Intentional Biology: nature as source and code

Technology Horizons Program | SR 1051

1 | INTRODUCTION: NATURE AS SOURCE AND CODE

For most of our history, humans have treated Nature as a gigantic warehouse and commissary. The natural world has been a source of raw materials, food, and other resources. Today, rapid advances in biological science and the growth of nanotechnology are taking that inspiration to a new level and driving the creation of a new field: intentional biology. Intentional biology, and its two main subfields, biomimicry and synthetic biology, treat nature not as a source of raw materials, but as source and code. This report, *Intentional Biology: Nature as Source and Code* (SR-1051), reviews the growth of these subfields; describes some of their key accomplishments; and explores their potential futures and impacts.

In the last decade, biomimicry has influenced everything from materials science and robotics to architecture and even management and organizational design. **Biomimicry sees Nature as a source of new materials**, **structures, and processes**, and it aims to create new, lightweight technologies and organizational forms based up on natural analogs. **Synthetic biology sees Nature as code**, as sets of instructions guiding the fashioning of living organisms. By learning how to manipulate this code, we'll not only genetically re-engineer existing life but actually create new life forms with purpose.

Borrowing from Nature is not new. The natural world has always been a source of materials and ideas for architects, artists, and engineers. That's exactly what makes intentional biology so important: it promises to bring novel scientific and technological knowledge to bear on design processes as old as life itself.

THE FACES OF BIOLOGICAL INSPIRATION

Humans have drawn on nature for resources and ideas since the earliest civilizations, and have sought to adapt or change nature for their own purposes. But the level at which those inspirations and adaptations have been applied are changing. To understand how, consider three scenes.

The first is a farmhouse in the 1600s. It's made of stone and timber with a thatch roof. In the winter, it's warmed by wood, charcoal, and perhaps peat. Outside, cows graze in a small field, chickens peck at the dirt, and a dog keeps a sleepy watch.

The second is an Art Nouveau townhouse around 1900. While it's located in the city, the windows, gate, and walls are decorated with a riot of natural shapes and forms. Iron railings twist into the shape of vines and creepers; lampshades look like violets and lilies; window details curve like the paths of waves on a beach. A

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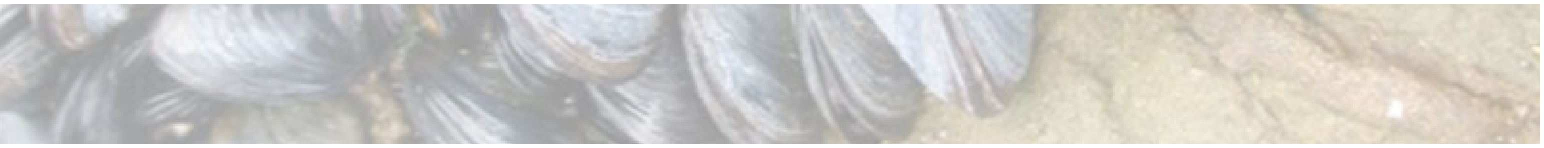
purebred Perisian cat sits in the window, while a small rooftop coop holds fancy pigeons.

The last is house is from the near future. In most respects, it looks like a conventional piece of modern architecture, with sleek, clean lines. But some of the construction materials used in the house were made in factories that produce no pollution. It has a ventilation system that eliminates the need for air conditioning, while keeping the house comfortable. Its windows have a self-cleaning coating that sloughs off dust and dirt. Its roof and driveway are covered in permeable bricks and genetically engineered grasses, not shingles or asphalt.

Each house, in its way, draws on the natural world, but does so in a very different ways. The farmhouse treats Nature as a source of materials. The house is built from natural resources chosen for their abundance and properties—the wood compresses and stretches as the temperature changes, the thatch expands when it rains—but humans do nothing to adjust those properties. The cows and chickens are descendents of animals domesticated thousands of years earlier. The Art Nouveau house treats Nature as a source of aesthetic beauty and inspiration, but while it is filled with objects that mimic natural shapes, those objects do not mimic natural functions: a gas light shaped like a snake is no more reptilian than a piece of lead pipe. The purebred animals are as customized and decorative: breeders have learned how to tailor animals' color and plumage, but their only tool is selective breeding, which yields results over the course of generations.

On the surface, the last house looks the least inspired by nature. But it doesn't just use natural materials, or use nature as an aesthetic guide; it copies natural structures and processes. The factories that make its construction materials are designed to use little energy and generate little pollution. The house's ventilation system is inspired by termite mounds, which use ventilation shafts and water catchments to maintain a constant temperature even in extremes of desert heat and cold. The windows are covered with a nano-engineered coating whose microstructure is similar to that of the lotus flower, which is famous for its ability to stay perfectly clean even in mud. And the roof and driveway have engineered grasses that, along with modified fungus and soil bacteria, are designed to break down airborne toxins, filter rainwater, and sequester unnaturally large amounts of carbon. In this house, Nature is not a warehouse of raw materials, or a source of aesthetic inspiration; it's an R&D and prototyping lab, a source of high-performance materials, architectural solutions, manufacturing processes, and building-blocks for hybrid organic-engineered systems.

Drawing inspiration from biological processes; copying designs at the molecular or cellular levels; reinventing organisms as tiny factories and machines: this is the world of intentional biology.

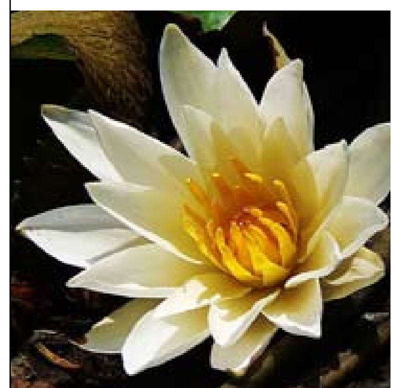


2 | BIOMIMICRY TODAY: DISCOVERIES AND USES

Biomimicry today operates at three levels: materials, machines, and processes.

Biomimicry is driven in part by recognition of just how remarkable Nature's engineering feats are. If in the past we created wealth from Nature by exploiting natural resources, in the future we'll also create wealth by collecting and leveraging information about how those resources were made and why they work.

Research in biomimicry falls into three broad areas: Nanotechnologists, chemists, and physicists are developing new kinds of materials that imitate molecular structures generated by plants and animals. Aerospace scientists, mechanical engineers, and roboticists are drawing inspiration from natural structures to create new designs for propulsion systems, bridges, and robots. Finally, architects, industrial engineers, and agriculturalists are trying to replicate natural processes for maintaining stable environments, manufacturing complex materials, and growing food.



Source: http://www.flickr.com/photos/pandiyan/51192366/

MATERIALS BIOMIMICRY

Chemists and physicists have spent centuries studying natural structures. One of the great works of Renaissance science was Robert Hooke's 1665 *Micrographia*. But until recently, scientists had a much harder time replicating those structures. Now, though, scientists working in *materials biomimicry* and using nanotechnology has made it possible to understand natural materials in far greater detail, and to design synthetic versions of them.

Just as in Hooke's day, some of the most interesting creatures are the most modest.

Enlightenment and the Lotus

The lotus flower has provided one of the more recent commercial successes. Its remarkable ability to stay clean even in muddy flats attracted the attention of engineers working on self-cleaning surfaces. Electron microscopy reveals that the lotus remains clean because of tiny indentations that trap air and prevent water or dirt from clinging to its surface. British and German scientists have created a transparent material that is used as a coating on windows.

Source: http://www.flickr.com/photos/automania/97936640/

Spinning Webs

Scientists are also closing in on a suggestion of Hooke's to create a synthetic analog to spider's silk. It's long been known that a spider's web consists of several different kinds of silk—the children's classic *Charlotte's Web* discusses them—but recently scientists have begun to unravel how spiders vary the chemical composition of their silk to produce different properties. No company has yet successfully manufactured artificial silk, but several are trying, and no wonder: spider's silk is stronger than steel by weight, and rivals expensive fabrics like Kevlar in its ability to deform and absorb energy, and has serious potential for use in surgery, prosthetics, and defense.

Hanging Around

Spiders hang around on their webs; but thanks to the nanoengineering on their feet, geckos can hang around on just about any surface. This talent has made geckos one of the most popular laboratory animals in biomimicry research. Scientists have found that geckos have microscopic cilia on their feet that attach to surfaces thanks to van der Waals forces—forces long known to chemists and physicists, but not often encountered, much less exploited, by engineers. Scientists are now trying to create a synthetic gecko tape that can be applied and removed as easily as a Post-It, but adheres without adhesives or chemicals.

Source: http://www.flickr.com/photos/68777870@N00/320270807/

Mussel Strength

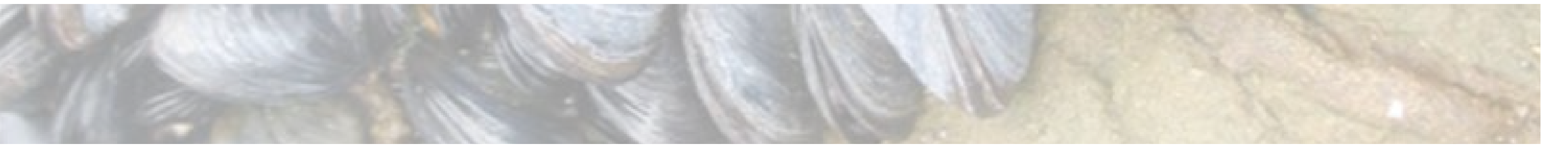
Finally, shellfish turn out to be some of Nature's most accomplished materials scientists. They can create exceptionally durable shells from a few basic materials, most notably calcium carbonate and proteins. An abalone shell, for example, consists of many alternating layers of calcium and organic polymer, a combination that gives it both strength and the flexibility necessary to form curved shapes; moreover, the polymers orient the calcium molecules in ways that maximize their strength. Other shellfish generate strong adhesives that they use to attach themselves to rocks and reefs; scientists have customized soy proteins to create an adhesive similar to the glue that blue mussels use to bind themselves to rocks. Not only is this cheap—soy is already extensively farmed in the United States, Europe, and Asia—it can also replace more toxic adhesives used in plywood and housing material.

Where It's Happening

Research on materials biomimicry is dominated by academic and industrial researchers, particularly in Germany, Great Britain, and the United States. The most notable projects have usually involved academic–industrial collaborations. "Lotus-effect" coatings, which are used to make self-cleaning glass paints, were developed by scientists at British glass maker Pilkington, and by a German botanist working with Rhineland glass and chemical companies. Scientists studying the biomechanics of gecko adhesion are academics, but are starting to collaborate with manufacturers interested in commercializing the effect. The soy-based adhesive that mimics mussel adhesive was developed by Oregon State professor Kaichang Li.

Future Directions

Work in materials biomimicry will grow rapidly in the coming decade, pushed by advances in nanotechnology, and demand for the improvements that materials biomimicry has to offer. First, bio-inspired products can be cheaper than their industrial competitors, since they often use very inexpensive ingredients, and can be made with less energy than more conventional materials. Second, they are often much



less toxic than more traditional materials, and as we become more aware of the environmental and health consequences of exposure to chemically harsh materials in our everyday environments, bio-inspired materials are likely to become more attractive.

MECHANICAL BIOMIMICRY

While chemists and physicists work at the molecular level with designs first developed by living forms, civil engineers, mechanical engineers and roboticists working in *mechanical biomimicry* are looking to birds, insects, and other animals to improve the design of larger-scale devices, like aircraft wings, rotors, and space probes.

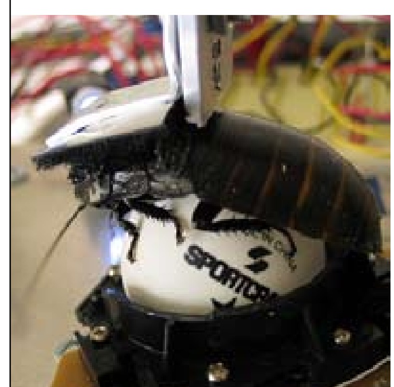
Source: http://www.flickr.com/photos/zevy/213492302/

Improving Wings and Rotors

Mechanical and aerospace engineers are studying birds and insects for clues about how to make vehicles quieter and more efficient. Scientists at NASA's Langley Research Center are working on aircraft wing designs that generate very little noise, thanks to a serrated trailing edge similar to the trailing feathers that make an owl's flight nearly silent. Biologically inspired rotor blades may also appear on wind turbines. Engineers in Britain are working on a radical new turbine blade design based on sycamore seeds, which could dramatically increase the amount of energy generated by wind farms.

Biorobotics and Microrobotics

Other scientists working in biorobotics are focusing on ground locomotion. Scientists have been working for decades on replicating human locomotion, for the purpose of creating humanoid robots (Sony's Asimo is a good current example), but more recently scientists have begun looking at other animals. A research group of engineers and physiologists at UC Berkeley, Stanford, Johns Hopkins, and Harvard has developed robot cockroaches; they're still larger than even the largest cockroaches, but their legs move in the same scurrying pattern. A multinational European research team is working on a robot cockroach that can infiltrate and poison nests, the first step in a broader program to develop robots that can influence the behavior of animals. (Indeed, robotic cockroaches are sufficiently well-known to have spawned an artistic commentary. In the Cockroach Controlled Mobile Robot, a Madagascar hissing cockroach pilots a wheeled robot by running on a trackball.) Roboticists at NASA Ames and the University of Bremen have created a robot scorpion for potential Mars exploration. Closer to home, Northeastern University's Biomimetic Underwater Robot Program has developed a robot lobster that can explore the bottoms of lakes and rivers.



Source: http://www.conceptlab.com/roachbot/

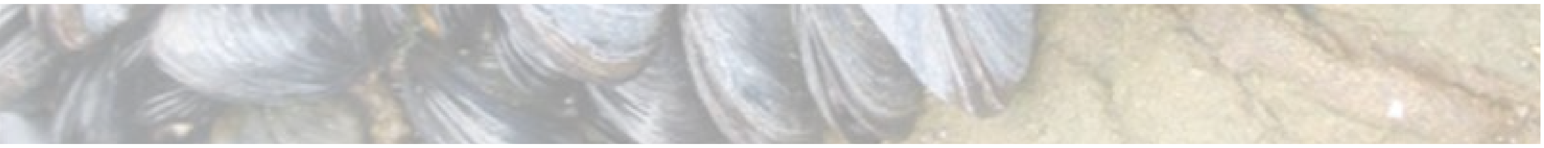
Microrobots are attractive because they could be relatively cheap—most use open-source or off-the-shelf sensors and actuators, microprocessors, and locomotion programs—and deployed in large numbers. This also means that it should be possible to make them swarm—to move in a coordinated manner, and work together on tasks. Space scientists have traditionally had to design missions around individual, expensive robots; this is an inherently risky strategy, since it makes space exploration an all-or-nothing enterprise. Mars, which is the next major target for space scientists, is a particularly difficult environment: more than a third of spacecraft sent there have failed, and its atmosphere is too thin to make exploration with fixed-wing aircraft practical. If scientists could send a package of dozens of robotic scorpions and dragonflies, rather than a single complex robot, they could explore more territory, take more risks, and absorb losses that are unthinkable with today's technology. Likewise, swarms of microrobots could be used for battlefield reconnaissance and in search and rescue (exploring collapsed buildings, for example).

Where It's Happening

Scientists working on *mechanical biomimicry* are likely to be academics, but unlike their entrepreneurial colleagues in materials biomimicry, they tend to be more connected to governments than the marketplace. Industrial robotics have been used to automate assembly lines in factories that, by definition, are very structured environments. Military and space environments, in contrast, are by definition rugged, highly variable, and dangerous, and require robots that are highly mobile. Biorobotics is almost wholly supported by the military, particularly in the United States. DARPA's Mesomachines for Military Applications project has funded a number of projects on insect-based robots, particularly airborne microrobots; the Office of Naval Research (ORN) has emerged as a major player in underwater microrobotics. On the civilian side, NASA has funded studies of insect locomotion, while the National Science Foundation (NSF) has supported work at the interface of biomimcry and materials science. It's not unusual for research groups to draw from several of these sources at once: Case Western Reserve University's Biorobotics Lab, for example, is funded by ONR, NASA, NSF, and DARPA.

Future Directions

In the coming decade, most of the leading-edge research on biomimicry and motion will not be aimed at improving the quality or efficiency of existing technologies, but will seek to create entirely new classes of objects: robots that can scurry over rocky terrain, fly and hover, and swarm. Research groups working on microrobots—tiny robots that could be used for scientific research and military reconnaissance—are scrutinizing the wing shapes of dragonflies and common house flies, with an eye to creating bots that can hover and turn quickly. This work presents a number of challenges, ranging from the design of the wings themselves, to the power source that moves the wings, and the controls necessary to keep the wings at exactly the right angle to hover or turn. Insects, it turns out, shouldn't be able to fly, given their mass-to-wingspan ratios; they get aloft thanks to a number of tricks that increase the amount of lift their wings generate.



PROCESS BIOMIMICRY

Natural forms are providing scientists with design templates and inspiration at the nanometer scale (in the case of new materials) and centimeter scale (in the case of insects). Process biomimicry applies emerging research on natural processes to innovative designs in architecture, resource conservation, and management. It looks not to spider's webs, but energy and food webs, to understand how to create lighter, more efficient, and sustainable (or self-sustaining) technologies and systems.

Architecture

Architects have always designed buildings that fit their environments, by adjusting their height and scale, or by using local materials. In the early 20th century, Frank Lloyd Wright's low, sweeping Prairie Style homes were designed to mimic the plains of the Midwest; at the same time, his California counterpart Julia Morgan used local materials to create a distinctive West Coast style of modern architecture. In the 1960s, a handful of architects began exploring designs that were more resource and energy efficient, and avoided chemically treated finishes and furnishings. Such tactics are now mainstream, thanks to concerns about energy costs and "sick-building syndrome."

Plantation Place

Source: http://www.arup.com/facadeengineering/project.cfm?pageid=1794

Architects are now moving to design systems that copy natural processes, or draw on their environments in clever ways. Arup Associates' Plantation Place has a ventilation system inspired by human lungs. Located in the center of the City of London, Plantation Place's air supply is drawn from the top of the building, passes through a garden terrace, and then circulates throughout the building: they designed the system after site planners discovered that the air at the top of the building would be considerably cleaner than that at street level. The Commerzbank Tower in Frankfurt likewise uses massive interior gardens off a central, 900-feet tall atrium to deliver fresh air to its 2,500 bankers. Most famously, the Eastgate Centre in Harare, Zimbabwe stays cool from cross breezes generated a ventilation system inspired by giant termite mounds. The ultimate aim of such designs, as Bob Berkebile and Jason McLennan put it, is to create buildings that are "designed to function like living organisms, specifically adapted to place and able to draw all of their requirements for energy and water from the surrounding sun, wind, and rain."

Eastgate Centre

Source: http://fremdsprachen.ws.fh-konstanz.de/llz/sa_schulz/images/eastgate01.jpg

Natural Resource Management

The African desert has produced other insects whose survival strategies are now inspiring architectural designs. The Namib desert beetle (*Onymacris unguicularis*) has become a model for water collection. The beetle's habitat is one of the driest parts of the world, and the only moisture comes from morning fog. The beetle has evolved wings covered with a waxy, hydrophobic (water-repelling) coating, punctuated by hydrophilic (water-attracting) ridges. In the morning, it raises its wings, and fog forms droplets on the ridges, which then trickle down the wing—into the beetle's mouth. Fog collectors are starting to copy

Source: http://upload.wikimedia.org/wikipedia/commons/7/7a/Nebeltrinker-K%C3%A4fer-1.jpg

this strategy of combining hydrophilic and hydrophobic surfaces to increase their efficiency, and plans for the University of Namibia's hydrological research center include a giant fog collector based on the desert beetle.

Human Resource Management

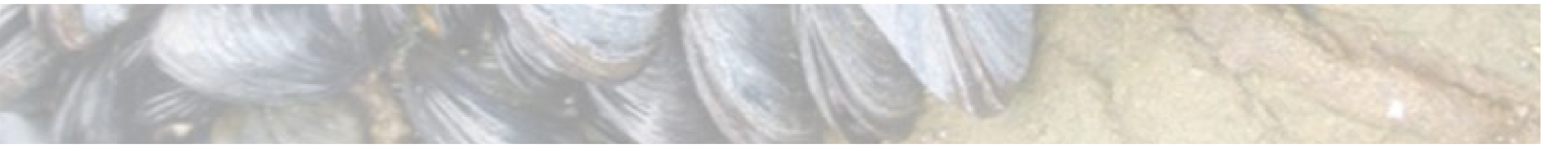
Finally, ideas from research in animal communication and behavior are being taken up in management and organizational design. Appeals to Nature are nothing new in organizations, of course; what is new is the push to move beyond metaphor into organizational design. Thus monarchists looked a beehive and saw absolute rule; today, biologists see a model of self-organization and swarming behavior. Students of netwar and smart mobs have already drawn parallels between pack and swarm behavior in the animal and human world; now software developers and project managers are starting to apply lessons from large-scale biological cooperative ventures to the design of distributed, collaborative tools and projects. The hope, as management theorist Ken Thompson puts it, is that by "looking at Nature's most successful biological teams," we can "uncover the secrets of extended cooperation and effective collaboration."

Where It's Happening

Process biomimicry is the broadest, and the least well-funded, of the three branches of biomimicry. Architects and civil engineers have done most of the work on applying insect ventilation systems to buildings; some have academic affiliations, but like their predecessors working on green architecture in the 1960s and 1970s, most have their own practices. Students of biological communication and collaboration are scattered among research institutes, universities, and consulting firms.

Future Directions

The future of process biomimicry is the most difficult to forecast, since it involves so diverse a collection of players and applications. However, it is clear that it will continue to be applied most aggressively in architecture, particularly as tenants and real estate managers struggle to lower the operating costs, energy consumption, and ecological footprint of new facilities. The architectural profession is also cohesive enough to allow innovative approaches and new technologies to spread rapidly, particularly when the payoff is clear. Resource management is, almost by its very nature, more localized and less cohesive, and innovations developed in one region are likely to require more time to spread, and more customization to work in new environments.



LINKS

Laboratory of Intelligent Interfaces
Seoul National University
http://chem1.snu.ac.kr/~lii/lii_research03.htm

LAMB: Laboratory for Active Materials and Biomimetics
Johns Hopkins University
http://pegasus.me.jhu.edu/r_biom.html

Biomimetic Underwater Robot Program
Northeastern University
http://www.neurotechnology.neu.edu/

Entomopter Project
Georgia Tech
http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html

Robotic Insects Lab
Plymouth University
http://www.cis.plym.ac.uk/cis/InsectRobotics/Locomotion.htm

Oxford University Animal Flight Group
http://users.ox.ac.uk/~zool0261/

Sustaining Tower Blocks:
The Design Guide for Sustainable Refurbishment
http://www.sustainingtowers.org/

The Living Building: Biomimicry in Architecture, Integrating Technology with Nature
Bob Berkebile and Jason McLennan
http://elements.bnim.com/resources/livingbuildingright.html

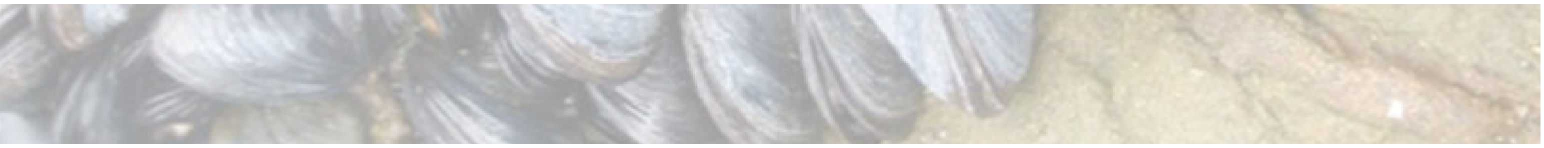
The Bumble Bee
A blog on biomimicry and management
http://www.bioteams.com/

3 | SYNTHETIC BIOLOGY TODAY: DISCOVERIES AND USES

Even as we look to Nature for inspiration and collaboration, we're also learning to hack life itself. For decades, molecular biologists have been shifting bits of DNA between organisms. This ability is at the core of the biotechnology industry. But traditional biotechnology draws from the parts that Mother Nature has already evolved. The next step is reengineering life itself. The aim of this emerging transdisciplinary research field is a parts store of interchangeable "biobricks"—genes, proteins, and cells that can be snapped together like Tinkertoys to build living systems. It's driven not only by a better understanding of biology, but also technology for cheaply sequencing and synthesizing DNA molecules.

Recently, Berkeley's Keasling Lab made strides in converting bacteria into chemical factories that produce the anti-malaria treatment artemisinin for pennies instead of dollars. The project, a collaborative effort with OneWorld Health, was supported with a $42.6 million five-year grant from the Bill & Melinda Gates Foundation. The research will inform the development of similar microbial factories that could crank out the costly anti-cancer drug Taxol, synthesized naturally by the Pacific yew tree, or produce a promising anti-AIDS drug derived from the Samoan mamala tree. Microbes are also in development that hone in on tumors in the body and release drugs to attack the cancer cells. Another prime target in synthetic biology is diatoms, algae with shells containing detailed features just a few nanometers in size. Designer diatom shells could be employed as filtration systems or self-contained catalysts for a lab-on-a-chip used for medical testing. Eventually, the structures could enable the fabrication of more powerful computer chips containing circuits patterned in three dimensions or act as substrates for the in vitro growth of human tissue for implantation.

But along with these possible pay-offs in medicine, materials science, and even electrical engineering, synthetic biology researchers have actively focused on lightweight infrastructure applications. Indeed, while the researchers think globally, these novel life-forms act very locally. Nature, re-engineered from the bottom up, could lead to entirely new methods to generate energy, remediate environmental damage, and leverage biology's own highly-evolved sensing machinery.



ENERGY GENERATION

Energy Becomes a Cash Crop, Literally

Since 1970, the worldwide consumption of energy has nearly doubled. In the next 20 years, it's expected to triple. As we're learning, our supply of fossil fuels is not limitless. Meanwhile, the consensus among scientists is that burning these fuels contributes to global warming. We need a sustainable source of energy that doesn't soak our atmosphere with carbon dioxide. Energy conservation will help, as might next-generation nuclear plants and wind farms. In the coming decades though, designer organisms are likely to emerge as a new clean fuel source for small- and large-scale systems and point-of-use production scenarios.

The best energy converter that the world has to offer is photosynthesis, the process that plants use to convert rays from the sun into chemical energy. While artificial solar cells inspired by Nature are in development, progress is slow. Leveraging the actual biological systems behind photosynthesis is likely to lead to new energy conversion systems sooner than biomimicry.

Biomass, specifically as a source of ethanol, is often touted as an ideal source of renewable energy. Ethanol is produced by fermenting renewable crops like corn or sugarcane. The problem though is that more fossil energy is used to fertilize, cultivate, transport, and distill the biomass than the energy contained within it. To tip the energy balance, researchers at the Department of Energy's Lawrence Berkeley National Laboratory are engineering plants that grow faster, fertilize themselves, and convert carbon dioxide, sunlight, water, and nutrients into biomass bursting with renewable energy.

The next step is to convert the biomass into fuels such as ethanol, methanol, methane, and hydrogen. Already, termites have evolved the ultimate cellulose-conversion machine inside their stomachs. Synthetic biology could lead to bacteria outfitted with similar cellulose-converting proteins that could efficiently convert the biomass and biowaste into fuel. Jay Keasling, who heads the Lawrence Berkeley National Laboratory's Synthetic Biology Department, and his colleagues began designing an organism that can ferment cellulose as a raw source of renewable energy.

While ethanol is often touted as an ideal alternative fuel whose production could be boosted with synthetic biology, Keasling points out that it can't be piped easily and has relatively low energy content. Instead, he'd like to engineer a benign organism to degrade waste paper or biomass and convert it into octane. However, inserting cellulose-converting proteins into a bacterium and scaling the process up to be practical is no easy task.

"You've got a relatively complicated and dirty system," Keasling says. "So you've got to engineer a microbe to actually go in, find the cellulose, turn it into sugar, and then through its metabolism turn that into fuel."

Source: http://www.flickr.com/photos/danellesheree/202844913/

E. Coli

Source: nanoarchitecture.net/article/?c=synthetic-biology

Bacterial Batteries Lead to Bioengineered Fuel Cells

While hydrogen fuel cells make front page news with the promise of non-polluting automobiles and energy-efficient homes, Boston University bioengineer Tim Gardner believes that synthetic biology could lead to fuel cells powered by bacteria. For example, certain bacteria convert glucose or even human waste directly into electricity. While simple microbial fuel cells have been demonstrated in the laboratory, they don't crank out nearly enough electricity for, say, cars and houses. Gardner is exploring whether bacteria can be engineered so that their energy output is enough for larger-scale fuel-cell applications.

"Some devices don't need much power or could benefit from the ability to use unusual fuel sources—a medical implant that gets power from the blood, for example, and never needs to get charged," he has said. "Or robots in the field that could grab a plant and convert it to power."

ECO REMEDIATION

Microbes Scrub Smokestacks

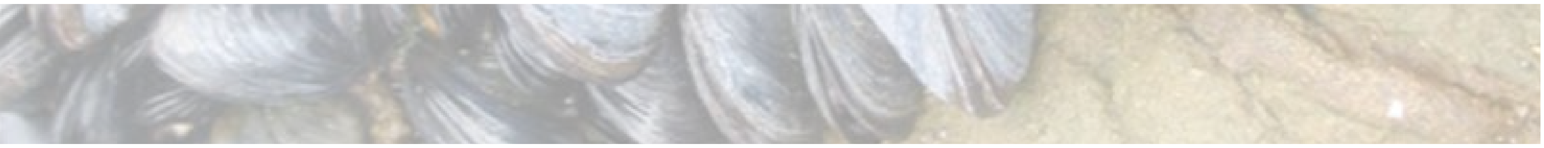
In 2005, J. Craig Venter, the biologist who famously led the commercial effort to sequence the Human Genome, launched Synthetic Genomics to develop industrial synthetic biology applications, particularly ethanol and hydrogen production.

For example, Venter suggested that the carbon dioxide spewing from power plant smokestacks could be converted by microbes into natural gas to power the boiler. The scientists at his company are also designing biological systems to convert sunlight directly into hydrogen through, once again, photosynthesis.

"We think this field has tremendous potential, possibly within a decade, to replace the petrochemical industry," Venter said at the recent Second International Conference on Synthetic Biology.

Engineered Organisms Clean Up Eco-Messes

Some organisms have the natural ability to degrade environmental contaminants or possibly biowarfare agents. Eventually, engineered organisms may not only have the ability to seek out various contaminants and toxins, as described above, but to digest them. Research is underway to modify *E. coli* so that it will "swarm" around a nerve agent and degrade it. Other bioengineers are exploring how microorganisms might be used to decontaminate hazardous waste spills and nuclear disposal sites.



“We have engineered *E. coli* and *Pseudomonas aeruginosa* to precipitate heavy metals, uranium, and plutonium on their cell wall,” Berkeley’s Keasling told S*cientific American*. “Once the cells have accumulated the metals, they settle out of solution, leaving cleaned wastewater.”

SENSORY AUGMENTATION

Bacteria and Plants Become Sensors

Recently, scientists from Duke University and the Office of Naval Research devised a way to alter sensing proteins in the *E. coli* bacterium so that they bind to different molecules such as TNT. Add a genetic circuit that causes the bacteria to light up in the presence of a certain chemical signal and you have a living landmine detector.

“A variety of uses are possible from this research,” said Dr. Keith Ward, the Office of Naval Research’s project manager, who collaborated with Duke biochemist Homme Hellinga. “This might include a glucose-sensing protein that could be used for monitoring diabetes, or a TNT-sensing protein to assist the U.S. Navy’s underwater robots with locating and disarming explosive devices.”

A similar technique could enable the leaves of engineered plants to shift color in the presence of some environmental toxin. Patches of the sensor plants might be grown near chemical facilities.

“Such scenarios might sound like something out of science fiction, but they are entirely feasible over the long term using computational design approaches to create sensor proteins,” Hellinga has said.

Researchers from the University of Texas and the University of California, San Francisco, engineered *E. coli* to sense light by adding a light-receptor protein from a blue-green algae. That sensor was then genetically wired to the bacteria’s pigment-making system such that light switches off a gene that regulates the pigment production. Now, when light is projected on a petri dish coated with the “photosensitive” *E. coli*, a biochemical print is created. Eventually, the novel genetic circuit could be used to build a cell that’s switched on and off with a beam of light. “There is kind of a hacker culture behind all of this,” Chris Voigt, one of the University of California, San Francisco researchers behind the project, told *Wired News*.

Biochemical print

Source: http://www.utexas.edu/opa/news/2005/11/nat_sci23.html

LINKS

Keasling Lab
Pharmaceuticals, Bioremediation, Bioenergy
https://keaslinglab.lbl.gov/

Bionanostructures Design Lab
http://pbd.lbl.gov/synthbio/bionanostructures.htm

"Nature's Nanoshells"
David Pescovitz (Lab Notes, December 2005)
http://www.coe.berkeley.edu/labnotes/1205/diatoms.html

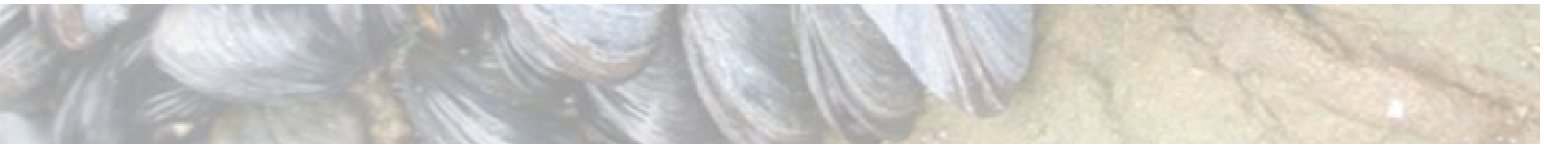
Future Energy Sources
A Berkeley Lab Research Initiative
http://pbd.lbl.gov/energy/

Tim Gardner Lab
Bioenergy and Bioremediation
http://gardnerlab.bu.edu/research.htm

Synthetic Genomics Inc.
http://www.syntheticgenomics.com/

Homme Hellinga
Biosensors for TNT and Nerve Agents
http://www.biochem.duke.edu/Hellinga/hellinga.html

"Student scientists create living bacterial photographs"
University of Texas news release, November 2005
http://www.utexas.edu/opa/news/2005/11/nat_sci23.html



4 | THE FUTURE OF INTENTIONAL BIOLOGY

In the coming decade, intentional biology is likely to evolve rapidly as a set of techniques, though it will probably not become a separate discipline. Biomimicry will not become a scientific discipline like physics or chemistry; nor will it become codified into a profession like architecture or medicine. Today it is a heterogeneous zone of ideas and solutions that draws on and contributes to ecology, physiology, molecular biology, physics, chemistry, computer science, mechanical and civil engineering, electronics, and economics. Given this variety, and the diversity of funding sources supporting biomimicry research, it is not likely to develop into a coherent, codified body of knowledge or profession.

In this respect, biomimicry resembles another, higher-profile field that has attracted even larger amounts of funding, and occasioned far more controversy: nanotechnology. Nanotechnology is another portmaneau field, less an intellectual landscape than a set of opportunities attracting scientists with varied disciplinary backgrounds working on many different kinds of problems. Indeed, biomimicry and nanotechnology are already playing off each other, and are likely to overlap much more substantially in the future. Biomimicry and nanotechnology have much to offer each other. Nanotechnology provides biomimicry with the tools to engineer molecule-by-molecule versions of organic materials. Biomimicry can investigate organic manufacturing and self-assembly techniques that may prove easier for nanotechnologists to exploit than molecular manufacturing. One provides designs and manufacturing tools, while the other contributes the tools to prototype bio-inspired materials.

“Biology is the nanotechnology that works,” says Tom Knight, who leads MIT’s intentional biology efforts.

Biomimicry also offers nanotechnology a measure of public legitimacy that could prove valuable should controversies over the environmental and health impacts of nanotechnology continue. Activist groups who see nanotechnology as a dangerous experiment in deforming Nature at the atomic level are probably not likely to agitate against biomimicry, which draws inspiration from and seeks to remain in balance with the natural world.

On the other hand, synthetic biology is more likely to agitate the public, fueled by the rallying cry of “Don’t mess with Mother Nature!” Already, genetic engineering has gotten a bad rap. Science touted the benefits of corn engineered for resistance to herbicides, rice genetically rejiggered to produce more vitamins, and fruit that produces oral vaccines. Still, genetically modified organisms (GMOs) are not to everyone’s taste. As the science progresses though, the benefit of gene jockeying will likely outweigh the risk. And even at this immature stage, synthetic biology researchers from the major institutions are developing a set of resolutions to address the dangers and ethical quandaries that may arise. For example, they hope to develop software tools that will help identify screen orders placed at DNA synthesis companies for sequences that encode hazardous biological systems. Ideally, as biomimicry and synthetic biology evolve, so will the self-regulations governing the field of intentional biology.

And like the living organisms it studies, intentional biology will continue to exist in a dynamic institutional state between chaos and stability. This will give the field intellectual flexibility, and responsiveness to both scientific and commercial opportunities. That notion is embodied by the new Berkeley-based Synthetic Biology Engineering Research Center (SynBERC), funded by a 5-year, $16 million NSF grant. The center draws researchers from MIT, Harvard University, UC San Francisco, and Prairie View A&M University in Texas along with more than a dozen industrial collaborators, from Amyris Biotechnology, Codon Devices, and Merck to General Electric, Sun Microsystems, and Hewlett-Packard.

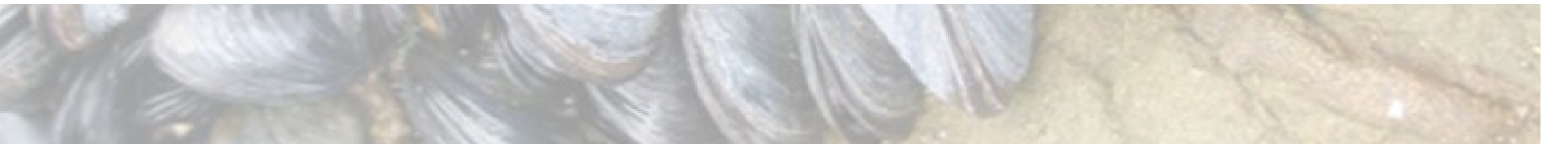
Source: http: www.synberc.org

TOMORROW'S INTENTIONAL BIOLOGY

How will intentional biology develop in the future? Intentional biology will be important as a tool for creating light infrastructures: systems that are decentralized, energy-efficient, and cannibalize older, more traditional infrastructures. (For more on light infrastructures, see *Innovation in the Urban Wilderness: Lightweight Infrastructure Meets Cooperative Strategy* [SR-1050].) This is already happening. Bioteaming aims to set teams free from traditional project-management tools and reporting systems, and teach them to operate as self-organizing, constantly communicating groups. Bioclimactic architecture seeks to create skyscrapers that are more ecologically efficient than small buildings, and eventually can generate their own power. In the next few years, the interweaving of intentional biology and light infrastructure will play out in five major ways.

- **Low-Cost Innovation.** Some patrons and scientists will see intentional biology as a source of low-cost innovation. Drawing on Nature's 4.6 billion year track record is more efficient than trying to create it yourself. Further, as our ability to understand the natural world deepens—as we become more adept at analyzing the molecular design of biominerals and adhesives, better at simulating ecosystem processes, and better able to reconstruct the processes that organisms use to survive in hostile environments—the range of solutions we can construct around that knowledge widens.

- **Green Design.** Many will look to intentional biology for more environmentally friendly, low-impact designs and manufacturing methods. The same incentives and desires that have driven work in sustainability, alternative energy, and cradle-to-cradle manufacturing will make biomimicry attractive and popular. For example,



electronics companies might offer green music players with cases made not of plastic, but a shell-like material that is strong yet biodegrades into harmless chemicals. Or perhaps new organisms will assist in accelerating the biodegredation process.

- **Product Opimization.** Others will use intentional biology to increase the efficiency or performance of existing products or technologies. Self-cleaning glass and paints are more expensive than their untreated competitors, but will last longer and consume fewer potentially toxic cleansing agents and water. Likewise, quieter aircraft that borrow design tricks from owl feathers will look and perform much like today's aircraft; they just won't make as much noise. On the smaller scale, genetically-engineered viruses may be used to self-assemble nanoscale transistors for computer processors and memory chips orders-of-magnitude faster and more powerful than today's technology.

- **Radical Invention.** In a few areas, intentional biology will be a source of radically new designs. Military and NASA sponsors of materials and mechanical biomimicry—in particular biorobotics research—are looking for a completely new category of cheap, high-performance robots that can be deployed in a wide variety of hostile situations. DARPA doesn't want cheaper versions of today's bomb-destroying robots: they want soliders and Marines operating in dense urban environments to be able to deploy swarms of cheap microbots that observe the enemy, monitor the environment, deliver basic first aid to wounded soldiers, and engage and destroy enemy microbots. These robots will likely be outfitted with living sensors to guide them and possibly even microbes that digest enemy weapons. In the field of medical manufaturing, bioengineers hope to someday engineer stem cells that can be programmed to build replacement organs for transplant into patients without rejection.

- **Organizational Ecologies.** Finally, some are attracted to intentional biology out of a desire to mimic Nature's capacity for dynamic equilibria and rapid evolution. This is more a philosophical position than a practical one: it assumes that if the world is becoming more dynamic and fast-changing, and if organizations must learn to evolve and respond rapidly and organically to challenges, looking to Nature for clues about how to meet these challenges is eminently sensible. Ken Thompson and Robin Good's *Bioteaming Manifesto*, for example, argues that "Nature's teams seem to work much better than ours," and that "we can base our teams on natural principles, which have developed and proved themselves useful through millions of years of evolution." This isn't a warrant for a feel-good kind of "natural" communication: Thompson and Good see Nature as red in tooth and claw, and good communication as a means of achieving ruthless focus and efficiency—just like hunting packs.

Source: http://www.flickr.com/photos/jembe/277621182/

DIRECTING EVOLUTION

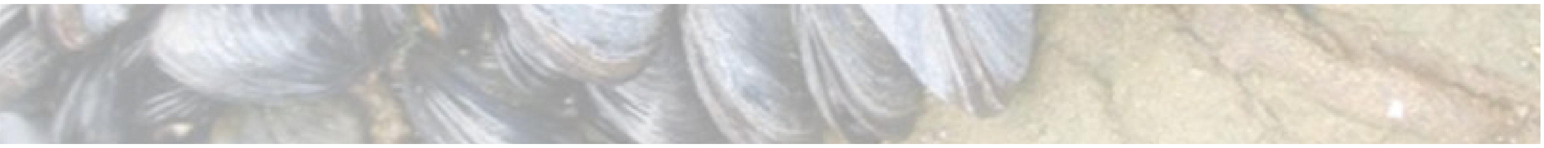
Intentional biology has one big roadblock to deal with. Many of the best-known successes in biomimicry have been the products of serendipity: Velcro, to take one famous example, was invented after Swiss engineer George de Mestral took notice of the burs that clung to the family dog's fur. But can we exploit Nature's design genius in a more systematic way?

Biomimicry faces a challenge in making the knowledge that biologists have of remarkable engineering feats accessible to engineers and entrepreneurs. Biologists have learned a great deal about how organisms and plants work, but—with few exceptions—they have not thought about those workings in the quantitative, functional terms that are the engineers' stock in trade. Further, the very breadth of biomimicry makes sharing knowledge across specialties and disciplines difficult: microbiologists, anatomists, and field ecologists all talk about their subjects differently. While all science has a tacit and social component, a field that is driven exclusively by personal networks is one that's destined to remain small.

To grow, the knowledge-base for biomimicry will have to become more systematic. Julian Vincent, a biologist at the University of Bath and a leading expert in biomimicry, is developing a database of organic designs that biologists have studied that solve particular problems—essentially, a cross between a Patent Office database and Wikipedia. Likewise, the Rocky Mountain Institute's biomimicry guild is developing a database that they hope will "bridge the gaps of terminology and specialization that separate biologists, chemists, and other researchers from engineers and other developers in industry."

In a similar vein is the BioBricks Foundation, a not-for-profit organization co-founded by MIT synthetic biology pioneer Drew Endy with colleagues from MIT, Harvard, and the University of California, San Francisco. The aim is to collect all standard DNA parts that encode basic biological functions. The BioBricks sequence information is freely available to the public through MIT's Registry of Standard Biological Parts. The raw materials are worth everything and nothing. It's what you do with them that matters, says University of Washington professor Rob Carlson, who coined the phrase "open-source biology."

"Biological manufacturing will be everywhere, making irrelevant standard notions of centralized production, and the real economy will be of design and infrastructure," Carlson concludes.



FURTHER READING

SYNTHETIC BIOLOGY

SyntheticBiology.org

Central information clearinghouse launched by MIT and Harvard researchers "committed to engineering biology in an open and ethical manner."
http://syntheticbiology.org/

**Second International Conference on Synthetic Biology
May 20-21, 2006
Webcast archives**

http://webcast.berkeley.edu/events/details.php?webcastid=15766

"Synthetic Life"

W. Wayt Gibbs (*Scientific American*, May 2004)

**Synthesis Blog
Rob Carlson, University of Washington**

http://synthesis.typepad.com/

SynBERC

http://www.synberc.org/

**OpenWetWare
A synthetic biology technical WIKI launched by Drew Endy and Tom Knight**

http://openwetware.org

BIOMIMICRY

IFTF biomimicry tag cloud

http://del.icio.us/iftf/biomimicry

Biomimicry: Innovation Inspired by Nature

Janine M. Benyus
Harper Perennial, 2002

The Gecko's Foot: Bio-inspiration: Engineering New Materials from Nature

Peter Forbes
W. W. Norton, 2006

Pulse: The Coming Age of Systems and Machines Inspired by Living Things

Robert Frenay
Farrar, Straus and Giroux, 2006

**Cradle to Cradle:
Remaking the Way We Make Things**

William McDonough and Michael Braungart
North Point Press, 2002

The Nature of Design: Ecology, Culture, and Human Intention

David W. Orr
Oxford University Press, 2004

Ecological Design

Sim Van der Ryn and Stuart Cowan
Island Press, 1995

ABOUT THE ...

TECHNOLOGY HORIZONS PROGRAM

The Technology Horizons Program combines a deep understanding of technology and societal forces to identify and evaluate discontinuities and innovations in the next three to ten years. We help organizations develop insights and strategic tools to better position themselves for the future. Our approach to technology forecasting is unique—we put humans in the middle of our forecasts. Understanding humans as consumers, workers, householders, and community members allows IFTF to help companies look beyond technical feasibility to identify the value in new technologies, forecast adoption and diffusion patterns, and discover new market opportunities and threats.

THE INSTITUTE FOR THE FUTURE

The Institute for the Future is an independent, nonprofit strategic research group with nearly 40 years of forecasting experience. The core of our work is identifying emerging trends and discontinuities that will transform global society and the global marketplace. We provide our members with insights into business strategy, design process, innovation, and social dilemmas. Our research generates the foresight needed to create insights that lead to action. Our research spans a broad territory of deeply transformative trends, from health and health care to technology, the workplace, and human identity. The Institute for the Future is located in Palo Alto, California.

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