Biomimetics

Mimicking Nature For Technological Breakthroughs

Being observant enough to capture the clues offered by nature, and pursuing these with multi-disciplinary research can lead to scientific breakthroughs and engineering wonders

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George de Mestral, a Swiss electrical engineer, invented the hook-and-loop fastener (now inseparable with the name of Velcro) by keenly observing how the seeds of burdock got stuck to his coat and his dog's fur every time they brushed against the plant. That was in 1941. This is neither the first nor the only example of nature-inspired technologies, but definitely a notable one. Since time immemorial, scientists have been inspired by nature to mimic and surpass its capabilities. Be it vision, hearing or energy-saving, there are numerous things that natural systems perform best.

Why not observe and learn from the workings of nature, and use that knowledge as the basis for man-made processes and products? This thought has indeed continued to fuel many a wonderful invention, and the trend continues till date.

A look at the current generation brings forth several examples of many advanced and commercially-viable technologies that have been inspired by nature: KPIT Cummins' patent-pending night vision system; Stanford University's Neurogrid; the path-breaking sunscreen and bio-plastic projects taken up by Dr Judith Braganca and her students at BITS Pilani's Goa campus; AutoFlex MARAG's special optical thin-film coating; the Ultracane aid for the visually-impaired; the Libelle High-G flight suit; LogiTek's Marble trackball; the BioAvert object-avoidance software program; the solar cell technology being developed by Dr Akhlesh Lakhtakia and his international team; the self-healing solar cells designed by researchers at the Massachusetts Institute of Technology (MIT) and Purdue University; and ant- and bee-colony algorithms used in computing and artificial intelligence (AI).

By chance or by design?

We come across a lot of nature-inspired technologies in the news. Neural networks based on the working of the human brain, semiconductor chip fabrication techniques inspired by the designs on butterfly wings, aeroplane designs inspired by the fins of whales and a lot more. Sometimes, these are serendipitous. Being an observant lot, scientists and engineers notice a lot of interesting things around them. Some of these fascinating sights might suddenly strike a loud gong in their heads and lead to a great invention. But, it is not always a stroke of luck!

"Since we are part and parcel of nature, inspiration from nature has been used for ages. There is nothing new there. My own work leading to sculptured thin films, which are nano-engineered meta-materials, was inspired by a specimen of ulexite, a mineral sometimes sold as 'TV rock'. Bio-inspiration is usually serendipitous. Biomimetics, on the other hand, can be either forced or serendipitous. For instance, the invention of Velcro was serendipitous, but robotic mountain climbers designed to mimic the gait of mountain goats and miniature flyers designed to emulate hummingbirds are examples of deliberately seeking solutions from nature to fulfil specific requirements," explains Dr Akhlesh Lakhtakia, the Charles G. Binder (Endowed) Professor of Engineering Science and Mechanics, Pennsylvania State University.

In the latter type of cases, once it is decided that certain natural solutions have to be emulated, researchers follow the usual patterns. They observe the natural solution, consult with colleagues in relevant biological subdisciplines, isolate essential characteristics and mechanisms of the natural solution and then work out emulation strategies, keeping in mind that a natural solution is not necessarily more efficient or economical than an artificial one. The scrutiny of natural phenomena, organisms, structures and such to solve problems, create better designs or develop new products, is developing into an organised field of study. In fact, universities such as the MIT have included biomimetics as part of their curriculum.

Delving upon whether bio-inspiration is by chance or by design, we can outline several approaches to nature-inspired technology development.

LogiTek'Marble trackball—a wireless computer mouse inspired by the fly's image processing system

Approach 1

"This is interesting; let me study it in detail."

Picking up a stray clue and turning it into a discovery or invention is one of the most admirable things to do. An apple fell on Newton's head and he discovered gravity, we say. However, Newton would admit it was not that easy! He discovered gravity because he questioned why the apple fell, and pursued to study the reasons behind it.

A researcher sees something interesting, is inspired by it, studies it further, and tries to apply that knowledge to develop a theory, design or product or whatever other fragment of technology. That is, the researcher is not in search of an idea, but chances upon one, and decides to pursue it.

The sculptured thin film mentioned by Dr Lakhtakia is one such nature-inspired technology. About two decades ago, he observed a mineral called ulexite which has a fibrous structure. It is often called TV rock because of its ability to transmit images as on a television screen, when cut and polished. Intrigued by this, Dr Lakhtakia asked a colleague whether such fibrous structures could be made with thin-film technology, and was glad when told that they could be!

He decided to lay down the fibres of the thin film at an oblique angle, to try and find out the mathematical basis of its dielectric, magnetic and magnetoelectric properties. Then, he decided to shape the fibres so that they were not straight. He found that the chirality, or left- or right-handedness of the film, affects the transmission of light. If the handedness of the light and the film are same, it can be very bright. If they are opposite, the transmission is low. He also showed that it was possible to shift the colour of the film after deposi-

Commercial successes

Dr Judith Braganca of BITS cites some examples of nature-inspired technologies that have gone on to become commercially-successful products.

1. AutoFlex MARAG, based on the structural surface features of moth eyes, is an optical thin-film coating that eliminates light reflection and glare. Applications include coatings for PDAs and solar cells. The 20μ optically perfect GRIN lenses found on the exoskeleton of certain brittle sea stars and the glass fibres found on a particular glass sea sponge, are influencing the development of micro-lenses and fibre optics respectively.
2. Ultracane, inspired by the bat's use of ultrasound, provides a blind person with a more comprehensive coverage of the spatial environment than afforded by the traditional cane.
3. The Libelle High-G flight suit, inspired by the fluid-control mechanics of dragonflies, has extended the ability of pilots to maintain function while experiencing high G forces.
4. LogiTek's Marble trackball, a wireless computer mouse, was inspired by the fly's image processing system.
5. BioAvert, an object-avoidance software program, is based on the neural network behaviour of cockroaches.
6. Super Microft, an award winning fabric developed by the Teijin Group of Japan, was developed by mimicking the water-repelling properties of the lotus leaf including the surface micro-texture.

tion by heating the film.

The sculptured thin films that resulted from Dr Lakhtakia's research have a large range of uses including light filters, fluid concentration sensors, biosensors, electrical switching, lab-on-a-chip, bio-replication and bio-scaffolding (as a substrate for cell growth). Their use in the reproduction of biological surfaces such as the multifaceted eyes of house flies, for possible light-harvesting purposes, etc, is quite interesting.

Approach 2

"I'll keep studying nature; I'm sure it'll lead to great things!"

In a report published in the *National Geographic*, Dr Andrew Parker, a proponent of biomimetics and a research fellow at London's Natural History Museum and the University of Sydney, exclaimed that he could come up with 50 biomimetic project ideas merely by observing the preserved specimens in a museum. Indeed, when he saw a 45-million-year-old fly trapped in amber in a museum in Warsaw, Poland, he noticed that it had microscopic corrugations that reduced light reflection. This observation is now engineered into solar panels.

Parker is the kind of person who would walk along the coastline consciously looking at the environment, the natural phenomena and the creatures, searching for a spark to solve problems in engineering, materials science, medicine and other fields. Apparently, his study of antireflective coatings in moth eyes and iridescence in butterflies and beetles has led to an anti-counterfeiting technique and brighter screens for cellular phones, respectively.

So, in a very challenging approach some researchers such as Dr Parker keep studying nature, cataloguing the information and constantly calculating upon whether it can solve any related engineering problem. This requires a very keen mind, knowledge of many science and engineering disciplines, and a strong will—because hundreds of ideas and years of study might lead to just a few breakthroughs.

Self-repairing solar cells

In a very recent example of nature-inspired breakthroughs, a team of researchers at MIT, led by Prof Michael Strano, has unveiled the logic for self-repairing solar cells, inspired by how plants perform photosynthesis. The design involves carbon nanotubes studded with phospholipid disks. The resulting photo-electrochemical solar cells are believed to be self-repairing and twice as efficient as the best solid-state solar panels available today.

Engineers try to prevent degradation in solar cells by using solid-state inorganic materials. Nature, on the other hand, does not try to prevent degradation, but uses various self-healing processes to anticipate and repair the damage caused to liquid-state organic materials. The process of photosynthesis includes mechanisms to periodically break down a plant's chemical-based engine into basic building blocks, renew the components and reassemble the engine. This process happens almost hourly.

Strano's design tries to mimic the refurbishing activity by using synthetic disk molecules called phospholipids, each of which carries its own internal reaction centre to covert light into an electric current. When dissolved in a solution containing carbon nanotubes, the disks self-assemble around them. Since carbon conducts electricity better than metals, the nanotubes enhance the transport of electrons freed inside the disks by their exposure to sunlight. Inside each disk there is a photosynthesis-like cyclical mechanism using seven different compounds that self-assemble into harvesters of light. By adding a surfactant, the seven-compound assembly can be broken apart into its original components. By forcing the whole solution through a filter that removes the surfactants, the original building blocks again self-assemble into a refurbished solar cell, much like the process followed by plants.

Inspired by the same process in plants, a team led by Jong Hyun Choi of Purdue University has also created artificial photosystems using optical nanomaterials to harvest solar energy that is converted to electrical power. This team's design exploits the unusual electrical properties of structures called single-wall carbon nanotubes, which they use as molecular wires in light-harvesting cells.

Approach 3

"I have a specific problem to solve; let me see if nature gives some ideas."

Dr Lakhtakia and an international team of researchers from USA, Italy and Spain were looking for a better strategy to channel sunlight into solar cells in small-scale installations. They believed that apart from harvesting direct sunlight, the cells should also recycle energy emitted by other lighting sources such as LED lamps. This requires solar cells that can harvest energy from diffused light. That is, we require solar cells with a large angular field of view to maximise the capture of incident light regardless of its direction.

Recently, the team consciously decided to look for solutions in nature. That is when they observed how difficult it was to catch houseflies.

"Houseflies have big eyes and can see 270 degrees around them. Certainly, this wide angular field of view arises from the positions of the two eyes; humans too would have a much wider angular field of view than what they have (170 degrees) if their eyes were located on their temples. But, the team reasoned that the wide angular field of view could also arise from the compound eyes of the housefly Musca domestica," says Dr Lakhtakia.

Other insects such as the blowfly and the horsefly also have compound eyes. Basically, in these insects, each eye is made up of innumerable micro-sized cylindrical eyelets arrayed on a curved surface. Light propagating along the axis of an eyelet is collected to form an image, but light propagating in other directions and reaching an eyelet is absorbed by its dark side wall. Although the spatial resolution of the overall image formed in the brain by the fusion of the individual images is quite low, the field of view is very large.

Two years ago, the team started a two-phase research program to adapt the scalloped and curved outer surface of a compound eye to texture the exposed face of a solar-cell device. They report good progress in both phases. Although this success is a measure of the scientists' sweat and blood, they also have nature to thank, at least for that timely spark.

In another interesting example, the engineers of Energid Robotics and Machine Vision set out to develop a humanoid robot that can work like a human arm. The company's director and country manager, Jayakrishnan T., says, "Our unique robot manipulator series, the Cyton humanoid manipulators mimic nature's ultimate engineering marvel—the human! We copied the configuration of the human arm to do the kinematics design of that robot. These robots have the properties of redundancy and bifurcation, which enable placement of multiple hands or tools at desired positions and orientations within the robot's workspace in an unlimited number of ways. This was our main focus while we tried to design the robot following the human arm geometry. These humanoid arms can perform any manipulation task that a human being can do with his arm with a limited payload capacity of up to one kilogram." Cyton was completely designed and developed in India.

In general, robotics offers many examples of the nature-inspired kind. Energid itself has another example to offer: their Citrus fruit harvester works much like how a frog hunts a bee.

Approach 4

"I was trying for long to solve a problem. Luckily, nature gave me a clue."

In the previous approach, the engineers decided consciously to study nature in order to find a solution to their problem. The experience of Dr Vinay Vaidya, chief technology officer, Engineering, and CREST Leader, KPIT Cummins Infosystems, is slightly different. Dr Vaidya was on the task of developing an image enhancement system for automobile, when he chanced upon a clue from nature in the form of the shape of the leaf. He was vigilant enough to notice it, research it further and use it to advance his technology.

Dr Vaidya recounts, "While we were working on finding a solution to enhance an image, especially under night driving conditions, I came across a leaf with a shape similar to that of cardioids."

Cyton humanoid manipulators mimic nature's ultimate engineering marvel—the human

A cardioid has remarkable properties. The shape is formed in an interesting way. Take two circles of unit radius, rotate one circle over the circumference of another and the trajectory that is formed takes the shape of a cardioid.

Dr Vaidya continues, "Our image enhancement solution is solely inspired by the shape of the leaf, which helped us to enhance the image. We could device a function around cardioids: if there are pixels which are very dark, then increase the pixel value; and reduce the value if there are brighter pixels. Through the entire exercise we actually came up with a solution for better images under night driving conditions. We have filed for a patent that includes cardioid method along with other novelties for night vision," he says.

Strongest playgrounds

Some areas of science and technology where biomimetic techniques have been found to be very effective are:

1. Machine vision systems
2. Machine hearing systems
3. Signal amplifiers
4. Navigational systems
5. Data converters
6. Neural networks
7. Nanorobot antibodies (to seek and destroy disease-causing bacteria)
8. Artificial organs, arms, legs, hands and feet
9. Implantable devices

Inspiration or imitation?

Nature-inspired technologies fall into a certain classification, or rather progression, of terminologies such as bio-inspired, biomimetic, biomorphic and bio-replication.

Bio-inspired. Any artificial design, process or product that is inspired by nature is a bio-inspired one. Some researchers say that it is an umbrella term that covers all the others, while some restrict it to just those products which exhibit a natural functionality but do not employ the underlying natural principles.

Bio-morphic. "Bio-inspired just takes inspiration from biology, whereas bio-morphic seeks to exploit the same solutions or employ the same organising principles. The term 'morphic' comes from structure, emphasising arriving at the same function by mimicking the underlying structure or architecture," explains Dr Kwabena Boahen, associate professor, Bioengineering Department, Stanford University.

Dr Boahen is principal investigator of their Brain in Silicon project—a biomorphic or rather neuromorphic one. The team tries to use existing knowledge of the brain's functioning to design an affordable supercomputer. The other complementary side of their research is to use the same supercomputer to further investigate the functioning of the brain.

According to the team, "We model brains using an approach far more efficient than software simulation: We emulate the flow of ions directly with the flow of electrons—don't worry, on the outside it looks just like software."

Developed through a neuromorphic approach, this supercomputer, called the Neurogrid, has a parallel, interconnected architecture like the brain. Its building block is not a logic gate—like in a digital computer—but a silicon neuron whose behaviour and connectivity are programmable. Read more about the programmable silicon neuron at http://www.stanford.edu/group/brainsinsilicon/about.html#Emulate.

Bio-replication. Some also use the term 'bio-replication' interchangeably with 'bio-morphic.' However, there is believed to be a subtle distinction. Bio-morphic mimics the underlying structure, whereas bio-replication completely reproduces it. The only difference between the natural and artificial designs in the case of replication is brought about by the difference in material.

Biomimetics. As a middle path, we have biomimetics, which involves mimicking a natural function with certain features of the natural structure that make the function possible reproduced in the design.

"Biomimetics utilises natural techniques for inspiration, and not the absolute blueprints. The needs of any individual organism are likely to be vastly different from our own, and most adaptations are reached through compromises. A given eye design may have good anti-reflection properties, but they may have been tuned specifically for a small cone of vision, or be restricted in the wavelengths of operation," comments Dr Judith Braganca, BITS Pilani, KK Birla Campus, Goa.

"Biomimetics provides an immense database of designs that can inspire creative thought. This technique evolves and grows with the development in research and technology much like the evolution of nature," he adds.

Dr Braganca works with a group of salt-loving micro-organisms that are known to inhabit salt pans. These grow under stress conditions of high solar radiation, 25 per cent salt and sometimes anoxic (anaerobic) conditions. They are brightly-pigmented with red, orange and pink pigments.

"These pigments have been implicated to protect the organisms from sunlight as their production can be increased with exposure to light. So, we are in the process of designing a sunscreen with these haloarchaeal pigments for human use so it will protect the skin from ultraviolet (UV) radiation," she explains.

Why let nature solve our problems?

The strongest reasons cited in favour of nature-inspired solutions are that they are likely to be evolutionary and sustainable. "Biology is really the only technology that we know is sustainable. The more we understand and exploit biological solutions, the more sustainable our technology will become. In the neuro realm, this means lower power, higher robustness, and the ability to scale to the nano-scale, despite increasing heterogeneity and randomness," says Dr Boahen.

Jayakrishnan opines that solutions based on nature are also very robust and adaptive. He says, "With over two billion years of research and development, nature has evolved highly-efficient materials, structures, tools, mechanisms, processes, algorithms, methods and systems. Design approaches inspired by nature often result in systems or processes that exhibit much greater robustness in performance in unstructured environments compared to existing ones."

Dr Lakhtakia points out that there might be certain advantages in hindsight too. "Imitation of a natural solution could be beneficial as it may open up a possibility not thought of earlier. For instance, one could copy the shape of a certain natural structure for optical purposes but later find that the shape confers mechanical robustness as well under certain conditions. In pharmaceutical ethnobotany, a certain drug isolated from a certain plant used traditionally for the treatment of a particular ailment may turn out to be useful against another ailment as well. Thus, there may be an additional advantage, but only in hindsight," he explains.

Respect and learn, do not underestimate

While it sounds all hunky-dory, nature-inspired theories, designs and products are not as easy as the simplified accounts of Newton's or Archimedes' discoveries that we read in primary school. It involves systematic research, a multi-disciplinary approach and lots of risk too.

In the course of the discussion, Jayakrishnan makes it clear that to gain inspiration and guidance from nature is not an easy task. It involves multidisciplinary research and a certain degree of reverse engineering too.

"The creations of nature are biological models subjected to principles of physics, chemistry, mechanical engineering, materials science and many other branches of science and engineering. So, it is required to perform a highly systematic reverse engineering by dividing the system or process based on each category of the principles involved, mathematically modelling and identifying an analogy for each from the artificial world," he says.

Dr Braganca agrees, "Creating any nature-inspired design or product requires an amalgamation of many sciences. To replicate the photomechanical heat-sensing mechanism of the beetle Melanophila acuminate for creating a biomimetic infrared sensor, one would require expertise in both the biology and engineering," she says.

So in general, mapping the concepts learnt from nature to the physical realm is a huge challenge. Nature has many complex creatures that have various ways of structure, survival and signalling. Applying these to product and design applications involves manifold challenges, which are not to be underestimated while undertaking a biomimetic project. Of course, it is obvious that the benefits make the efforts worthwhile. So, wish these researchers all the best! ●

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