From imitation to inspiration

Biomimicry experiences a revival driven by a more systematic approach to explore nature's inventions for human use

Philip Hunter

Biomimicry has been a buzzword for decades to describe efforts to exploit nature's inventions for technological innovation. Until recently, it has been largely confined to a few "poster child" applications or products, such as Velcro or self-cleaning surfaces. The field never really gained momentum in terms of technology transfer, serious investment from industry, or even academic funding. But there are signs of a revival driven by an accumulating body of knowledge and expertise in what might be called fundamental biomimicry, which trawls nature for inspiration in a more systematic way by matching the products of evolution with specific target applications.

Inspiration rather than mimicry

This change came with the realization that natural systems can rarely be exploited directly for various reasons, such as the choice of materials or a lack of understanding of the underlying mechanisms. A good example of this wrongheaded approach is artificial photosynthesis. Scientists realized early on that proteins are not the best materials for artificial systems to harness sunlight for energy production, because they have to be constantly renewed. Alternative materials such as ruthenium are therefore preferred as catalysts to exploit the principles of photosynthesis [1].

To this extent, biomimicry has therefore not been oversold, but mis-sold or misrepresented. Exploiting nature's inventions is more about ideas and inspiration rather than blind mimicry. This argument is forcibly made by Toby Kiers, who conducts biomimicry research at the Vrije Universiteit (VU) in Amsterdam, the Netherlands. "Mimicry

implies copying something regardless of whether you understand it, imitating rather than understanding", she said. "In this way, we need to be skeptical because nature never works how we think it works. When I speak at biomimicry conferences, it is usually in the role of the skeptic. My aim is to get the audience to understand the traps of blindly copying nature when we don't understand the underlying processes".

.....
"Exploiting nature's inventions is more about ideas and inspiration rather than blind mimicry."

Kiers cited her own specialty, which is cooperation in nature as in symbiotic relationships. "We see incredible examples of cooperation in nature, between different species", she said. "You could view this as a harmonious cooperative unit, and try to recreate this harmony. But the truth is that these cooperative relationships are built on reciprocal exploitation, so that both parties may benefit but with an inherent tension. Both parties are trying to maximize their gains and there is really nothing harmonious about it. These are lessons we need to understand when trying to recreate cooperative systems in the field of biomimicry".

What biomimicry is not

Other examples of what is not biomimicry include wastewater cleaning with bacteria. This is rather bioutilization, where the organism is selected or engineered to provide a particular function. For true

biomimicry, it is essential to understand the underlying functions down to the molecular level as in the case of photosynthesis, or higher-level interactions between organisms when exploiting symbiosis.

One field where biomimicry has been applied widely and sometimes inappropriately is architecture, where it has almost become a dogma in some quarters. In fact, architects have been copying nature for centuries, with birds' nests inspiring huts or by emulating termite nests for efficient ventilation and temperature control in larger buildings. However, this is rather a genuine application of biomimetics, as in Zimbabwe's Eastgate Building (<http://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/>).

At the same time, though, there has been mounting criticism of a slavish adherence to biomimetics driven by a desire for environmental correctness rather than hard science. Among such critics is Wynn Buzzell, Lead Designer at Demiurge Sculptural and Architectural Fabricators in Boulder, CO, USA, who identifies the problem partly as a failure to understand the dynamics of scale, geometry, and material properties, which can render a design unfit for purpose even when the underlying natural system has been understood (http://descomp.uncc.edu/sites/descomp.uncc.edu/files/fields/abstract/file/Biomimicry_ACSA.pdf).

Patching holes

Such considerations do not apply so much for the design of materials with specific properties, such as stickiness. In one case, this has led to a novel solution for a previously intractable problem, namely sealing holes in children's hearts during surgery.

Jeff Karp, a specialist in medical application of biomimicry at the Harvard Medical School in Boston, MA, USA, was approached in 2009 by Pedro J. del Nido, chief of cardiac surgery at Boston Children's Hospital, to help improve the outcomes of operations on children with ventricular septal defect (VSD), or hole in the heart, a fairly common congenital defect. "He described how when a surgeon tries to suture this tissue, it is so fragile it just tears", Karp explained. "They have devices to solve this problem but these are developed for adults. Downsizing them simply does not work for kids. Their hearts are growing. That means the surgeons need to come back over and over again for revision procedures to upgrade the device to fit the larger heart".

.....
"... architects have been copying nature for centuries, with birds' nests inspiring huts or by emulating termite nests for efficient ventilation and temperature control in larger buildings."

Karp and his colleagues envisioned a patch coated with glue that could be placed into the heart and pushed up against the hole. "And then, over time, the patient's own cells would migrate over and into this material and create a tissue bridge as the material completely disappeared", he explained. "We had materials that were degradable, elastic, and biocompatible, but to solve this problem, we also needed to ensure the glue wouldn't dilute or react with blood, as well as ensure it would resist washout in the heart prior to curing".

It seemed the sort of problem that might have cropped up in nature among creatures inhabiting wet environments and eventually inspiration was found from more than one organism. "There are sandcastle worms in the sea and slugs and snails on land that all have viscous secretions that stay put like honey on a plate, even with rain or surf hitting it", Karp described. "And then if you look carefully at these viscous secretions, you find they contain hydrophobic components which can repel water. So, we thought, what if you can develop an adhesive like that, that was entirely hydrophobic. You put it inside a beating heart onto the

tissue surface and it would repel the blood away from the surface and then because it's viscous it would remain in place, even in the presence of flowing blood, long enough for us then to cure it in place. And so, after a highly iterative process, we came up with a material that addressed all of these criteria".

The material has been shown to seal the carotid artery and aorta in pigs, as well as holes in the hearts of rats [2]. "We have also shown that we can use the glue to attach a patch inside a beating pig heart, as well as attach it to nearly any tissue in the body", Karp explained. "Because the glue can be immediately useful to so many surgeons, we created a company called Gecko Biomedical in Paris, in December of 2013, and a version of the material that has been designed as a tissue sealant entered the clinic this year in Europe for vascular reconstruction".

Artificial silk

Materials is indeed a broad area for biomimicry, as it overlaps with medicine as in the case of Karp's surgical glue, but in principle might also find non-medical uses. Silk, produced by spiders and the silk worm, has long been a cheerleader for bioinspired materials because of its combination of strength, elasticity, and lightness. Yet, exploiting these properties, either artificially or through recombinant approaches, has proven difficult.

Unlike silk worms, spiders cannot readily be harnessed for fabricating silk at scale because they begin to eat each other if reared in close proximity. Thus, efforts have focused on isolating the relevant genes and transferring them to suitable organisms. One example is the BioSteel™ fiber from the milk of transgenic goats by Nexia Biotechnologies, which went bankrupt in 2009. Yet, work on transgenic spider silk continued in Randy Lewis' laboratory at the University of Wyoming and Utah State University, which acquired the herd of about 30 recombinant "spider goats" (http://www.uwyo.edu/spider/transap_goat.asp).

Two new biotech companies are also working on large-scale production of spider silk using recombinant technology. Spiber Systems, based in Stockholm, Sweden, uses recombinant *E. coli* to make spidroin, the principle constituent protein of spider silk. Bolt Threads, in Emeryville, CA, USA, ferments recombinant yeast with spidroin genes to produce silk at large scale, with the

aim of at least matching the costs of producing fibers by established techniques, including silkworm silk and fine wools. Unlike Spiber, which focuses on medical applications, Bolt Threads aims at the textile market. "We can tune our proteins to have desired material properties, for example focusing on strength or stretchiness", said Michele Dragoescu, Bolt Threads Marketing Manager. "Our first products will be in apparel".

Fending off bacteria

Another, nearly classical, application for biomimicry is anti-bacterial surfaces. The design goal is to resist bacteria and biofilms without resorting to anti-bacterial or toxic compounds. Preventing the formation of biofilms, which are difficult to destroy, is also a challenge for natural structures, such as insect wings.

.....
"Silk, produced by spiders and the silk worm, has long been a cheerleader for bioinspired materials because of its combination of strength, elasticity and lightness."

Studying cicada wings, researchers at the Universitat Rovira i Virgili in Tarragona, Spain, discovered that these sprout needle-sharp nanostructures on their surface on which bacteria simply impale themselves. Based on this discovery, they developed and patented a new design for anti-bacterial surfaces [3]. The patent has since been acquired by Global Orthopaedic Technology, an Australian maker of medical implants. "We seek to apply the technology to a range of medical devices to address the 1–2% of implants that need to be revised to cope with infection", commented Dan Barker, the company's Chief Technology Officer. The key property is resistance against infection without the need for antibiotics or chemicals, which enables such materials to bypass clinical approval processes, Barker added. "The killing mechanism is purely mechanical: the cell wall of bacteria is ruptured due to physical contact with very tiny and sharp nanopillars that shred bacteria in pieces", he explained. Another significant characteristic relevant for medical implants is the fact that

these structures do not appear to affect eukaryotic cells [4].

Barker also highlighted recent work distinguishing between the anti-bacterial capabilities of different insect wings. “After the earlier work on cicada wings, it was discovered that other insects have anti-bacterial nanopatterns which are more efficient than cicada wings”, he said. “While cicada wings kill only gram-negative bacteria, dragonfly wings are efficient against both gram-positive and gram-negative. In addition, the mechanism seems to be quite different and we are now working more closely to understand why nanostructures on dragonfly wings are so efficient and how to reproduce this nanopattern on fabricated surfaces. It is quite challenging to understand the mechanisms and find the critical control parameters behind the anti-microbial activity”.

.....
“Insect eyes are particularly inspiring given their mechanisms for increasing both width and depth of field, which are both constrained for current camera lenses.”

A parallel development has shown that an artificial material has similar features to dragonfly wings. Black silicon sprouts multiple nanoscale needles on its surface that consist of single silicon crystals protruding 10 μm with a diameter of $< 1 \mu\text{m}$. These needles absorb light, giving black silicon its name, but also confer anti-bacterial properties. A study found that these silicon needles, like the protrusions on the wings of *D. bipunctata*, a dragonfly species, form hierarchical structures of adjacent needle clusters [5]. “It was demonstrated that black silicon reproduces closely the structures on dragonfly wings and that this material is very efficient against both gram-negative and gram-positive bacteria”, Barker commented. This is a different slant on biomimicry where, by accident, a fabricated material is discovered to have properties that could have been inspired by nature.

Copying the insect eye

Optics is another important and fast-growing sector of biomimicry, which exploits the

innovations of animal eyes, especially insect eyes. Here, the focus is much on copying basic principles, rather than mimicking, to develop new cameras and microscopic devices. Insect eyes are particularly inspiring given their mechanisms for increasing both width and depth of field, which are both constrained for current camera lenses. Insect evolution has been driven by the need to detect predators in all directions and distances and has led to the development of hemispherical 360-degree vision. Another advantage of many insect eyes is visual acuity, or clarity, when viewing fast-moving objects, again driven by the need to see fast-moving predators or prey.

While industrial applications are yet to come, a team led by John Rogers at the University of Illinois at Urbana-Champaign in the USA has already developed materials and schemes for arthropod-inspired cameras with nearly full hemispherical shapes [6]. They integrate compound optical elements with deformable arrays of thin silicon photodetectors into sheets that can be elastically transformed into hemispherical shapes for integration into apposition cameras. These emulate the elasticity and viscosity of the insect eye, both of which are necessary for a compound eye with consistent optical properties across the whole field of vision.

The team continues to characterize the properties of such systems as a prelude to commercial manufacture. “Because of basic limitations in the kind of cleanroom processing that we can do in an academic lab, we have focused mainly on modeling efforts to understand the capabilities of scaled devices, that is size, angular coverage and number of ommatidia (the units of compound arthropod eyes), that should be readily possible with industrial-quality manufacturing capabilities”, Rogers commented.

Inspiration from birds

While the examples discussed so far exploit or manipulate natural materials at the molecular level, biomimicry also looks at the macroscopic level, for example in fluid dynamics. At a crude level, humans have been inspired by birds in numerous—and sometimes fatal—attempts to fly, and emulated structures such as beaks to design high-speed trains. But biomimicry at this scale has become more sophisticated and is now influencing the design of fans,

propellers, and wind turbines, with potentially huge economic and societal benefits.

In some cases, the goal is greater efficiency and speed; for wind turbines, noise was the prime motive for seeking inspiration from one particular bird. Hunting mainly at night, the owl swoops almost noiselessly, particularly at the higher audible frequencies above 1.6 KHz. This observation prompted study of the owl's wing to address a problem that has handicapped wind farms over land, namely the excessive noise the blades make at higher speeds. Wind turbines are therefore braked when the wind is at all high to minimize noise, impairing their efficiency.

.....
“... for wind turbines, noise was the prime motive for seeking inspiration from one particular bird”

Microscopic observation found that owl wing feathers are different from nearly all other birds: They sprout hairs rising almost perpendicularly from the surface that are able to bend in unison with air flow during flight to form a canopy with a large open area [7]. The principle is similar to a forest whose trees can bow together in the direction of the wind to reduce the exposed area and absorb the shock more effectively, although the evolutionary motive was different.

Further experiments revealed that the owl wing canopy greatly reduces pressure fluctuations on the underlying surface. While the canopy can produce its own sound, particularly at high frequencies, the reduction in fluctuations also reduces the noise from the underlying rough surface at lower frequencies, which are audible to many owls' prey. This principle has been applied in a newly designed material that mimics the wing structure of owls [7]. The potential applications include computer fans and airplane engines, as well as wind turbines. Early wind tunnel tests demonstrated a substantial reduction of noise without any noticeable effect on aerodynamics.

Given the breadth of biomimicry, it is hard to generalize overall progress, but a number of new products and developments over a wide range of sectors show that nature has great potential to inspire technological advances. In many cases, this is a

result of both technical advances and a greater understanding of the biology rather than direct copying.

References

1. Concepcion JJ, House RL, Papanikolas JM, Meyer TJ (2012) Chemical approaches to artificial photosynthesis. *Proc Natl Acad Sci USA* 109: 15560–15564
2. Lang N, Pereira MJ, Lee Y, Friehs I, Vasilyev NV, Feins EN, Ablasser K, O’Cearbhaill ED, Xu C, Fabozzo A *et al* (2014) A blood-resistant surgical glue for minimally invasive repair of vessels and heart defects. *Sci Transl Med* 6: 218ra6
3. Pogodin S, Hasan J, Baulin VA, Webb HK, Truong VK, Phong Nguyen TH, Boshkovikj V, Fluke CJ, Watson GS, Watson JA *et al* (2013) Biophysical model of bacterial cell interactions with nanopatterned cicada wing surfaces. *Biophys J* 104: 835–840
4. Pham VT, Truong VK, Orłowska A, Ghanaati S, Barbeck M, Booms P, Fulcher AJ, Bhadra CM, Buividas R, Baulin V *et al* (2016) “Race for the surface”: eukaryotic cells can win. *ACS Appl Mater Interfaces* 8: 22025–22031
5. Ivanova EP, Hasan J, Webb HK, Gervinskas G, Juodkazis S, Truong VK, Wu AH, Lamb RN, Baulin VA, Watson GS *et al* (2013) Bactericidal activity of black silicon. *Nat Commun* 4: 2838
6. Song YM, Xie Y, Malyarchuk V, Xiao J, Jung I, Choi KJ, Liu Z, Park H, Lu C, Kim RH *et al* (2013) Digital cameras with designs inspired by the arthropod eye. *Nature* 497: 95–99
7. Clark IA, Daly CA, Devenport W, Alexander N, Peake N, Jaworski JW, Glegg S (2016) Bio-inspired canopies for the reduction of roughness noise. *J Sound Vib* 385: 33–54