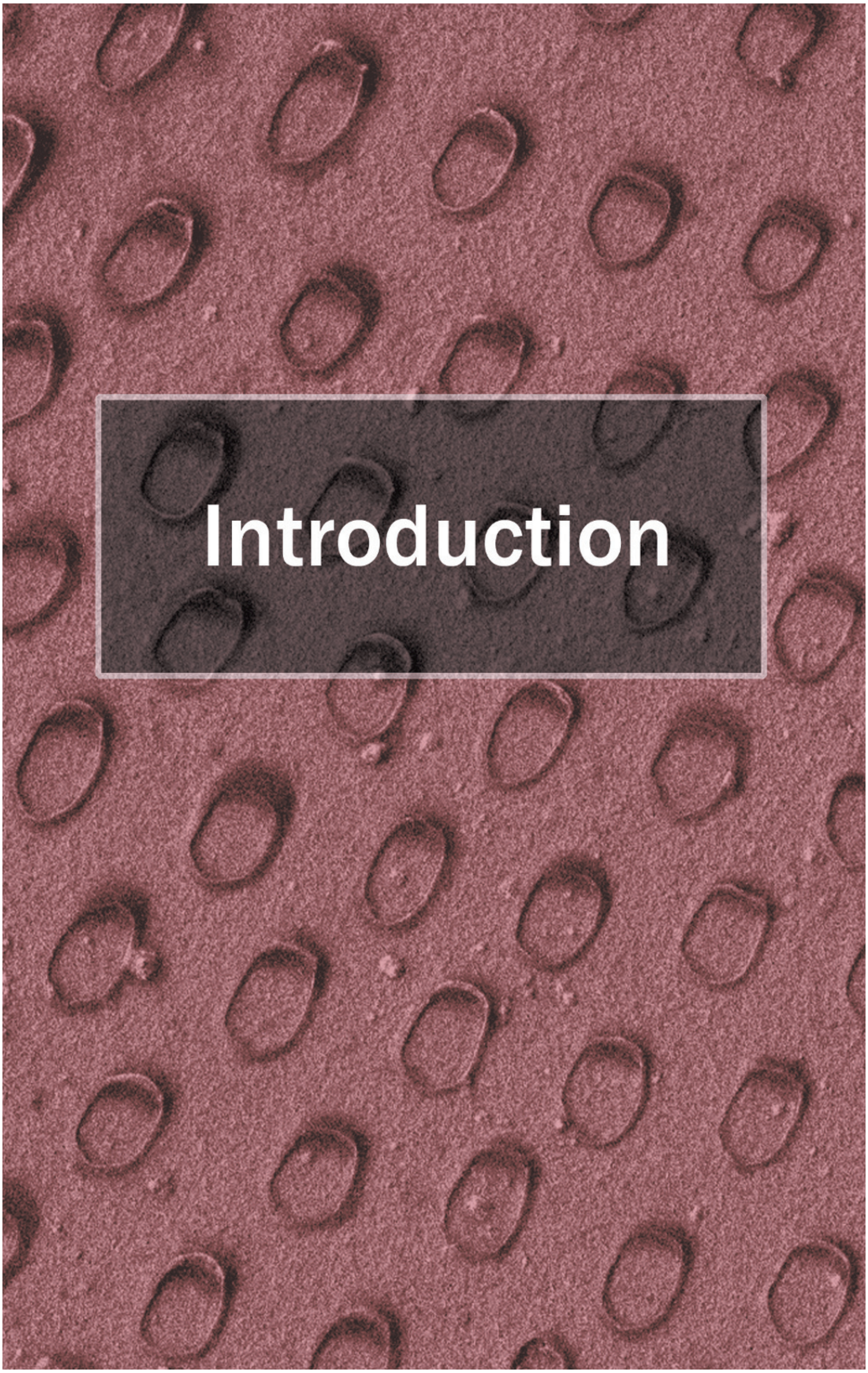
Introduction



Introduction: Surface Properties and their Functions in Biological Systems

Stanislav Gorb

Biological surfaces represent the interface between living organisms and the environment and serve many different functions. (1) They may delimit dimensions, often give the shape to organism, and provide mechanical stability to the body. (2) They are barriers against dry, wet, cold or hot environments. (3) They take part in respiration and in the transport of diverse secretions, and serve as a chemical reservoir for the storage of metabolic waste products. (4) A variety of specialised surface structures are parts of mechano- and chemoreceptors. (5) Optical properties may contribute to thermoregulation and the physical coloration pattern is often involved in diverse communication systems. (6) A number of specialised surface structures may serve a variety of other functions, such as air retention, food grinding, body cleaning, etc. (Gorb 2005).

The biological world is part of the physical world and, therefore, physical rules are also applicable to living systems. Living creatures move on land, in the air, and in water. There are complex motions inside their bodies to provide fluid circulation or to generate forces for locomotion. The resistance against motion mediated by surrounding media and by mechanical contact with various substrates was an evolutionary factor which contributed to the appearance of many surfaces adapted to reduce such resistance. On the other hand, some surfaces bear different mechanisms related to optics: reflection reduction, generation of colour due to a particular micro- and nanostructure pattern. Small surface structures at the micrometer and nanometer scales are often vitally important for a particular function or a set of diverse functions.

There are numerous publications describing biological surfaces using light and electron microscopy. Because of the structural and chemical complexity of biological surfaces, exact working mechanisms have been clarified only for some systems. Since all biological surfaces are multifunctional, it makes them even more interesting from the point of view of biomimetics. In the present volume, we discuss some functions of biological surfaces and their relationship with the structure. The volume is subdivided into the following topics: (1) Protection and defence (two chapters),

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(2) Anti-wetting (five chapters), (3) Transport (one chapter), (4) Aerodynamics (one chapter), (5) Acoustics (one chapter), (6) Sensory systems (one chapter), (7) Optics (four chapters).

This volume begins with a chapter by A. Kreitschitz on the variety of functions of the plant seed slime envelope. The envelope plays an essential role in seed dispersal and creates conditions suitable for germination (either stimulation or inhibition depending on environmental cues). By adhesion of the diaspore to the soil, it is protected from unwanted moves to unfavourable habitats. By anchoring the seed in substratum, it regulates its orientation and root penetration. Additionally, the slime envelope supplies the embryo and developing seedling with water and nutrients and defends it against viral or fungal pathogenic attack.

The defence function of the easily-broken, membranous cuticle of sawflies (Insecta, Hymenoptera) is discussed in Chapter 2 by J.-L. Boevé. The so-called "easy bleeding" phenomenon is the capability of the body surface of some tenthredinid larvae to be easily damaged. This defence strategy includes, in addition to micro-morphological characters of the surface, some behavioral, chemical, and physiological traits.

The section on anti-wetting and self cleaning is represented by five chapters devoted to various organisms and begins with the chapter by U. Hiller on the anti-wetting function of the reptilian skin. The author has studied gecko-skin that is covered by a pronounced keratinized uppermost layer, protecting the body from both extensive transcutaneous water loss and mechanical damage. Additionally, geckos possess micro-structured surfaces affecting its superhydrophobic and self-cleaning properties.

In Chapter 4, P. Perez-Goodwyn shows that, in the evolution of water bugs, different functional requirements have resulted in the appearance of structures adapted to either submersion resistance or waterproofing. In the case of waterproofing, large and stable setae at a relatively low density promote fast runoff of water. The submersion resistance function is fulfilled by long and thin setae or microtrichia in a compressible bubble, or by short, thin, densely packed microtrichia, as in the case of a plastron. An optimal compromise between these two extremes is a combination of long and stable setae and an underlying cover of thin microtrichia.

Spiders also bear hairy, water repellent surfaces described in Chapter 5 by G.E. Stratton and R.B. Suter. The authors show that water repellency not only varies widely among spider species, but also within an individual across its ventral topography, and that the support of respiratory and other functions (e.g., defence against pathogen intrusion) by hair-bearing cuticle is likely to have played an important role in the evolutionary history of spiders.

In plants, epicuticular wax crystals sometimes combined with trichomes or cuticular folds, also lead to the effect of water forming spherical droplets that bounce and roll off the surface even at the slightest inclination. This amazing water-repellency is caused by hydrophobic chemistry, together with a micro- and nanostructure of the plant's surfaces. Such a superhydrophobicity of plant surfaces correlates with their self-cleaning properties. Although self-cleaning properties of plants have already been described as Lotus-Effect (Barthlott and Neinhuis 1997) and even transferred from biological models to technical applications, the underlying physical principles of superhydrophobic surfaces are quite complex and offer another interesting application that has not yet been considered: water-repellent surfaces keeping air under water and even reducing drag in mobile objects. In Chapter 6, Z. Cerman, B.F. Striffler and W. Barthlott discuss the *Salvinia* plant as a possible model for technical submerged surfaces, and provide information about recent advances in the interpretation of physical and chemical basics of plant superhydrophobicity.

Some insects have developed a solution similar to plant wax crystal coverage. The particles (brochosomes) formed on the integument of leafhoppers from the family Cicadellidae create a superhydrophobic surface, apparently due to the complex fractal geometry of their surface at the micron-to-nanometer scale (Chapter 7 by R. Rakitov). These coatings serve multiple biological functions analogous to those of crystalline wax coatings of other insects and plants. At the same time, among several such functions hypothesized, only protection of the integument from wetting by water and the leafhoppers' own liquid excreta can explain the nearly universal occurrence of brochosomes in such a diverse leafhopper family as Cicadellidae.

Wetting phenomena are also of crucial importance for plant water supply. Surface microstructures are responsible for the functionality and integrity of water transport under tension. This transport mechanism allows for water flowing through the plant. The ultimate need for coping with bubbles and embolisms is of significance for the functionality of plant water-transporting structures, and was identified as a main driving force for xylem evolution (Sperry 2003). The interrelationship between xylem structure and water transport function is documented by the fact that the earliest tree, *Archaeopteris*, bears a xylem which is very similar to modern wood. It is very probable that the surface effects, described by A. Roth-Nebelsick in Chapter 8, were already at work in this ancient taxon. It is therefore to be expected that more surface-related adaptations can be found which are of biophysical relevance for maintaining the water flow.

Feathers have been an essential preadaptation of reptiles and ancient birds to the evolvement of the flight ability. Material properties and microstructure of feathers also in recent birds are responsible for aerodynamic activity of the feathers. The origin of feathers and their microstructures remained an unresolved question, which is discussed in details by L. Alibardi in Chapter 9.

An important general question about biological surfaces is the multifunctionality of surface microstructures and change of their functions due to small changes in the geometry. As it will be shown in the final section of the book, devoted to the optical effects, the scales of Lepidoptera are famous for specialized surface structures that interact with light to produce colour. Such scales occur in a variety of butterfly and moth species, and, like other scales and bristles of the arthropod cuticle, develop from a single epidermal cell (Ghiradella 1994). An unusual function of butterfly scales, namely the production of acoustic signals is reported for male moths of the Uraniidae family (Chapter 10 by A. Barro, M. Vater, M. Pérez and F. Coro). The sound emission organs of males in three *Urania* species are situated on the prothoracic legs and consist of two zones of specialized scales located on opposite sides of the coxa and the femur of each foreleg. On the external side of the coxa, opposite the femur, there is a peg which consists of a bundle of elongated scales that are hooked at the tip. In the proximal part of the femur, in front of the peg, there is a shallow concave surface, densely covered with scales that differ from scales on other parts of the femur (Lees 1992). The sound emission organ of *Urania* moths is discussed in the context of independently evolved lepidopteran sound producing surfaces that can be located on the legs, the wings, the thorax and the abdomen, including the genitalia.

Filiform hairs and their sockets on cerci of *Grillus bimaculatus* crickets are mechanically coupled to much smaller campaniform sensilla. Chapter 11 by R. Heußlein, H. Gras and W. Gnatzy demonstrates that strong deflection of the hair shaft parallel to the longitudinal axis of cercus causes tilting of the socket. Also, the sickle shaped area of thin cuticle around the large sockets of filiform hairs (with long hair shaft) is deformed for as long as the socket is deflected toward the cercus tip. The coupling of filiform hairs with campaniform sensilla creates a composite mechanoreceptor with an extended working range, with some limitations on the precision of directional and intensity coding.

Structural colours are the result of the interaction of light with physical structures, now generally termed photonic crystals, which are in the surface of a substratum. Such colours usually cause bright directional effects as opposed to chemical pigments, which scatter light diffusely. Structural coloration, due to the presence of scales and bristles, is well-known in insects, such as butterflies and beetles. The last section of the book consists of four chapters devoted to this topic. The most interesting type of structural coloration is so-called iridescence, which is well known in insects and birds, and has been characterized for many different species. Iridescence is a result of optical interference within multilayer structures, which are rather complex in their architecture and may be incorporated into systems that can produce several different optical effects. Such effects include diffraction-assisted reflection angle broadening, structural colour mixing and polarization effects. By describing specific structural colour examples in detail, within a general context of Lepidopteran microstructure classification, Chapter 12 by P. Vukusic presents an introduction to current work on photonics in these natural systems. Chapter 15 by A. Ingram provides an overview of numerous butterfly species showing a tremendous diversity of wing scale structures coupled to underlying photonic effects.

Another interesting optical property of surface structures has been described from the insect surface. Ommatidial gratings are anti-reflective structures on the eyes of insects, especially those which are nocturnally active. These protuberances are very small microtrichia (200 nm in diameter), which increase visual efficiency through decreased surface reflection in their density, and increased photon capture for a given stimulus condition (Chapter 13 by A. Parker). Such a grating is particularly useful on a curved corneal surface, as it would increase the transmission of incident light through the cornea, compared with a smooth surface.

Animal colors have, of course, a biological meaning other than taking an observer's fancy. Well-known biological functions for body colors are display and camouflage, both of which can be executed by pigment colors. Iridescent colors presumably always have a visual function, either to call the attention of conspecifics or to warn potential predators. Occasionally, the insect's eyes themselves are iridescent, due to multilayers in the facet lenses. Furthermore, insect eye surface structures employ various optical methods to improve visual functions. Chapter 14 by D. Stavenga reviews surface phenomena, not only from a purely optical viewpoint, but also considering their visual and biological functions.

Unfortunately, it was not possible to include all chapters on interesting surface structure-function effects in one volume. For this reason numerous contact mechanics effects related to friction and adhesion can be found in Volume 2: *Functional Surfaces in Biology: Adhesion Related Phenomena*.

The two volumes on *Functional Surfaces in Biology* taken together, present an overview of current research activities on functions in various biological surfaces. They provide a reference for a novice in the field. The chapters generally have an overview along with new research data. The volumes are also intended for use by researchers who are active, or intend to become active, in the field. The appeal of this topic is expected to be broad, ranging from classical biology, biomechanics and physics to surface engineering.

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