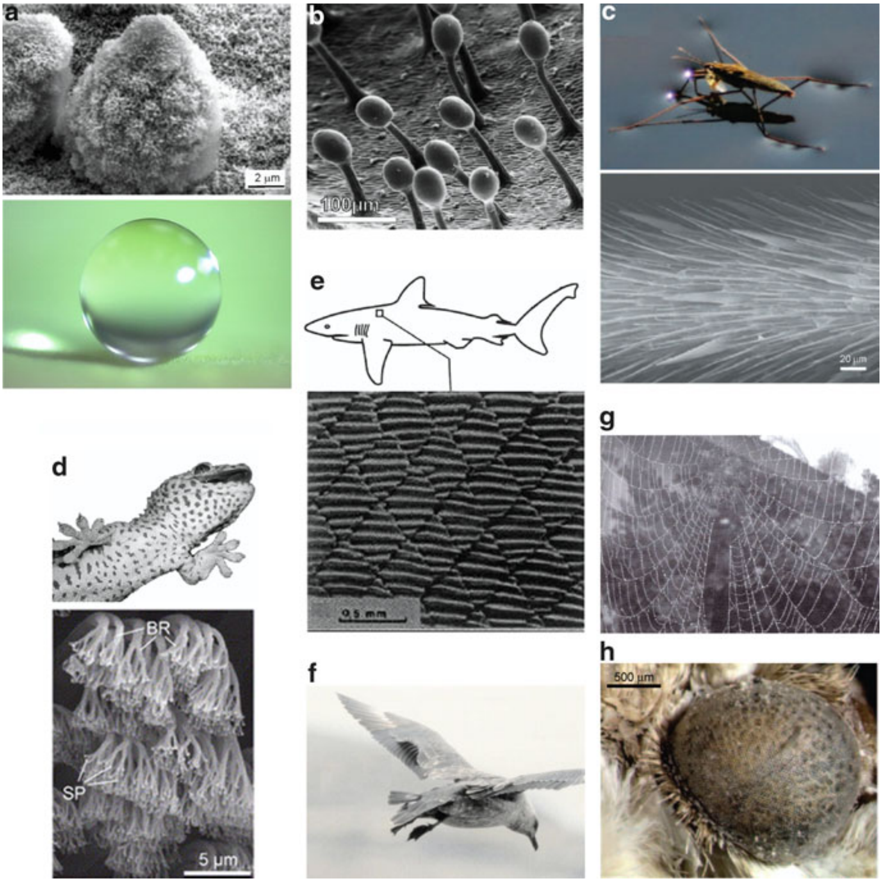

Fig. 1.2 Montage of some examples from nature (**a**) Lotus effect (Bhushan et al., 2009), (**b**) glands of carnivorous plant secrete adhesive to trap insects (Koch et al., 2009), (**c**) water strider walking on water (Gao and Jiang, 2004), (**d**) gecko foot exhibiting reversible adhesion (Gao et al., 2005), (**e**) scale structure of shark reducing drag (Jung and Bhushan, 2010), (**f**) wings of a bird in landing approach, (**g**) spiderweb made of silk material (Bar-Cohen, 2011), and (**h**) antireflective moth's eye (Genzer and Efimenko, 2006)

in water moving efficiently over their surface (Bechert et al., 2000; Dean and Bhushan, 2010). The spacing between these dermal denticles is such that microscopic aquatic organisms have difficulty adhering to the surface, making the skin surface antifouling (Carman et al., 2006; Genzer and Efimenko, 2006; Kesel and Liedert, 2007; Ralston and Swain, 2009; Bixler and Bhushan, 2012). An example of scale structure on the right front of a Galapagos shark (*Carcharhinus galapagensis*) is shown in Fig. 1.2e (Jung and Bhushan, 2010).

Birds consist of several consecutive rows of covering feathers on their wings, which are flexible (Fig. 1.2f). These movable flaps develop the lift. When a bird

Fig. 1.3 Biomimetics-inspired antique jewelry pieces crafted by Van Cleef and Arpels in early 1900s

lands, a few feathers are deployed in front of the leading edges of the wings, which help to reduce the drag on the wings.

The spider generates silk fiber and has a sufficient supply of raw material for its silk to span great distances (Jin and Kaplan, 2003; Bar-Cohen, 2011). Spiderweb is a structure built of a one-dimensional fiber (Fig. 1.2g). The fiber is very strong and continuous and is insoluble in water. The web can hold a significant amount of water droplets, and it is resistant to rain, wind, and sunlight (Sarikaya and Aksay, 1995; Bar-Cohen, 2011).

The eyes of moths are antireflective to visible light and consist of hundreds of hexagonally organized nanoscopic pillars, each approximately 200 nm in diameter and height, which result in a very low reflectance for visible light (Fig. 1.2h) (Genzer and Efimenko, 2006; Mueller, 2008). These nanostructures' optical surfaces make the eye surface nearly antireflective in any direction.

Scientists and engineers take inspiration from nature for the purpose of functionality and commercial applications. Artists take inspiration from nature for the purpose of beauty and design. Figure 1.3 shows four examples of bioinspired antique jewelry pieces crafted by Van Cleef and Arpels in the early 1900s.

1.2 Industrial Significance

The word biomimetics is relatively new; however, our ancestors looked to nature for inspiration and development of various materials and devices many centuries ago (Ball, 2002; Bar-Cohen, 2011; Vincent et al., 2006; Anonymous, 2007; Meyers et al., 2008). For example, the Chinese tried to make artificial silk some 3,000 years ago. Leonardo da Vinci, a genius of his time, studied how birds fly and proposed designs of flying machines. In the twentieth century, various products, including the design of aircraft, have been inspired by nature. Since the 1980s, the artificial intelligence and neural networks in information technology have been inspired by the desire to mimic the human brain. The existence of biocells and deoxyribonucleic acid (DNA) serves as a source of inspiration for nanotechnologists who hope to one day build self-assembled molecular-scale devices. In molecular biomimetics, proteins are being utilized in controlling materials formation in practical engineering toward self-assembled, hybrid, and functional materials structure (Grunwald et al., 2009; Tamerler and Sarikaya, 2009). Since the mid-1990s, the so-called Lotus effect has been used to develop a variety of surfaces for superhydrophobicity, self-cleaning, low adhesion, and drag reduction in fluid flow, as well as antifouling (Bhushan et al., 2009; Bhushan, 2011; Bhushan and Jung 2011). Replication of the dynamic climbing and peeling ability of geckos has been carried out to develop treads of wall-climbing robots (Cutkosky and Kim, 2009). Replication of shark skin has been used to develop moving objects with low drag, e.g., whole-body swimsuits (Dean and Bhushan, 2010). Nanoscale architecture used in nature for optical reflection and antireflection has been used to develop reflecting and antireflecting surfaces. In the field of biomimetic materials, there is an area of bioinspired ceramics based on sea shells and other biomimetic materials. Inspired by the fur of the polar bear, artificial furs and textiles have been developed. Self-healing of biological systems found in nature is of interest for self-repair. Biomimetics is also guiding in the development of sensory-aid devices.

Various features found in nature objects are on the nanoscale. The major emphasis on nanoscience and nanotechnology since early 1990s has provided a significant impetus in mimicking nature using nanofabrication techniques for commercial applications (Bhushan, 2010). Biomimetics has spurred interest across many disciplines. It is estimated that the 100 largest biomimetic products had generated US $1.5 billion over 2005–2008. The annual sales are expected to continue to increase dramatically.

1.3 Research Objective and Approach

The objective of biomimetics research is to develop biologically inspired materials and surfaces of commercial interest. The approach is threefold:

(1) Objects are selected from nature which provide functionality of commercial interest.

(2) The objects are characterized to understand how a natural object provides functionality. Then, it is modeled and structures are generally fabricated in the lab using nature's route to verify one's understanding. Modeling is used to develop optimum structures.
(3) Nature has a limited toolbox and uses rather basic materials and routine fabrication methods; it capitalizes on hierarchical structures. Once one understands how nature does it, one can then fabricate optimum structures using smart materials and fabrication techniques to provide functionality of interest.

1.4 Organization of the Book

This book primarily focuses on the Lotus Effect which exhibits superhydrophobicity, self-cleaning, and low adhesion/drag reduction, as well as antifouling. The book also includes the floating water fern which floats over water, rose petal effect which can provide either low adhesion or high adhesion, oleophobic/oleophilic surfaces inspired from aquatic animals, shark skin which exhibits low drag and antifouling, and gecko feet which exhibit reversible adhesion. We start with an introduction to roughness-induced superomniphobic surfaces and modeling of contact angle for a liquid in contact with a rough surface followed by the five topics just mentioned.

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