Turning nature's inspiration into a production line

Exploits of natural designs have become a systematic research field to create new materials and designs for architecture, medicinal devices and other products

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Nature has long been a rich inspiration for artists and poets and an endless source of wonder for biologists to understand its workings. For millennia, humans have also relied on natural products in medicine, buildings or clothing and nature has inspired numerous technological inventions, architecture and design. But it is only recently that human efforts to exploit the design and functions of natural systems have become a systematic field of research in its own right. To date, the examples of technologies and materials that were inspired by nature have been limited to isolated and often almost chance discoveries, initially confined to the world of materials. The best known and first major commercial success was the Velcro hook and loop fastener, conceived in 1941 by Swiss engineer George de Mestral, who was inspired by the way burrs or seeds of the burdock plant kept sticking to his clothes. He examined them under a microscope and noted that hundreds of miniature hooks caught on anything with a loop, such as clothing, animal fur, or hair.

The case of Velcro was fairly unique as it was inspired by simple observation with the naked eye in combination with a low-powered microscope. Since then a number of other important technologies or materials were developed based on natural systems, but these involved more detailed probing at smaller scales down to the molecular level. Another well-known example of such biomimicry is the ability of molecular structures on the surface of plant leaves to repel water that has been copied to varying degrees in artificial materials or technologies.

Yet, the field has been expanding beyond materials to embrace medicine, renewable energy production and chemical engineering, stimulated in recent years by the growing movement toward sustainability and reuse, which, the proponents of biomimicry hope, will be easier to attain by following nature's design principles.

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In particular, concerns over consumption of fossil fuels have led to a rapid proliferation of research on solar energy conversion based on either natural or artificial photosynthesis, commented Stenbjörn Styring from Uppsala University and chairman of the Swedish Consortium for Artificial Photosynthesis. “The main game changer for our field was probably the election of Obama, because he instilled as his energy minister the Nobel Prize winning physicist Stephen Chu,” he said. Chu is no longer in that post in Barack Obama's second term, but, according to Styring, his original appointment led to the formation of several US national centers and the establishment of the Joint Center for Artificial Photosynthesis (JCAP) in 2010 in a five-year US\$120 million initiative that involves the California Institute of Technology (Caltech) and Lawrence Berkeley National Laboratory, with help from

several universities. “This led other nations to join the bandwagon, both on the biological and artificial side,” Styring said.

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While artificial photosynthesis has gained its own momentum, developing technology based on natural systems to solve human problems is becoming an organized discipline in itself under the banner of biomimetics or bionics, rather than just being an adjunct to existing fields such as metallurgy and chemical engineering. A milestone in the history of biomimetics was the creation of the first fellowships in biomimicry at the University of Akron in Ohio, USA, in 2014, in collaboration with faculty from The Cleveland Institute of Art. These fellowships are affiliated to the Biomimicry Institute in Missoula, MT, USA, which was established in 1998 in response to growing demand from major enterprises, such as General Electric, Boeing or Nike, to identify whether nature had already in some way come up with a solution to a particular problem, according to its co-founder Janine Benyus. “At the time I realized that there was a lot of functional biological information gathered in scientific papers, but it was only for other biologists

Figure 1. The Namibian Desert beetle (*Stenocara spec*) can collect water vapor from the air through a series of nanoscaled bumps on his back.

to read,” Benyus said. “It wasn’t designed by function, so you couldn’t for example read about how Nature filters and yet filtering strategies in the natural world occur all over in fungi, plants and animals. There was a real need to curate this biological intelligence and organize by function, so you could for example look up how to achieve water repellence without Teflon.”

The Biomimicry Institute went on to develop its functional taxonomy, now available online under asknature.org, arranged as a hierarchy of eight groups with 30 subgroups comprising more than 160 functions in total. The aim, said Benyus, is to extract the design principle so that it can readily be applied in artificial systems. One recent example is the method used by the Namibian beetle to extract water from mist. It is an important adaptation for this particular desert dweller because, although the

climate is very dry, frequent mists occur in Namibia’s coastal desert inhabited by the beetle. The beetle has evolved to gather water from mist or fog via nanoscale bumps on its back that have hydrophilic and hydrophobic domains in very close proximity. The hydrophilic areas attract tiny water droplets from the mist and the adjacent hydrophobic components quickly eject the water down through the nanobumps so that it can be absorbed by the beetle before it evaporates (Fig 1). “You can then make that work out of plastic that has squares of hydrophobic and hydrophilic patterns,” said Benyus.

This idea has already been developed into an array of carbon nanotubes by a joint Indian/South Korean team as a possible way of producing fresh clean drinking water in arid regions [1]. However, it is not clear whether this example would meet all the Biomimicry Institute’s criteria for natural

designs, which include sustainable and local production, as well as being nontoxic both in use and manufacture. “We try and make it as biomimetic as possible, with the concept of sustainability towards a circular economy making use of local materials,” Benyus explained. “It doesn’t make a lot of sense to make something that, say, is going to harvest water that might be toxic in its manufacture.”

Another broad objective, particularly for developing novel materials, is to seek universal design principles that were perfected through evolution. One particular challenge during the past few years was to analyze the molecular configuration of structural materials that are particularly tough, meaning that they resist fracture under strain or collision. Toughness is one required property of some materials, others being stiffness or resistance to bending, hardness or resistance to compressive forces, and strength, which is the ability to carry loads without deformation or breaking. Some materials, such as steel, are strong, hard and tough but not particularly stiff. Ceramics on the other hand are strong, hard and stiff, but not tough and fracture easily. Again, Nature has already solved this problem: various natural structures, notably mollusk shells and vertebrate bone, are strong, stiff, hard and tough, with a high degree of fracture resistance because of their laminated architecture, similar to the way bricks are bound together by mortar in buildings. In this case, the “bricks”, comprising around 95% of the weight of mollusk shells, are made up of calcium carbonate crystals, while the 5% “mortar” is organic, mostly proteins. However, the structure is much more complex than brick and mortar walls and comprises laminated layers at five different length scales, which have remarkable resistance to fracturing. Mollusk shells are typically up to 1,000—and occasionally 10,000—times tougher than the calcium carbonate comprising the bulk of their substance, for only a small sacrifice in stiffness [2].

One obvious question is whether these structures represent the best that can be achieved, or whether there is scope for even further improvement. There are strong indications from a recent study that nature has indeed evolved the best possible structure for toughness in a hybrid material of hard and soft elements, given the strong selective

Figure 2. The eggbeater-shaped hairs on the surface of *Salvinia* leaves.

The end cells of each hair form evenly distributed hydrophilic patches that attract water and stabilize the air layer.

advantage for protective shells [3]. “We’ve tried 7,000 different microstructures and we showed that the brick and mortar structure is the most efficient for resisting crack propagation,” said study co-author Francois Barthelat from McGill University in Montreal, Canada. “The challenge is that you cannot change the structure of biological materials in any case. So instead, we go on a computer and model this microstructure and use simulations to assess the mechanical properties.” The team concluded that nature has already converged on the same micro-architecture in different systems, including bone and teeth made largely from calcium phosphate, as well as shells comprising mostly calcium carbonate. “Even within shells there are different branches that have evolved completely independently and reached the same solution,” said Barthelat.

This common structure is more complex and sophisticated than was originally thought, with many details yet to be resolved, but the key point is that it relies not just on structure at the molecular level but spans all dimensions up to observable surface properties in an interlocking

hierarchical arrangement, according to André Studart, Assistant Professor for Complex Materials in the Department of Materials at the ETH Zurich in Switzerland. “People have tried to make materials with strong molecular bonds, but that just gives strength,” he said. “It doesn’t give ductility or extensibility. If you look at biological materials, you have molecular bonding but also attraction at the fibril level, fiber level and then bundles of fibers. So there’s dissipation of energy at many different length scales.” This arrangement resists fracture, because if a crack forms say at the nanoscale level, its propagation is resisted when it encounters structures at a higher level of the hierarchy, which may involve grains running in a different direction.

Mimicking the full hierarchical complexity of these structures is challenging: so far, commercially successful naturally inspired materials are confined essentially to two-dimensional structures. “Most of what has been turned into products are surface related,” commented Studart. “There are examples of simple solutions that are biologically

inspired, like the Lotus effect.” This term was coined in 1977 following observations of the Lotus flower leaves’ self-cleaning ability owing to high water repellence [4]. It causes water droplets to form on the surface during rainfall and pick up dirt particles, which are then removed as the droplets fall off. The repellence is caused by complex micro- and nanoscopic structures on the leaves’ surface, not so different in principle from that of the Namibian desert beetle.

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There are other surface-related properties with great commercial promise that have yet to be exploited. One example is the ability to retain air that lies behind the invasive success of the *Salvinia* water lily, which is regarded as a pest through its colonization

of ponds. The plant traps air around its leaves through a hierarchical surface structure dominated by complex elastic hairs, the shape of eggbeaters coated with nanoscopic wax crystals. The end cells of each hair lack those wax crystals and form evenly distributed hydrophilic patches that attract water and stabilize the air layer by pinning the air–water interface to the tips of the eggbeater hairs (Fig 2). It prevents loss of air from formation and detachment of gas bubbles in the unstable turbulent flow close to the leaves [5]. “*Salvinia’s* invasive success is most probably aided by its air retaining properties,” said Matthias Mayser from the Microfluidics Laboratory at the University of Liege in Belgium. “Because of the air layers kept under water the plant is able to maintain photosynthesis when submerged. Thereby it can survive in a higher density compared to what would be possible just at the surface.” Work is now underway to mimic these properties in both transportation and pipeline systems. “The most promising application would be air retaining coating for ship hulls that would reduce the drag between ship and water, increasing fuel efficiency and additionally helping to prevent biofouling,” said Mayser. “Other applications could include drag reduction in water pipelines or simply swimsuits that stay dry in the water.”

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When it comes to exploiting the more complex three-dimensional architecture of shells or bone, there is potential in two directions, Studart commented. The first is to copy Nature’s principles but not materials to achieve design goals that might be rather different from those pursued by evolution. “The other idea is to stay with those weak materials (such as calcium carbonate and calcium phosphate), which have their advantages and use them with these hierarchical structures to have them reach a guaranteed minimum performance,” said Studart.

One advantage of the second approach is that such materials would be biocompatible and therefore suitable for medical applications. It could be used for screws to hold fractured bones together while they heal, which currently requires metals such as titanium. A major emerging application for biomimetics will be creating implants or screws out of calcium carbonate or calcium phosphate in such a way that they are strong enough to do the same job as those made out of metals or other materials but that over time become absorbed or integrated into the new bone structure so that they effectively disappear. This, suggested Studart, would improve fracture healing to the extent that the bone would regain its former strength without being compromised by the presence of permanent implants.

Another class of potential medical applications is associated with a different property of some natural systems, namely the ability to change shape, as seed pods do when they release their contents into the air or soil. This has promising application, for example, for stents to widen arteries in or near the heart to treat angina. Stents must be sufficiently thin to insert into an artery but, as a result usually of being warmed to blood temperature, change shape and expand to widen the vessel without bursting it. Currently, this is achieved with metal alloys, such as “Nitinol” (nickel and titanium), which have the property of “shape memory” so that they can reversibly change shape when heated. The advantage of a natural system is that it would not require any specific chemical composition to change shape under heating, instead exploiting the physical arrangement of cellulose fibers in a seed pod, which in turn has been driven by evolution. “If we were able to replicate that arrangement of fibers in a synthetic system, then we could work with any type of material and again choose ones that are resorbed after they have done their job,” said Studart.

Nature’s inspiration has also been sought for building design, primarily to optimize temperature control. Here, one natural model is the various hives, nests and mounds built by insects. The termite mound has been most widely studied because of its complexity and size extending to several meters, which requires more sophisticated cooling and environmental control. The best known example of a building designed to mimic the termite

mounds’ air conditioning system was the Eastgate shopping and office center in Harare, Zimbabwe, which opened in 1996 based on studies of the mound structures by J. Scott Turner, a specialist in collective intelligence among organisms. It has contemporary interest because it turned out that, although the Eastgate center’s cooling system is successful, it was based on a false view of how termites regulate their mounds. It had been assumed that the mounds worked like complex chimneys, drawing air in at the bottom and exhaling it at the top, driven by the heat generated from the metabolism of the whole nest. The building was designed along those lines, taking advantage of Harare’s relatively cool climate for its tropical location. The building takes in air low down at the end of the night when temperatures are lowest which then this flows through cavities in the floor slabs and through chimney-like vents until the desired temperature has been reached. By avoiding too much glass and having good insulation, the building remains within its temperature range even after absorbing heat during the day.

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But subsequent work by Turner using Magnetic Resonance Imaging to analyze the mounds revealed that the mechanism used by termites was far more complex and sophisticated than had been thought and was not entirely passive. It extended beyond temperature control to include regulation of oxygen and carbon dioxide: in other words, the nest functions more like a lung than a chimney. The energy source is indeed passive, being the wind blowing against the nest combined with the metabolic heat and solar radiation, but the termites regulate the flow of air through a complex network of internal reticulated tunnels that end in a central chimney connected to surface conduits. A key point is that termites do not actually reside in the mound itself but in a nest just below it. The mound then acts as

the nest's respiratory and air conditioning system and according to the Biomimicry Institute's Benyus is regulated by termites as conditions vary through widening or narrowing of the tunnels. The termites also adapt to long-term changes by extending or altering the mound appropriately, which explains the wide variety of shapes and architectures.

According to Benyus, architects are now taking account of the revised understanding of how termites regulate their nests in construction of environmentally friendly buildings. But as she pointed out, the example of Eastgate Centre shows that nature can inspire us toward better designs even when initially the wrong conclusions are drawn.

She anticipates that we are on the cusp of a wave of products, materials, technologies and therapies derived from biological systems either directly or through research inspired by their study.

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