An Introduction to Bio-Inspired Design

Nature's inspiration may help scientists find solutions to technological, biomedical or industrial challenges.

By Pete Vukusic, PhD

The biological world is laden with examples of highly functional and adapted design. Across a breadth of different animal classes, evolutionary selection pressures have led to the production of protocols and functionalities with which animals and other biological systems may be advantaged in their interaction with each other and with their surroundings.

In most cases, such sophisticated designs are a fundamental component of the systems' biological compositions. In some cases, however, they are more easily discernable as specific identifiable features of the animal or biological system.

This latter category of natural design is progressively becoming the subject of mainstream academic and commercial research and development activity. Scientists and technologists are increasingly identifying optimal biological design solutions to specific natural circumstances in individual or in a range of animal or plant species.[1] Their intention is to seek inspiration from the natural world that might offer solutions to technological, biomedical or industrial challenges (Figure 1). This is the world of bio-inspiration.

Bio-inspired design, sometimes known as biomimetic design, has wide-ranging relevance. Many single specific biological design features, often identified and characterized by academic research, can be adapted to inspire scientists or applications engi-

Figure 1. Scientists are investigating biological systems for inspiration in technological and industrial problem-solving and design. Bio-inspiration, or biomimetics, is a rapidly growing field. Bio-inspired optical and photonic research, such as that involved in the characterization of structurally colored Lepidoptera (shown here), is particularly active.

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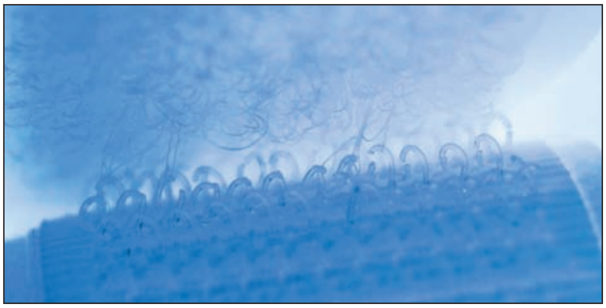

Figure 2. The hook and loop structure which underpins the adhesive nature of Velcro surfaces is a commonly seen example of bio-inspired design.

neers with the appropriate insight for exploitation and development in a technological, biomedical or industrial process or product.[2] One specific invention from recent technological history exemplifies this and is often used to publicize the practice of bio-inspiration. This invention is branded Velcro. The discovery of the mechanism that underpins the function of Velcro is attributed to a Swiss engineer, George de Mestral in 1941.[2] Returning after a walk in the Alps with his dog, he noticed the animal's fur had collected burdock plant seeds. Closer inspection revealed the seeds had a great many small hooks on the end of their protective spikes. These had bound the seeds tightly to the loops formed by the animal's hair. This simple observation led him to recognize the opportunity of binding two synthetic surfaces by fabricating an equivalent artificial system comprising hooks and loops that could be fixed to those surfaces. It required significant effort to determine and refine the compositional materials and manufacturing processes, but his invention was patented and its commercial production soon began (Figure 2). Velcro, the trademark coined from the French words for velvet, "velour", and hook, "crochet", found limited success until the aerospace industry adopted it and their use of it was publicized. Since then, it has fulfilled a range of functions for various domestic, scientific, industrial and military consumers for an array of very different applications.

Much more recently, studies of biology and the natural world have uncovered the potential for many other bio-inspired products. Among these is an adhesive tape invention, the function of which is underpinned by the principle by which geckos' feet adhere strongly to smooth surfaces. It has become known as Gecko Tape.[3] The impressive surface adhesion properties exhibited by geckos, lizards known for their extraordinary climbing ability, allow them to run quickly along most surfaces, even vertical ones, with the ability to release their foot adhesion in milliseconds. This function is far superior to many conventional pressure-sensitive adhesives that comprise soft viscoelastic polymers which degrade, foul, self-adhere and attach accidentally to inappropriate surfaces. The source of gecko surface adhesion relies on the presence of microscopic branch-like fibers that cover the undersides of their feet (Figure 3). These fibers, known as setae, comprise stiff spring-like hydrophobic keratin and are self-cleaning.[4] They offer an anisotropic frictional adhesion, which can be electrostatic or capillary in nature, and which rely on the presence of a directed shear load. This offers the capacity for rapid attachment and detachment and maintains performance for many months' of use, often in variable conditions.

Synthetic surfaces that have been designed to function in this way and which form the Gecko Tape in question are in early stages of development through the microfabrication of dense arrays of flexible plastic pillars, the geometry of which is optimized to ensure their collective adhesion. For certain niche applications, they will offer far more efficient and appropriate adhesion properties than conventional viscoelastic polymer-based adhesives. Furthermore, they can be very highly tailored for the specificity of their intended purpose.

Though faunal systems provide strong potential for bio-inspiration in technology, industry and biomedical fields, floral systems have also been shown to be a valuable source. One notable example is the leaf of the lotus plant, from the genus *Nelumbo nucifera* (Figure 4a). This leaf exhibits the property of super-hydrophobicity, referred to often as the Lotus Effect due to the plant leaves' very high water repellency.

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Figure 3. The lizard *G. gecko* with one foot adhering to a glass plate (foreground) and setal structures of its attachment organs (background). **[Scale bar: 10 µm (background image)]**

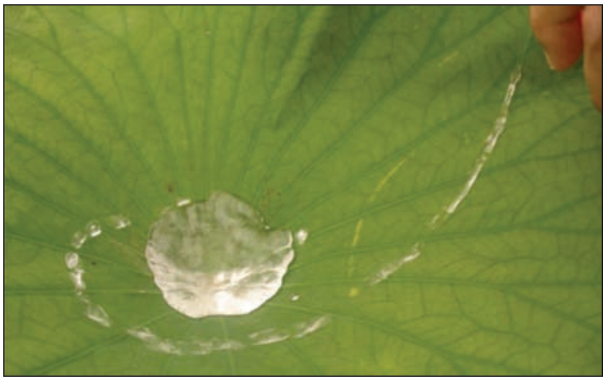

IMAGE COURTESY OF RALF PFEIFER

Figure 4a. Water rolls down the surface of this Lotus plant leaf (*Nelumbo nucifera*) due to its superhydrophobicity. As the water droplets roll across this surface, they accumulate particles of dirt and bacteria from the surface, thereby leaving the surface cleaner.

IMAGE COURTESY OF BASF

Figure 4b. Water droplets on a wood surface treated with BASF's "Lotus Spray," which makes the surface extremely water-repellant (superhydrophobic).

Synthetic mimics of the mechanism responsible for this effect have found application in biomedicine, large-area glazing and architectural coatings. The principle of high water repellency from the lotus leaf surface arises from the presence of surface roughness at two different length scales; micro-scale protuberances and nano-scale hair-like structures.[5] These are also coupled with the leaf's waxy chemical surface composition. Subsequently, when water (such as from a raindrop) falls on the leaf, it forms a very high contact angle that causes it to create a spherical bead. Such beads have less than 5% of their surface area in contact with the surface of a leaf and, together with the effect of the air trapped between the raindrop and the leaf's micro- and nano-structures, they are free to roll across the leaf's surface when the leaf is tilted. This results in the collection and removal of dirt and bacteria from the leaf's surface as multiple droplets roll across its surface. The lotus leaves' superhydrophobicity thereby leads to a natural process of self-cleaning.[6,7]

When this effect is used as the basis for technological or biomedical applications, it serves alternate niche functions. Aerosol-based architectural spray coatings, developed and distributed by BASF (Figure 4b), have been formulated to create an exterior wall that is water repellent and subsequently relatively self-cleaning. Equally, the external glass surfaces of some large area exterior displays have been textured appropriately to produce a self-cleaning function through analogous lotus leaf effects. With products such as glass-fronted solar cell panels, appropriately designed microscale and nanoscale texture required to enhance a dirt-free surface may also have the effect, concurrently, of enhancing multi-angle optical transmission through the glass to improve solar-cell efficiency.[8,9] This is a dual purpose bio-inspired pair of applications.

The lotus leaf effect also inspired a biomedical application developed by the Instrument Technology Research Center of the National Applied Research Laboratories of Taiwan in the form of a liquid-drop centering function within an intra-chip diagnosis unit. The incorporation of a concentric series of progressively changing micro-textured regions provides the facility with which blood, plasma, medication or other fluid may be spatially positioned forexamination or treatment in automatic analysis processes.

Another equally revolutionary bio-inspired product arose from the study of Arctic species of fish. They exist in sea-water at temperatures that are below zero Celsius. To prevent the water within their own systems from forming ice crystals, such animals have evolved specialized proteins in their own blood that are referred to as ice-structuring proteins (ISPs).[10] These proteins inhibit the formation of ice crystals from pure water in temperatures at which water would normally freeze. Unilever scientists have harvested the analog of this polar fish ISP from specially processed yeast and are developing it for use in some of their commercially marketed ice cream products to improve its transportability and texture.

The practice of designing and developing applications for optical functions through bio-inspiration has gained considerable momentum in the last decade. This arose from the realization that biological systems have evolved distinctive advantageous methods to manipulate the propagation of light and color. The rapid growth of the field of technological photonics from the early 1990s emphatically helped to establish an awareness and appreciation of the nature and extent of the photonics-based designs that are to be found among biological systems.[11]

The field of photonics is founded on the principles by which electromagnetic radiation may be manipulated strongly when it interacts with periodic variations in refractive index. Simple systems, such as grooves on a compact disc or antireflection coatings on spectacle lenses, are unsophisticated examples of this. In these examples, spectral colors are observed due to the diffractive effect of compact discs' grooves, while colored reflection is observed from lenses due to interference in their multilayer coating. This form of color generation is distinctly different from that produced by light absorption in pigments or dyes. The latter is produced by chromophores; these are pigments which selectively absorb some wavelengths while scattering others. Photonic systems, conversely, manipulate light directly by coherent scattering.[12] This allows some bands of wavelength to propagate through the system in question while preventing others. Those bands that are inhibited from propagating are reflected, creating or contributing to the system's colored appearance. Common examples of this are the blue feathers on a peacock, or the silver scales on some fish.

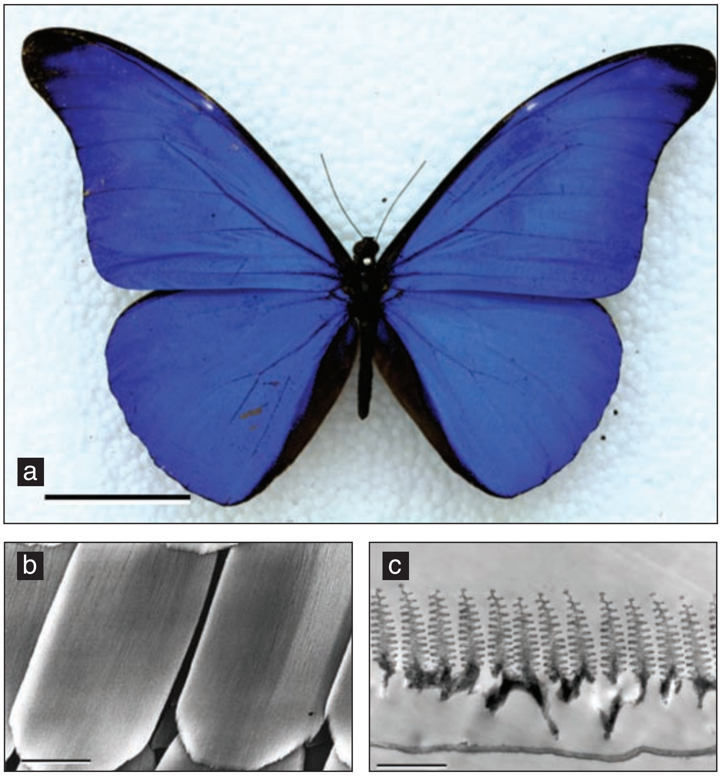

Figure 5. The highly conspicuous blue-colored appearance of Morpho butterflies (M. rhetenor pictured here) arises due to coherent scattering of light within periodic nano- and micron-sized features on and within the creatures' wing scales. This form of color production offers much more control over the flow of light and color associated with its appearance and patterning. Scanning and transmission electron microscopy images are shown in b) of two neighboring wing scales and c) a small cross-sectional region through one wing scale.
[Scale bars: a)1.5 cm b) 50 μm and c) 1 μm]

In certain animal and plant species, photonic-based colored appearances, namely those associated with the presence of arrays of periodic micro- and nano-structure, are very highly evolved. They offer the host animal or plant distinct selection advantages in aspects of intraspecific communication, crypsis from or for predation, light collection and in enhancing the working function of visual systems.[11] Many of these systems have been very well investigated and characterized.[13] Among these are the systems responsible for the brilliant blue iridescent color of *Morpho* butterflies (Figure 5a); the highly reflective colored feathers of some hummingbird feathers; the ultra-bright whiteness of certain beetle scales; the calcitic microlensing that adorns the tentacles of some brittlestars and the extremely efficient fluorescent scales that cover some *Papilio* butterflies. The physical mechanisms underpinning highly efficient light collection in biological systems, many associated with those of animal eyes, also have been the subject of detailed study. Many different and distinctive naturally evolved designs for manipulating light and color have been discovered in the course of these studies. Their common theme is frequently the degree to which they have been optimized for their various intended purposes. Since their discoveries, their designs have inspired and continue to inspire specific optical, photonic, biomedical, industrial and more general appearance-related applications.

Take, for instance, the bright iridescent color of *Morpho* butterflies (Figure 5a). Several detailed investigations revealed that their intense hues and remarkable conspicuousness is the result of a discretized series of highly layered coherent scattering structures that cover the scales which imbricate their wings (Figure 5b). The nature of the layered structure and the ridging into which it is distributed (Figure 5c) produces not only bright iridescence, but concurrently enhances the creature's angular visibility.[14] This angular visibility is enhanced still further in some other *Morpho* species by the presence of an additional layer of surface scales that cover those which brightly reflect blue wavelengths. These surface scales' ridges act as efficient diffracting elements that serve to broaden their reflected light cone still further in angle. They render a much more diffuse appearance to the entire wing.[14]

Significant efforts have been directed toward understanding the scale structure photonic protocols in *Morpho* and other butterflies. The results of some of these have been used to inspire the design of successful commercial products. Two of these, especially, are prominent in the field of bio-inspired optics. MorphoTex is a high-end fashion fabric, whose fibers' design is attributed to inspiration from the *Morpho* butterfly. It was designed and is marketed by the Teijin Corporation of Japan. MorphoTex fibers comprise a particularly ingenious periodic variation in the refractive index of their interior, which in turn gives them an iridescent color effect. When they are woven together, this structural color dominates the appearance-aesthetic of the whole fabric and offers an additional self-cleaning property that is modeled on the lotus leaf effect.

The design of cosmetics has taken similar inspiration from *Morpho* and other butterflies. L'Oreal, in particular, has led bio-optics inspiration in the cosmetics industry. By mimicking the way in which light and color are manipulated in *Morpho* butterfly scales and in other structurally colored natural systems, but using inert synthetic materials to form a series of periodic micro and nanostructures, L'Oreal has brought about a revolutionary and successful advance in the aesthetic of this brand of their cosmetic products after development of a naturally inspired design (Figure 6).

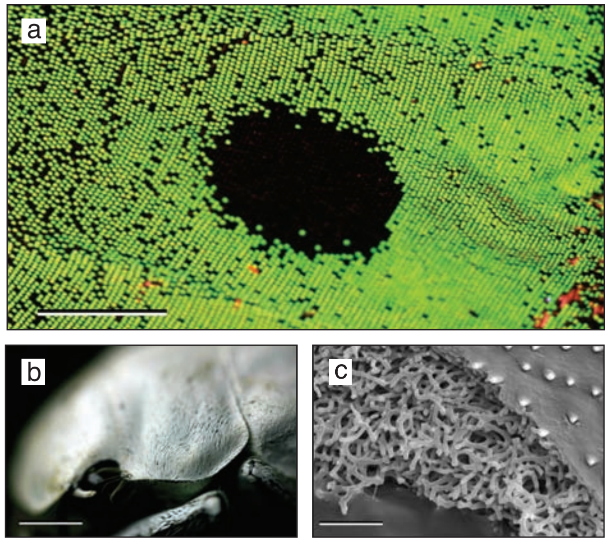

Figure 7. Black- and white-colored surfaces can form extremely important components of biological appearance in many animals such as in a) the ultra-black wing-spot region on a lepidopteran wing or b) on a brilliant white beetle's surface. In each case, there is a structural component that optimizes the efficiency of the optical scattering process. The scanning electron micrograph in c) shows a broken section of one of the white scales that cover the body and legs of the *Cyphochilus* beetle shown in b). The size and spatial distribution of the random network of cuticular filaments is the design key to such optimal whiteness. [Scale bars: a) 1.5 mm; b) 2 mm and c) 1 μm]

IMAGE COURTESY OF L'OREAL

Figure 6. L'Oreal has used inspiration from biological photonic systems to design their series of photonic-based cosmetics that are marketed in Lancôme's LUCI range of products.

It is not just bright optically saturated colored biological systems which have inspired technology. Both black and white biological surfaces have generated valuable understanding in relation to the variables critical for consideration when designing equivalent surfaces in technology. Studies of ultra-black wing-scale regions in Lepidoptera have (Figure 7a) revealed the importance of a photonic component to enhance the optimal absorption of incident light and create a deep black appearance.[15] This discovery has been inspiring the development of high efficiency photovoltaic cells for the energy industry, in which the quality of the cell's photon-absorbing semiconductor surface is critical for its wavelength-dependent and angle-dependent light collection efficiency.

For other applications, highly scattering surfaces are of enormous commercial value. Recently, a study of the brilliant whiteness from ultrathin beetle scales offered important insight to the understanding of how white surfaces may be made very thin while still achieving their diffuse broadband and high intensity scattering character. The photonics-based study of the *Cyphochilus* beetle (Figure 7b) revealed the potential for bio-inspiration in synthetic objects and systems that require a white appearance. The study revealed that the beetle's evolved structure comprises a randomly arranged interconnected series of protein-based nanofilaments, packed together with a carefully controlled spacing, or packing fraction, between them (Figure 7c).[16] It is the control of this packing fraction within a very limited scale thickness that creates the optimal light scattering conditions observed in the *Cyphochilus*' brilliant white visual appearance. This natural evolved design feature has inspired the development of optimization principles for the industrial processes involved in the manufacture of white paper.[17]

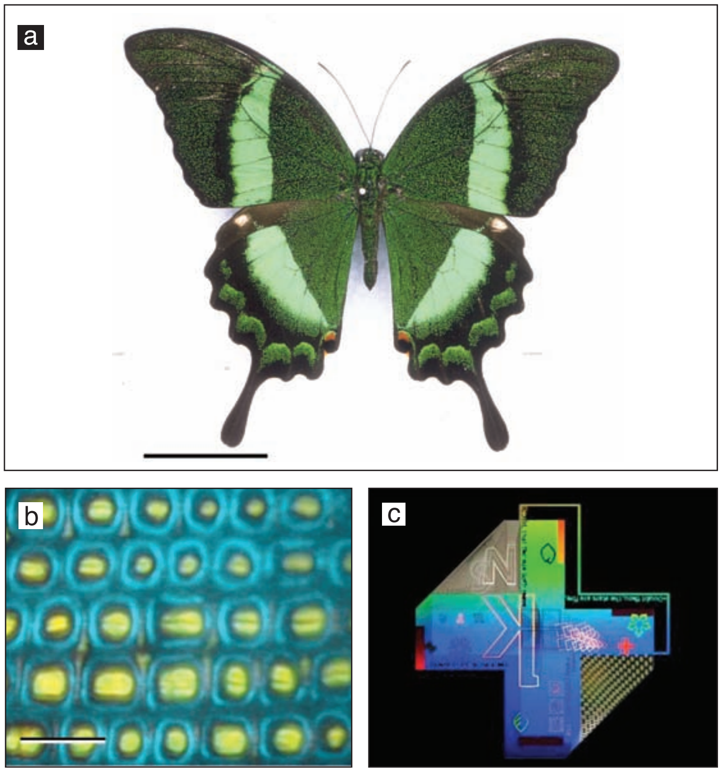

Figure 8. The bright green wing color of Papilio palinurus in (a) is the result of additive color mixing arising from microscopic juxtaposed color centers that simultaneously reflect structural colors, yellow and blue (shown in b), from the same single photonic nano-structure. The appearance not only comprises complex color-mixing processes but is also strongly linearly polarized. Such features can be used as the basis for advanced anticounterfeiting logos in currency, such as the OVD Kinegram featured in (c). [Scale bars: a) 2 cm; b) 8 μm]

The visual appearances of many animal species concurrently comprise optical features that are overtly conspicuous to human vision and those that are covertly concealed beyond human visual sensitivity. This has led directly to associated bio-inspiration in anticounterfeiting applications. Much of the commercial development work in this area remains highly secretive, significantly more so than the details associated with the majority of all other commercially valuable intellectual property rights involving bio-inspired applications. Despite this, however, patent searches can reveal some information. One specific bio-inspired anticounterfeiting logo design, for intended use in forms of currency, is based on the photonic nanostructure responsible for the visual appearance of a *Papilio* butterfly. *Papilio palinurus* is green to human vision (Figure 8a), but its wing scales comprise micron-sized regions of juxtaposed yellow and blue color centers, both of which arise from the same multilayer concavity array profile.[18] Human vision cannot resolve such small individual color center regions, so additive mixing processes create the appearance of an entirely green wing. In a synthetically fabricated analog, this effect would function as an overt security feature, discernable by magnifying a small region of wing. The additional potential for a concurrent covert security feature arises due to the nature of the reflection of one of the two individual colors (Figure 8b). The blue color center components, only, result from a double reflection of incident light from the inclined sides of each multilayer concavity structure. This has the effect of strongly linearly polarizing the blue reflection and provides it with a property that is absent from the reflected yellow component. Appropriate lab-based illumination and imaging of the wing surface, using polarization-sensitive apparatus reveals a stark optical appearance difference, mimicking the manner in which this species interacts with conspecifics. It provides a visually clandestine communication channel that is believed to form the evolutionary purpose of the animal's photonic structure. For anticounterfeiting purposes, synthetic structural variations on a theme of this biological system offer distinct allure and are currently under development for currency-related applications (Figure 8c).[19]

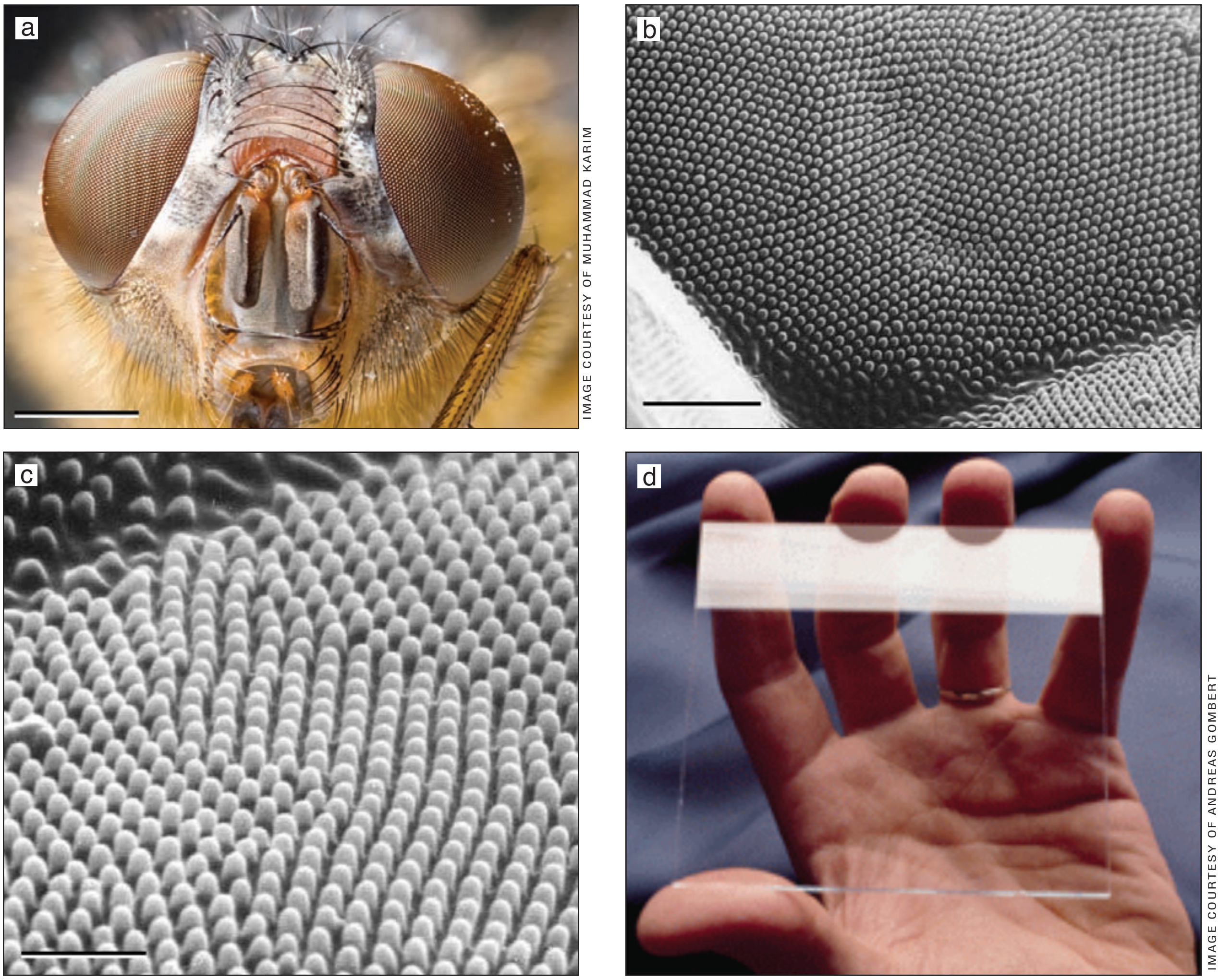

Figure 9. Animal visual systems are highly adapted and can offer inspiration for technological designs. The image of *Calliphora* sp. in (a) shows its highly complex compound eyes, the surface of one corner of one ommatidium of which is represented by the scanning electron micrograph in (b). Both images in (b) and (c) feature the sub-wavelength anti-reflective structural elements that have evolved to enhance the function of its visual system. These forms of surface geometric patterning have been applied to antireflection in glass by sol-gel methods; in (d) the handheld glass pane has a porous sol-gel anti-reflection coating in its lower section, but this coating is absent in the section nearer the upper edge. [Scale bars: a) 2 mm; b) 5 μm and c) 1 μm]

Animal visual systems can be just as highly adapted and precisely functional as the systems which dictate animal appearances. They have similarly been the subject of a very wide range of detailed investigations, offering equivalent series of concepts and inspirational designs for scientific and commercial applications.

An outstanding example of this relates to the discovery of the reflecting superposition eye of lobsters. These animals' eyes comprise arrays of channels arranged in such a manner that light from a wide range of angles is focused onto specific receptor regions.[20] This enables these eyes to collect photons from an extremely wide range of angles, in this way presenting the animal with a view of virtually the whole hemisphere above it. X-ray astronomers recognized the value of an image-capture device design that offered such a large field of view.[21] It inspired them to design and develop a device that operated in a wholly analogous manner to the lobster system that enabled them to capture x-ray astronomical information from up to 1000 square degrees of space at once, rather than from only a few square degrees as with previous conventional imaging devices. Work is also under way to use the 'lobster eye lenses' as a collimator, for producing a parallel beam from an x-ray source. This could provide a relatively inexpensive basis for x-ray lithography, which is a prerequisite for forming microcircuits with sub-micrometer dimensions.[22]

In insect eyes (Figure 9a), a distinct surface nanostructural feature was discovered and investigated. Its potential for bio-inspired applications has only recently begun to be appreciated. The ommatidial surfaces of the majority of insect compound eyes are adorned with a regular sub-wavelength nanostructure in the form of a two-dimensional array of surface protuberances (Figure 9b and c). Investigations have shown that this nanostructure serves the function of an impedance-matching mechanism,[23] gradually changing the optical impedance of air to that of the ommatidial material itself. This has the effect of improving the transparency of this surface by significantly reducing the intensity of light that it reflects, thereby optimising the eyes' overall optical collection efficiency. Engineers of the protective coverings on solar cells and architects designing buildings incorporating large glazed openings for maximum lighting function, have been working toward implementation of this biological principle. It is the performance of the insect eye surface array design, based on its highly evolved shape and distribution, which inspires its synthetic analogue in these very different technologies.

Evolutionary processes have brought the biological world to its current position. The present form and function of all animals and plants is the result, to date, of such natural processes. They have been in progress from when life on Earth began. For the scientist and engineer, these processes can be considered as the analogues of research and development processes in science, medicine and technology.[2] To exploit or use valid inspiration from these many millions of years of natural research and development is both good product design practice and good business sense. **CLS**

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