Chapter 1

Biomimetics of Skins

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The skin is the interface between an organism and its world. It has many functions, some of which are of current interest (e.g. superhydrophobicity, color, rheological effects). It is probably the most versatile of all organ systems, having mechano-sensory and skeletal functions as well, whose relative importance is different in different groups of animals. These functions can all be incorporated into our technology, contributing to the new area of bio-inspired design.

1. Introduction

Life is made possible by membranes. Part of their function is to provide a surface on or from which interactions and reactions can occur and be controlled, and part is to provide selective barriers to keep reactants together and the rest of the world out. These membranes can occur at any level within the hierarchy of the organism. Within the cell, certain organelles such as mitochondria, the endoplasmic reticulum, and the Golgi are made of, recycle, or produce, membranes. Then there are the membranes around the nucleus and around the cell itself. In plants, the hierarchy almost stops here, since all cells are surrounded by a stiff cell wall that, in various guises, supplies the skeletal structure of the entire plant. Size for size, plants are much simpler than animals, requiring only a tenth or a hundredth of the number of cell types.[1] In plants, the cells then form sheets and tubes which gain rigidity from internal pressure, commonly about 1 MPa; the forces so generated are largely resisted by the skin (epidermis) which is made of thick cell walls and is stiff. Whilst multicellular plants are relatively rigid and stationary, most animals are mobile, so the skin has to be compliant, either locally (hinges) or globally. Rigidity is selectively adaptive and supplied by muscular tissues; internal pressures are rarely more than 0.05 MPa. In all cases, both plant and animal,

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the skin is specialized not only as a covering but also as a selective barrier to passage in both directions of mechanical, physical, and chemical stimuli such as force, heat, water, and volatiles. Since this single layer has to perform many different functions, it is inevitable that there will be conflict between the various requirements. We make the assumption that in biology these conflicts have been largely resolved by evolution, and that we can benefit from the abstraction of concepts from these natural structures into a form that can be integrated into our own technology. This transfer of technologies is known as biomimetics (or, equally, biomimicry, bionics, bionique, bio-inspiration, bio-inspired design, biognosis, etc.). The variety of applications described in this book both underline the variety of functions in skins and demonstrates how concepts can be shifted from one context to another, thus solving design problems and increasing the effectiveness of our technology.

The definition of a problem as a conflict in design requirements, and the solution of the problem as the resolution of this conflict, has been pointed out several times, apparently first by the ancient Greeks. More recently, Genrich Altshuller used it in the development of one of the main components in his system of inventive problem solving ("TRIZ" — *Theoriya Resheniya Izobreatatel'skih Zadatch*) that he and others in Russia have developed as a design tool for engineering. His approach was to derive a set of standardized factors (weight, speed, ease of use, etc. — 39 in all) and to select from these, the properties that the problem definition would bring into conflict. Thus the problem is then defined as a pair of properties that are apparently mutually incompatible: for instance, if one parameter (e.g. strength) is improved it will probably compromise another (e.g. lightness). The properties are listed along orthogonal sides of a matrix (known as the "Contradiction Matrix") so that in the square where the two properties coincide is the solution for resolving the conflicts (known as "Inventive Principles" in TRIZ; there are about 40 of them). The Inventive Principles cover all possible manipulations of the system, context, and components under examination. The properties and the Inventive Principles were derived from successful patents and so represent a collection of best engineering practices.[2,3] Thus in comparing the resolutions provided from TRIZ with the resolutions to similar problems provided from biology, we are able to provide a measure of the similarity between technology and biology, and thus to test (a) whether the emerging study of biomimetics is likely to provide novel practical solutions to technical problems and (b) how those solutions can be expressed in a technical environment.[4] We can then express the various morphological and physiological mechanisms found in biology in the same way as Altshuller did with engineering — what is the novelty that the mechanism requires, and what is the adjustment that will deliver that novelty? In this way we have quantified adaptations as solved technical problems in the same way that inventive innovations in engineering can be defined in patents. There are differences. In very general terms, the similarity between biological and technological solutions to problems is only about 12%; biology solves problems in very different ways to ourselves. This may be an important insight, since it suggests that we are looking to biology for solutions to technical problems, we may quite frequently be looking in the wrong place since we have mis-identified the problem! More important for the development of our technology (which is presumably what biomimetics is about) is the realization that where technology uses energy as the main controlling parameter, especially in the processing of materials, biology uses the information from DNA embedded in those materials when they were synthesized (Fig. 1). In fact, living organisms rely very little on energy to solve technical problems, and it should be the *main* objective of biomimetics to show how we can similarly rid our technology of the energy requirement, thus giving us a more sustainable future on this planet.

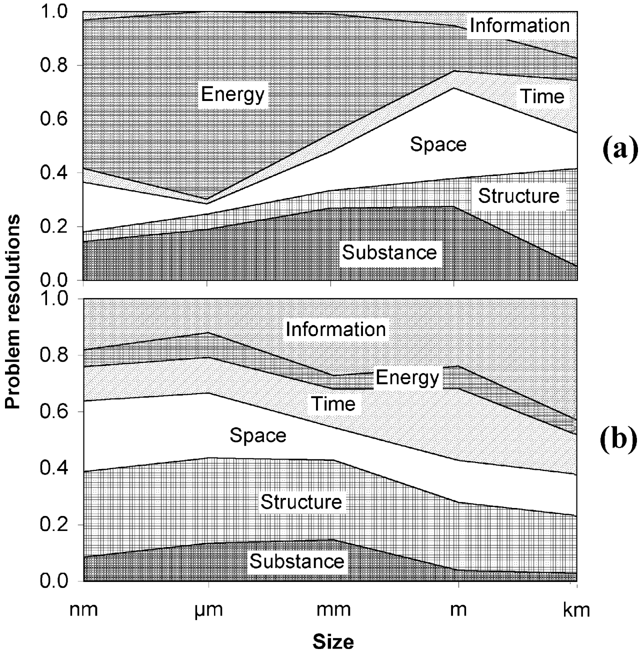

Fig. 1. These two graphs show the main factor which is changed in order to solve a problem over a range of size scales. For instance energy can be increased, decreased, the source can be changed, it can be localized or spread out, etc. The upper graph shows the way technology uses these factors while the lower graph shows how biology does it. Energy is not an important variable in biology; information (more or less ignored by technology) is paramount.[4]

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In a recent case study,[5] the conflicts inherent in the functional requirements (about 20 of them) of insect cuticle, a relatively simple but well-studied "skin," were defined and resolved using the TRIZ system. This showed that most of the functions of cuticle are provided by detailed control of properties over a very short distance at a chemical and morphological level, summarized by the Inventive Principle "Local Quality," a principle which is rarely used in technology. The manipulations which "Local Quality" suggests are:

- Change an object's structure, or its environment, from homo- to heterogeneous; use gradients instead of uniformity.
- Make each part of an object more adapted to its own purpose; compartmentalize.
- Make each part of an object fulfill a different function, e.g. pencil with eraser; hammer with nail-puller; Swiss army knife.

The other Principles most used by insect cuticle were "spheroidality," "flexible shell," and "composite material." These three are related to the skeletal function of the insect cuticle, being concerned with providing a good supportive structure that is strong and light.[6] But this reflects the predominance of skeletal functions in insect cuticle when it is compared with vertebrate skin (Fig. 2). None of these principles would be so commonly used in our technology, which tends to use a blunter, more global approach, the commonest resolution involving changing a parameter such as temperature or pressure. Thus the main outcome of this study was that biology and technology "solve" problems in design in very different ways, and that most of the functions of cuticle are provided by detailed control of properties over a very short distance. The only area where solutions seemed to be held in common were in the control of spectral response, both in the production of physical and pigmentary colors and the use of UV filters to protect underlying tissues.

2. Surface Hardening

These are examples of "Local Quality" in insect (arthropod) cuticle.

Wear resistance is required in the tips of ovipositors, claws, and mouth-parts of insects, all of them localized areas or layers. Most work has been on the mandibles of herbivorous insects. Wood, plant leaves, and seeds are commonly hard, either because they are dense and dry or because they are reinforced by silica or calcium oxalate monohydrate crystals.[7] The cuticle of the cutting and grinding surfaces of the mandibles of these insects (Fig. 3) is reinforced.[8,9] The Vicker's hardness of the cutting edge of dry mandibles compares to that of enamel and is about twice as high as that of the sheared face of the dry mandible and several times that of wet cuticle which has a hardness in the range of that of dentine. Studies on a number of insect orders (locusts,

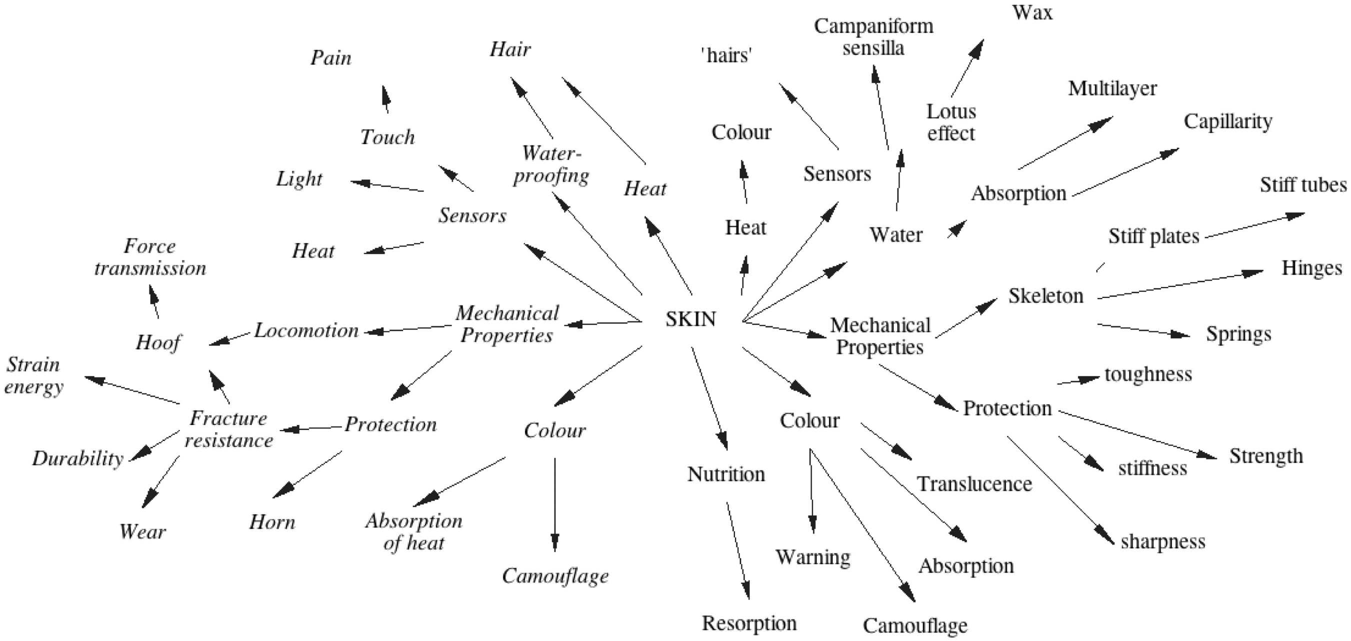

Fig. 2. The functions of skin (left, italic) and insect cuticle (right, roman). Not an accurate or detailed diagram, merely an indicator of relative importance of the various functions.

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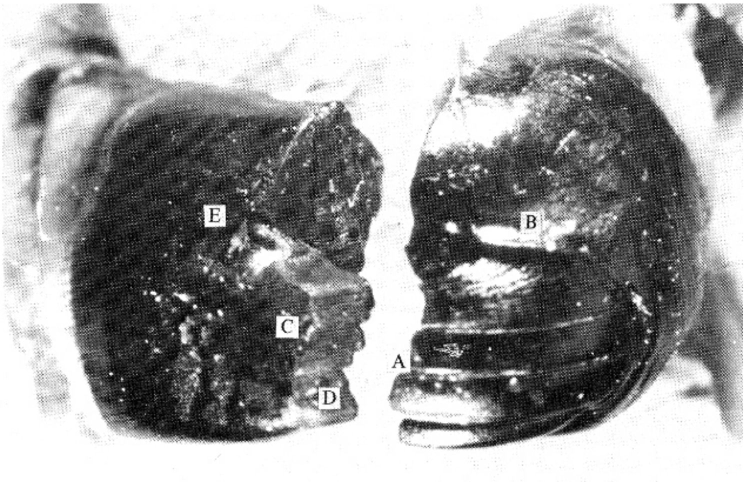

Fig. 3. Surface hardening of insect cuticle, showing how the hard outer surface (A) of the right mandible (B) of locust wears away (D) the soft outer surface (C) of the left mandible (E). The inner surfaces are soft and hard respectively, so the hard surfaces are continually being undercut, break away, and so leave a sharp edge (A), rather like the break-off blade of a hobby knife.[10]

stick-insects, butterflies, ants, wasps, and beetles)[10–12] revealed that the reinforcement against wear and tear is achieved by impregnating the hardened cuticle of the mandible with heavy metals (form unknown) such as Zn, Mn, or occasionally Fe. These metals are present in relatively large amounts ranging from a few percent to up to 16% of dry mass of the mandibular cutting edges and increase their hardness significantly, trebling it from about 25 to 80 $\mathrm{kgf\,mm^2}$.[9] How the incorporation of metals into the cuticle hardens and stiffens the cuticle is not yet understood, nor why metals are preferred to the more common mineralization with Ca-salts.

3. Strain Sensors

An external skeleton is a barrier to transmission of sensory information about the external environment. The resolution here is achieved by having holes through it (an Inventive Principle of "porosity"), although the holes have to be carefully designed if they are to give reliable information, be sensitive and not weaken the material (control of local quality again).

Insects strain sensors are basically oval holes in the cuticle with a domed bell shaped cap, hence called campaniform sensilla. These organs allow the animal to measure displacements in the plane of the cuticle, and they do it by introducing compliance due to the hole. The geometry and mechanical properties of the suspension cause the cap to move up and down as the hole changes its dimensions when the plate is stretched, compressed, bent or twisted. Thus the cap system rotates deformation in the plane of the plate through 90°, allowing the deformation to be detected out of the plane.[13,14] In insects the sensillum, together with its associated sensory and nerve cells, forms a simple yet sensitive mechanism[15,16] which is capable of detecting displacements of the order of a nanometer.[17] The plate in which the sensillum is formed can be anisotropic depending on the orientation of the chitin fibers and heterogeneous depending on the volume fractions of the components, degree of cross-linking of the matrix, etc. There is therefore, considerable freedom in the design parameters. In most arthropods (including insects and crustaceans) the sensillum hole is oval, so it can be "aimed" to pick up and amplify displacements in defined directions.[14,18,19] These organs are always placed in areas where the load is likely to be the greatest. These are also the places where the organ in which the load is being measured — the wing (Fig. 4) or the leg — seems most likely to break.[20] The animal seems to be weakening those areas that we would expect it would most want to strengthen. The design conflict seems to be met

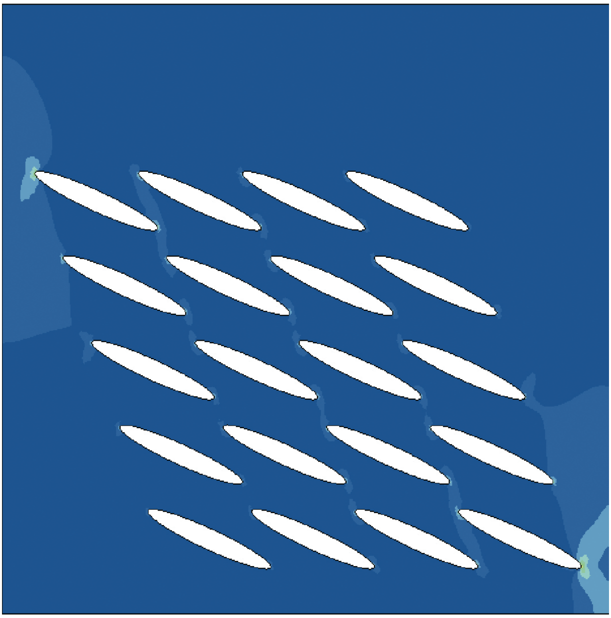

Fig. 4. Campaniform sensilla — a finite elements model of part of the array of sensilla at the base of the haltere (the balancing organ) of a fly. The oval holes are the sensilla and the only significant stress concentrations are top left and bottom right, indicated by a lighter shade of blue.

by two factors, neither of them yet adequately investigated. These are the orientation of the chitin fibers which reinforce the cuticle, and the clustering of the holes, which evens out the stress concentrations[21] or confines the stress concentrations to specific areas where a small amount of reinforcement associated with two holes at opposite corners of the array seems to be sufficient without compromising the performance of the remainder.[22] In spiders the strain sensors have a much higher aspect ratio and are called slit sensilla. They work on the same design principle, but also seem to be frequency analyzers, allowing the animal not only to detect vibration, as in a spider's web, but to differentiate the frequencies of vibration peripherally, and thus reduce the amount of neural processing of information. Once again, "local quality" is the main design consideration.

4. Water Repellence

One of the major surface effects of skins found over the last 20 or more years is related to the concept of superhydrophobicity. This has been reinforced by the development of self-cleaning surfaces based on the "Lotus effect" (Chap. 3 pp. 23 and 24). Such surfaces are found not only on leaves but on insect wings and, no doubt, will be found on many other surfaces. The concept is a product of two effects: a hydrophobic surface created by a layer of hydrocarbons, usually crystalline, and a rugose morphology of bumps at a spacing of about 10 μm. There is no indication how many times such surfaces have been evolved. However, research on these surfaces is not new.[25] At one end of the scale is lumpy surfaces that Chinese researchers have dubbed "nonsmooth" and are covered in small bumps or domes. The surface presented by the denticles on shark skin come into this category (Chap. 2, pp. 26–28). At the other end of the scale is the insect plastron, an arrangement of "hairs" (actually outgrowths of the cuticle, and so very different from mammalian hairs) a few micrometers long arranged at a density of 10^7 or more per cm^2.[29] The plastron is a well-researched system for repelling water, therefore keeping a thin layer of air next to the surface of the animal and providing an air–water interface at the tips of the hairs across which exchange of gases can occur (Fig. 5), thus giving the animal an aquatic gill.[30] This is not only a common adaptation of insects living on and around water, but is obviously also a technique for keeping the immediate skin of the animal dry and insulated.[31] Thus a plastron in the shape of a thick pile or pelage of hairs gives a waterproof surface, since water cannot penetrate between the hairs. In the way TRIZ is normally expressed, the conflict being resolved here is obviously that the animal is living beneath the water surface and yet it is breathing air — there is air yet there is no air! Such a conflict (categorized as "A and not A" where "A" is a thing, property or function) is called a "Physical Conflict." Classical (engineering) TRIZ does not indicate an equivalent in

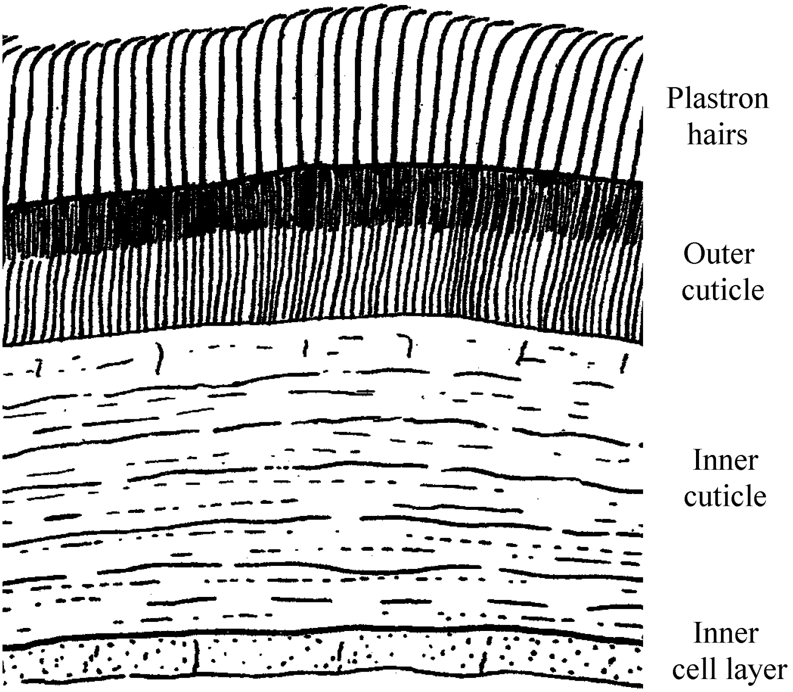

Fig. 5. A section through the plastron of Aphelocheirus showing the densely arranged hairs on the surface of the cuticle. Reproduced with permission from.[40]

technology, so this device is therefore a novel biomimetic solution. A textile similar to velvet has been developed by a sportswear company in the UK as a breathable and warm waterproof material for surfers to wear. It is very successful. The inventor did not realize he was reinventing the plastron, although he based his initial concepts on the waterproof pelage of seals and otters. Another technical version of the same concept is provided by the surface of an extremely water-repellent foam which mimics this mechanism and allows direct extraction of oxygen from aerated water[32] and so, presumably, the evaporation of water from the skin surface providing the equivalent of Goretex as a 3D material rather than a single sheet. Water-repellent surfaces are also being developed to make devices which can walk on water.[33] This is clearly a rich area for development.

The "non-smooth" surfaces found on the elytra of many soil-burrowing beetles have also been shown to be self-cleaning, but in a totally different way from the lotus effect. The mechanism appears to be due to the high local shear stresses developed at the top of the domes. Experiments showed that the main characteristic is simply the unevenness of the surface, which reduces friction against the soil by up to 40%. The morphology has been used in the design and development of new mould-boards on ploughs and new bulldozing plates in China[34,35] and has shown significant fuel savings. In TRIZ terms, the conflict is again physical — the surface should be there to contain the object or transmit the force, and should not be there in order to reduce the friction of plate and soil. The solution is separation in space — small contact areas (bumps) and air between them. An equivalent in engineering would be a ball or roller bearing, where two surfaces are held apart by rotating components with minimal contact area. Ultimately, of course, one would want a fluid bearing, which would be a plain bearing (filled with the fluid, oil) or an air bearing. An agricultural version might use something like a cartilaginous (e.g. knee) bearing which "weeps," producing a liquid (hyaluronic acid or synovial fluid) when it is under load.

5. Color

Coloration can be physical or chemical (pigmentary) or a combination, and biomimetic versions of the principles involved are contributing to textiles, plastics, and camouflage systems. There are several types of physical coloration, loosely classified as scattering (coherent and incoherent), diffraction, and interference. They can be produced by close-packed arrays of spheres or platelets, by surface lines, by layered materials with varying refractive index and responses to polarized light, and by 3D structures. The reflection of colors is probably the best known from the physics point of view, and was investigated by Newton. Biology has managed to produce systems which not only produce physical colors, but can do so over a much wider range of viewing angles.[36] The details of this form of color production are still unknown, but some of the mechanisms are used in textiles. In some scarab beetles the cuticle is made of structures which look like liquid crystals, mainly nematic and cholesteric. Of the incident light on the cuticle, the right circularly polarized component can be reflected and the left circularly polarized light can penetrate the helicoidally structured cuticle. However, at a certain depth there is a layer of nematic structure which acts as a half-wave plate, reversing the sense of polarization of the light, which is then reflected when it reaches the next layer of helicoidal structure, is reflected, has its sense reversed again by the nematic layer, and continues back out through the helicoidal cuticle with very little loss. The refractive index of the cuticle is increased by the addition of uric acid. Thus the cuticle is an almost perfect reflector, making the beetle appear the same green as its surroundings. This system will only work when the color and light intensity are the same in all directions.[37] In some cephalopods there is a very bright white reflection, which cannot be due to a mirror because there is no layer of silvering which could be the reflecting layer. Stacks of platelets in the iridophores contain reflectins, proteins rich in aromatic and sulfur-containing amino acids.[38] The photonic structures reflect light through alternating layers of high and low index materials, with the high-index layer comprising reflectins. The refractive index of recombinant reflectin was calculated to be 1.591 ± 0.002 which is the highest reported refractive index for a naturally occurring protein. These proteins self-assemble into a variety of structures. Another way of producing total reflection is a stack of platelets of different thicknesses. Each will refract light of a different wavelength, so reflecting the entire spectrum of colors as discrete wavebands. Since the platelets can be suspended in soft tissue such as skin, and the orientation and order (in terms of graded thickness) of the platelets is not important, this system produces a flexible mirror. It is common in "silvery" fish, where the platelets are made of guanine.[39]

TRIZ does not have much specifically to say about color and its generation or control, although the general trend within biology to control color by splitting it up into its components and manipulate each one separately is rather different to technical systems and can be much more effective. Once again biology maximizes the possibilities inherent in self-assembly systems and the production of small repeating structures.

6. Envoi

The rest of this book deals with a number of surface functions of skins that have been well researched in recent years, and I have touched on some of them above. But anyone should realize that not only is this a small selection of what skin can do, and what we can use for inspiration and innovation, but that the engineering environment into which we are transferring these functions may not be the ideal. In making the technological transfer, we strip away the uniqueness of biology since that is the only way the transfer is currently possible. Perhaps we should spend more time understanding how the function is generated and made adaptive and make that part of the biomimetics. I have the feeling biomimetic materials processing would be far more important than the functions which are currently being copied.

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