Opening **Nature's Toolbox**

By Brent Barker

Nature has been in the research and development business for 3.8 billion years, and has in the process filled a toolbox with ingenious solutions that we are just beginning to open, understand and appreciate. The fields of energy, computing, and communications, to name just a few, are already drawing upon aspects of biologically inspired design for novel engineering solutions, but the potential has barely been scratched. If we are to give credit where credit is due, some of the great engineering designers of the 21st century will likely include not only human beings, but whales, termites, birds, butterflies, fish, bees, reptiles, and slime mold.

Slime mold—not quite plant, not quite animal—forages on the forest floors in wet temperate climates. They are not particularly smart, but in one experiment recently written up in *Science* Magazine, they optimized a food transport system that replicated the existing rail system in Japan. The researchers placed oat flakes in the exact geographical pattern of Japanese cities, and started the creature's growth from Tokyo. It spread out in every direction, initially filling all the available land space, but once it found food sources, it thinned out the network, leaving a network of transport tubes to carry food to all parts of the organism. It found the shortest path connecting all points and built redundant paths in case of an accidental disconnection, thereby making the overall system highly resilient.

"We show that the slime mold, *physarum polycephalum*, forms networks with comparable efficiency, fault tolerance, and cost to those of real-world infrastructure networks—in this case, the Tokyo rail system," said Atsushi Tero and his colleagues at Hokkaido University. "The core mechanism needed for adaptive network formation can be captured in a biologically inspired mathematical model that may be useful to guide network construction in other domains." This could one day include electrical system design.

A companion study by researchers Adam Adamatzky and Jeff Jones in England used oat flakes to represent Britain's principal cities and found, once again, that the slime mold was able to replicate the design of the British motorway network with uncanny accuracy. This suggests that the potential benefit of tapping into the embedded intelligence of even the most primitive creatures on the planet is great.

When asked about the slime mold research, Marc Weissburg, professor and co-director of the Center for Biologically Inspired Design (CBID) at Georgia Institute of Technology, said, "I wasn't surprised. Biological systems are really constrained to be very efficient users of energy. As a physiologist, I know that one of the constraints of complicated animal systems is to minimize transport costs. Some of the really rich theories in animal physiology today concern scaling and growth and how animals can minimize transport costs as they grow.

Some early analysis suggests cities follow the same rules that animals use in scaling and metabolism."

Some of today's most pressing problems in energy and the environment line up well with solutions nature has been slowly developing through trial and error. The long time period over which evolution can work and the large number of organisms out there to test novel design solutions means "biology is a good place to look for energy efficiency, a good place to look for waste minimization, and a good place to look for things that don't rely upon expensive materials," said Weissburg. "Metals are horribly expensive materials, both biologically and technically. Biology works with protein, the cheapest thing out there. So that is what is in animals."

The kingfisher bird can dive for fish without a splash and efficienctly traverse both environments. Researchers in Japan used this to create a nose for bullet trains that is both quieter and uses less electricity while travelling faster.

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Examples of energy efficient design abound in nature because even a 1 percent improvement in energy efficiency over millions of years can provide real competitive advantage. The humpback whale is a case in point. The leading edge of their fins contain a noticeable series of bumps, incongruous with classic aerodynamic design that says the leading edge on wings and rotors should be smooth to reduce turbulence and maintain stability. However, Frank Fish, a biology professor at West Chester College in Pennsylvania, found that the bumps provide distinct aerodynamic advantage, channeling the flow of water over the fins more efficiently, reducing turbulence and allowing the humpback to maintain thrust at a higher angle of attack. Testing the design in a wind tunnel using a wing with a serrated leading edge, Fish found the serration reduced drag by 32 percent and increased lift by 8 percent. Fish has patented his "tubercle technology," created a company called WhalePower and is now moving into the wind power business, partnering with EnviraNorth Systems Ltd in Toronto. Their machines are notable for being able to operate at much lower wind speeds than conventional turbines, thereby improving economics and expanding the range of useful wind resources.

Janine Benyus, president of the Biomimicry Institute in Missoula, Mont., suggests that engineers faced with a problem might well ask themselves, "Who or what in the natural world is doing exactly what I want to do and doing it well?" This often takes an engineer with specific knowledge of the natural world to see or stumble upon the connection, what Marc Weissburg calls the "ah ha moment." The most famous in modern lore was the Swiss engineer, George de Mestral, who in 1948 returned home after a walk with his dog and examined the cockleburs stuck to his jacket and the dog's fur. That was the inspiration for Velcro.

Less well known is the high-speed rail engineer in Japan who was also an amateur birder. Nakatsu Eiji was struggling with the noise problems associated with the Shinkansen train of the West Japan Railway, specifically the problem of the world's fastest bullet train, running up to 200 mph, when passing through a tunnel. The train would push the air in the tunnel into a pressure wave that would slow the train down and release a sonic boom when it exited the tunnel. With Japan's strict noise ordinances, it was an untenable situation, startling people up to half mile away. Nakatsu asked himself, "If there is something in nature that travels quickly and smoothly between two different mediums?" He thought of the kingfisher bird, which can dive for fish without a splash, and efficiently traverse both environments. He worked with his colleagues to digitize the profile of the kingfisher. The end result is a new 50-foot nose on the bullet train modeled directly on the kingfisher's head and beak that spearheads a train that is not only quieter, but uses 15 percent less electricity while traveling 10 percent faster.

A similar noise problem existed with the overhead electrical connection of the bullet train, specifically the sound made by the panto-

The natural HVAC systems found in large termite mounds in Sub-Saharan Africa were used as models for the systems in the Eastgate building in Harare, Zimbabwe.

Fish harvest the energy from the vortex that is shed by the fish near them to make their own propulsion more efficient.

graph, which draws electrical current from the overhead catenary. In this case, the engineers drew upon a design feature of the owl, specifically the tiny, splayed terminal feathers of their wings that can break the flow of air passing over them into miniscule vortices that are barely audible. With this design, the owl can fly right past your ear and you can't hear it, a distinct advantage for night hunting. The train's pantograph was redesigned with a series of tiny protrusions like the tines of a comb to break up the air flow into small, inaudible vortices.

Building design is also being influenced. The Eastgate building in Harare, Zimbabwe, for example, is designed after the natural HVAC system of the large termite mounds found in the sub-Saharan region of Africa. Whereas the outside temperature surrounding the mounds varies between 107 degrees Fahrenheit during the day and 37 degrees Fahrenheit at night, the hive remains at a constant 87 degrees Fahrenheit. The mound reaches down into the cooler earth unaffected by the daily heating cycle, and employs a series of fins and channels to bring air in through the bottom, cool it, and let it rise using natural buoyancy currents and the pressure difference created by the air flowing over top of the mound. Sufficient heat is retained in the large mud and straw structure to keep the temperature steady during the cold nights. The Eastgate building reportedly uses only 10 percent of the electricity used in conventional buildings in Zimbabwe for HVAC.

A number of more speculative design concepts have emerged that show promise in fields as diverse as energy, photonics, and computing, three fields with future significance for power engineering. One idea involves the energy potential of animal aggregation found in schools of fish and flocks of birds. According to Weissburg, "Fish get energy from the vortex that is shed by the fish near them. They harvest this energy to make their own propulsion efficient, much as the cyclists do in the *Tour de France*. Even salmon running upstream use the energy from the vortices created by large rocks and boulders in the stream bed. They find the whirls and use them to help power their swimming." This is a long way from practical application but it's the kind of challenge that Center for Biologically Inspired Design Director Jeannette Yen loves to throw at her students. "Could you use this to generate power? What if you combined this idea of harvesting vortices with the energy of a flapping foil?"

Another idea mimics the foraging process of honeybees to create a forward-looking, adaptive decision making tool (an algorithm) for allocating computer server time. The problem is one endemic to organizations like Amazon.com that process orders where the frequency and volume of traffic is erratic and processing time is highly variable. The question is how to optimize the allocation of computer server time for a variety of different applications. Traditionally, the analysts trying to solve this problem would gather as much historical data as possible, find the patterns, and then write code to allocate what the servers should do based on historic patterns. It can be effective, but it takes a lot of time to develop and it is inherently backward looking. If the situation is dynamic and evolving rapidly, the usefulness of the algorithm will degrade rapidly. Sunil Nakrani of Oxford University and Craig Tovey of Georgia Tech have found that the server requests are "patchy" and that honeybees solved a very similar problem eons ago. "Foraging bees visiting flower patches return to the hive with nectar and with a value rating on the nectar quality, nectar bounty, and distance from the hive. …and then do an enlisting signal known as the waggle dance. The waggle dance is performed on the dance floor where inactive foragers can observe and follow." Each bee then decides opportunistically where and when to go, which is the equivalent of the computer decision of how to allocate processing time. Nakrani and Tovey believe it will be much simpler to create an algorithm that follows the honeybee rules than to construct a set of rules based on data. Moreover, the system will be much better at adapting to changing conditions just as the honeybees adapt to flower patches that come and go.

A third idea is to use the photonic techniques animals use to manipulate light and eventually adapt them to improve the light collection efficiency of solar technologies. The electric blue color of tropical butterflies comes not from pigments but from structural design. In fact, if you shined a light through the wings, it would appear translucent. The bright blue comes from the micro-structure of the scales on the butterfly's wings, which are made of protein and shaped like columns and pillars. These structures bounce light around and are capable of producing multiple colors visible from wide angles. "The principles are well known and referred to as Braggs Reflectors," said Weissburg, "but if you asked someone to design a multicolor Bragg reflector from scratch they would tear their hair out." Nature's designs can be extraordinarily complex even if the underlying principles are understood.

Efficient use of energy and light is necessary for survival in the natural world. Fireflies had developed a biological design that can transform oxygen, luciferin and luciferase in its abdomen into light with nearly 100 percent conversion efficiency. Some animals, such as deep-sea creatures, have become very good at channeling what little light they receive to their photo receptors. Some use photonic pistils to transmit light very efficiently over large distances like highly efficient fiber optic cable.

Where will these lead? It is too early to tell, but important to remember when lasers first came on the scene in the early 1960s the primary application most people envisioned was the ability to survey a straight line. It was beyond comprehension that someday lasers would be used for eye surgery, playing music, and transmitting long

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distance communications. Qualcomm has begun to use photonic principles for display technology in cell phones, but this is just a beginning. The full flowering, as with lasers, will take decades.

Biologically inspired design (BID) lies at the nexus between engineering and biology, falling into the exciting but institutional gray area of cross-fertilization. Centers of excellence have been set up at a number of leading universities to pull faculty together into specific areas of collaborative research; Duke, for example, has a renowned program in materials, Harvard in biomedicine, University of California–Berkeley in biomechanics and robotics, and the University of Arizona in complex systems. Georgia Tech's Center for Biologically Inspired Design (CBID) is somewhat unique by focusing not so much on specific technical areas, but rather on the education and training processes underlying BID. One of their strengths is working with cognitive scientists to figure out how to teach BID more effectively and how to stimulate the core thinking process, particularly at the undergraduate level. Georgia Tech is among the few, if not the only, centers of its kind in the United States to take a comprehensive and systematic approach to BID education.

Ironically, in an area filled with so much promise, the United States has been slow to embrace it. "We in the U.S. are way behind the curve on BID," said Weissburg. "There are very large efforts in the U.K. and Japan to fund BID from an industrial and research perspective. We've been invited to Japan to talk and educate people on how to do BID but have rarely been approached by American companies. We've had people here from Hatachi, Diahatsu, Fujitsu, but unfortunately U.S. industry has not shown up; they have not wanted to engage in more formal training in BID. BID is coming into its own and where are we? Where do we want to be in 20 years?"

Biologically inspired design is not new conceptually. It goes back to Leonardo daVinci and before that to the Greeks and Romans, and before that back into pre-history when people observed and adapted useful things from nature. But now the need for a more systematic approach is needed. As a society we are now facing the same kind of constraints that biological systems have faced for millions of years in terms of the urgency for greater energy efficiency, waste management, and sustainable development.

"Biologically inspired design is transformational," said Weissburg. "Our history of technology is very different from the history of biological organisms, and everything we think about a problem is conditioned by the toolbox we know about. Biology represents an alternative view and offers us an alternative toolbox of solutions. ■

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