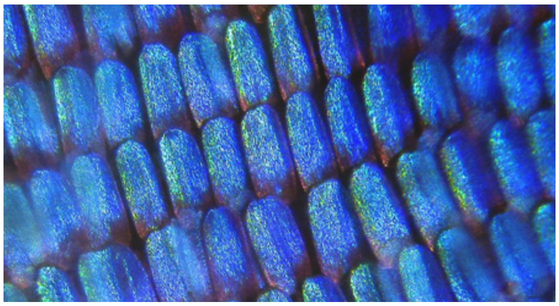
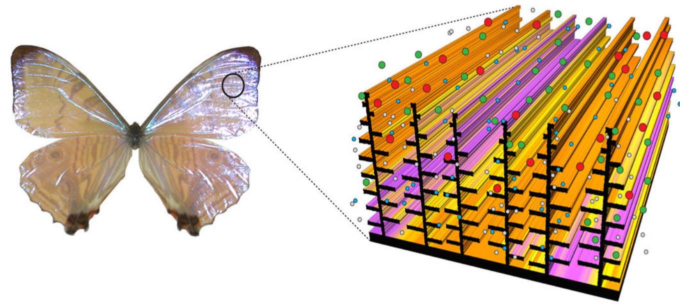
BIOMIMICRY AND PHOTONICS

Organisms employ an array of strategies to generate, detect, absorb, scatter, and otherwise process light. Researchers in optics and photonics are studying these strategies and increasingly use them as blueprints in the development of advanced sensing and imaging devices.

BUTTERFLY WINGS INSPIRE ADVANCED SENSOR TECHNOLOGIES





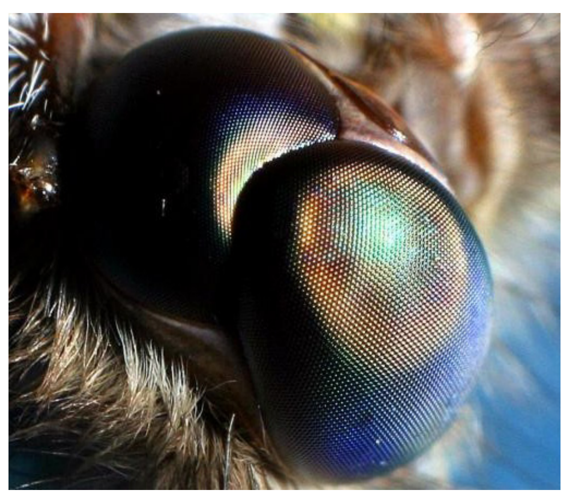
The wings of *Morpho* butterflies produce bright, vibrant, iridescent colors when light interacts with the micro- and nanoscale architecture of the wing scales. Each scale is made of chitin—an abundant biopolymer—and supports an array of minute parallel ridges. In cross-section, each individual ridge shows a periodic nano-scale structure consisting of vertical and horizontal struts, resembling the shape of a tree. The iridescence of the *Morpho* wings is produced by interference of light on the horizontal sections and by light diffraction on the vertical portions.

New research on the color of *Morpho* wings at GE Global Research has determined that the scales also have an optical response to changes in thermal energy. Absorption of infrared (IR) radiation and the subsequent conversion to thermal energy by the chitin results in an expansion of the nanostructure; this morphological change produces an observable change in the wing's iridescence.

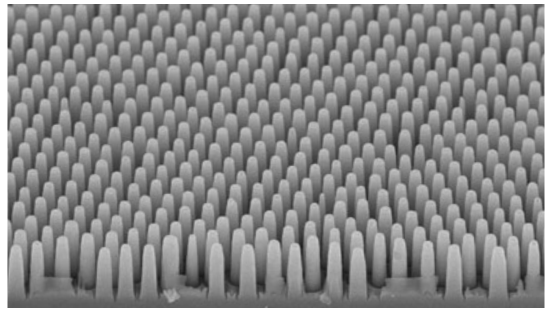
The speed and sensitivity with which the layered wing scales react to IR photons were previously unattainable in manufactured sensors. Scientists are now developing thermal sensors based on the nanoscale structure of *Morpho* wings to improve not only response speed and thermal sensitivity but also to reduce the pixel size. Studies are also in progress to evaluate the vapor-response selectivity of the nanoscale structure of *Morpho* wings. Continued research on *Morpho* wings may spur a new generation of sensor technologies.

COMPOUND EYE OF NOCTURNAL INSECTS INSPIRES ANTI-REFLECTIVE NANOSCALE SURFACES

Nocturnal moths are able to see at night because their eyes absorb a high proportion of light instead of reflecting it. Made of nanoscale structures in a hexagonal lattice, this architecture advantageously directs incident light to increase the insect's light sensitivity and to decrease external reflection visible to predators. The two components responsible for this light interaction are the tapetal mirror and the corneal nipple array. The tapetal mirror situated behind the moth eye's photoreceptors allows light to reflect back through the eye structure, providing two opportunities to absorb incoming photons. The corneal nipple array—otherwise known as the "moth-eye" structure—covers the micron-sized facets of the eye and acts as an anti-reflective coating. As a result, the moth is able to see in very low light conditions. Additionally, because the nanostructure of the



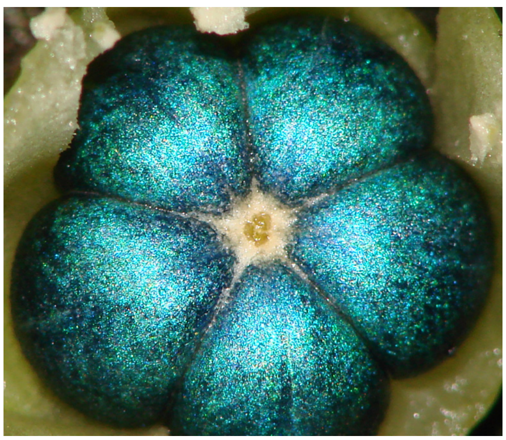
eye absorbs such a high degree of light, the compound eye reflects little incident light, protecting it from detection by predators.



Researchers at Nagaoka University of Technology in Japan have shown that applying anti-reflective "moth-eye" films onto existing solar panels increases the conversion of incident photons to usable electricity by 5%. Additionally, manufacturing techniques to include moth-eye nanostructures in a thin film during solar cell production have been developed by researchers in the United States.

TROPICAL SEEDS INSPIRE SMART MATERIALS

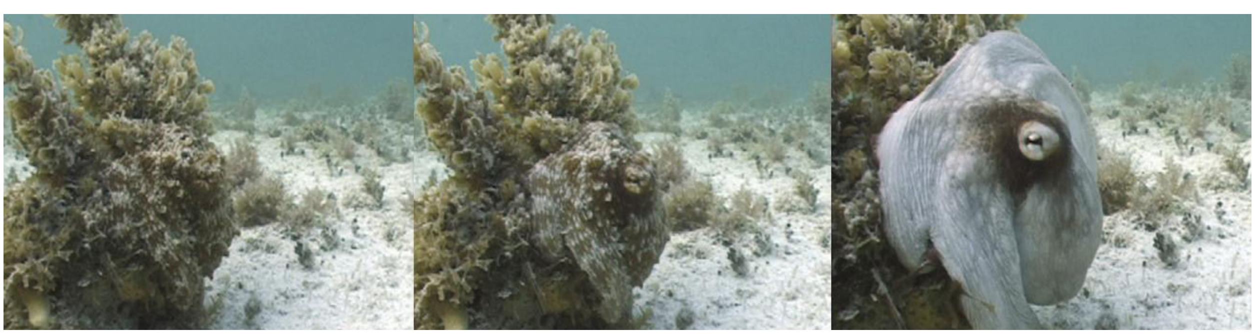
Of the many fruits and seeds in tropical forests that have striking colors to encourage seed dispersal, *Margaritaria nobilis* has a unique color strategy. The blue-green hue attracts birds to eat and disperse the seeds even though they have low nutritional value. The color and luster of *M. nobilis* seeds are due to a hierarchical photonic structure. The seed coat contains cells whose interiors are composed of concentrically-layered tissue. When light interacts with these layers, it is reflected as blue or green light due to optical interference. The angle of incidence and seed curvature—both microscopic and macroscopic—also account for the multihued reflections.



The concentrically layered cell architecture of the *Margaritaria nobilis* has inspired the development of a photonic fiber that reflects varying colors when stretched. The lab-scale fabrication process includes a rolling technique that creates a multilayer cladding around a central flexible fiber. These concentric multilayers—formed using two different materials—result in a photonic structure due to the materials' different refractive indices. Unlike in conventional thermal drawing processes, these multilayer fibers are produced at room temperature, which allows fabrication with a wide range of polymers.

CEPHALOPOD SKIN INSPIRES DISPLAY MATERIALS

Certain species of octopus, squid, and cuttlefish are able to blend into their surroundings, camouflaging themselves to protect against predators. This ability is due to the unique combination of pigments and photonic structures in the skin of cephalopods. The intricate interaction of these optical elements—chromatophores, iridophores, and leucophores—allows the animals to alter their appearance. Chromatophores are small pigment-containing organs that are capable of dynamic, neurologically-controlled changes in volume. Their pigmentation provides varying hues of red, brown, black, orange, and yellow. Iridophore cells feature a photonic structure



that reflects blue and green colors. While many artificial photonic structures (e.g. diffraction gratings) are static, cephalopods are capable of modulating their iridophores to vary the reflected colors. The final aspect of their camouflage is the reflection of incident light. Leucophore cells—which contain light-scattering protein spheres—allow cephalopods to reflect white light. Together, all of these optical devices allow the organisms to display a wide palette of colors.

Technologies that feature cephalopods' optical tricks include photonic gels that may be used in future electronic displays. Using the iridophores as inspiration, researchers in the United States are developing tunable photonic-crystal pixels for display applications. Electronic displays using these dynamic, diffraction grating pixels would not require rear or peripheral lighting systems to illuminate the pixel; instead, ambient light is the light source. A new generation of low-energy flat panel displays may be made possible from this research.

SPIDER WEBS INSPIRE BIRD-SAFE GLASS

A spider's ability to protect its web from predators has recently inspired the development of window glass that prevents birds from striking it. Research conducted on the decorative patterns of spider webs, technically known as the stabilimenta, found that the center decorations serve as a warning signal to birds. Birds are capable of perceiving ultraviolet light reflecting off the silk and altering their path to avoid the webs. Depending on the direction of light, spiders create denser designs to provide more surface area for reflection. Studies indicate that the presence of a decorative center on spider webs reduces damage from flying birds.

The reflectivity of the stabilimenta inspired a company in California, Arnold Glas, to design an insulated glass sheet called ORNILUX. The glass has a unique ultraviolet-reflective coating that appears almost transparent to humans but is clearly perceptible to birds. The coating mimics the reflectivity and patterns of spider silk. The use of ORNILUX reduces bird collisions by 77% compared to standard window glass.

Morpho References:

R. Potyrailo *et al.*, "*Morpho* butterfly wing scales demonstrate highly selective vapor response," *Nature Photonics*, vol. 1, pp. 123-129, 2007.

A. Pris *et al.*, "Towards high-speed imaging of infrared photons with bio-inspired nanoarchitectures," *Nature Photonics*, vol. 6, pp. 195-200, 2012.

R. Potyrailo *et al.*, "Discovery of the surface polarity gradient on iridescent *Morpho* butterfly scales reveals a mechanism of their selective vapor response," *PNAS*, vol. 110, pp. 15567-15572, 2013.

Image Sources: Grover Schrayer; Radislav A. Potyrailo

Moth-eye References:

S-Y. Takemura *et al.*, "Absence of eye shine and tapetum in the heterogeneous eye of *Anthocharis* butterflies (Pieridae)," *Journal of Experimental Biology*, vol. 210, pp. 3075-3081, 2007.

N. Yamada *et al.*, "Characterization of antireflection moth-eye film on crystalline silicon photovoltaic module," *Optics Express*, vol. 19, pp. A118-A125, 2011.

C. Sun *et al.*, "Broadband moth-eye antireflection coatings on silicon," *Applied Physics Letters*, vol. 92, pp. 0611121-0611123, 2008.

Image Sources: Rick Cowen; Wei-Lun Min

M. nobilis References:

M. Kolle *et al*., "Bio-Inspired Band-Gap Tunable Elastic Optical Multilayer Fibers," *Advanced Materials*, vol. 25, pp. 2239-2245, 2013.

E. Cazetta *et al*., "Frugivory on *Margaritaria nobilis* L.f. (Euphorbiaceae): poor investment and mimetism," *Brazilian Journal of Botany*, vol. 31, pp. 303-308, 2008.

Image Source: Herbario Universidad Católica De Oriente

Cephalopod References:

L. Mäthger *et al*., "Mechanisms and behavioral functions of structural coloration in cephalopods," *Journal of the Royal Society Interface*, vol. 6, pp. S149-S163, 2009.

J. Walish *et al*., "Bioinspired electrochemically tunable block copolymer full color pixels," *Advanced Materials*, vol. 21, pp. 3078-3081, 2009.

W. J. Crookes *et al*., "Reflectins: The Unusual Proteins of Squid Reflective Tissues," *Science*, vol. 303, pp. 235-238, 2004.

Image Source: Roger Hanlon

Spider Web References:

M.J. Bruce *et al*., "Spider signals: Are web decorations visible to birds and bees?" *Biology Letters*, vol. 3, pp. 299-302, 2005.

M. E. Herberstein and A. F. Fleisch, "Effect of abiotic factors on the foraging strategy of the orb-web spider *Argiope keyserlingi* (Araneae: Araneidae)," *Austral Ecology*, vol. 28, pp. 622-628, 2003.

T. Eisner and S. Nowicki, "Spider web protection through visual advertisement: role of the stabilimentum," *Science*, vol. 219, pp. 185-187, 1983.

H-W. Ley, "Experimentelle Tests zur Wahrnehmbarkeit von UV-reflektierenden "Vogelschutzgläsern" durch mitteleuropäische Singvögel," *Berichte zum Vogelschutz*, vol. 43, pp. 87-91, 2006.

Image Source: Flickr user spiderkakes