

The Evolution of Ideas in Biomimicry

by

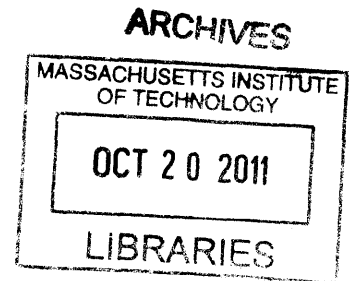
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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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at the
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ABSTRACT

The aim of this paper is to perform a review of Biomimicry as a science today in environmental, engineering, and manufacturing fields, as well as to educate readers on the history of Biomimicry as a whole and how it is studied. As more evidence surfaces about the effect of our presence on the Earth, the scientific community is faced with the challenge of solving these problems. After introducing these concepts, an in-depth review of two of the most studied topics in biomimicry is conducted: how the lotus remains clean in a dirty swamp and how the gecko can stick to any surface. These two topics are taken from the classical beliefs on how they work and leads them through into today's world, focusing on how the mechanisms behind them were discovered. Both sections end with a review of current applications of the technologies that have been developed by studying these living organisms. Everything is wrapped up with a discussion of why we must continue to study biomimicry and apply its principles to our engineering and production practices.

Thesis Supervisor: James H. Williams Jr.
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Introduction

Biomimicry is a science that is still young and is making its way into many of the most popular and important areas of research. Put simply, it is the study and imitation of movements, materials, and processes created in nature. To those working and learning in the scientific world, it represents a new way to look at the world around us, as well as a new way to produce products. Outside of academia, the products of biomimicry are everywhere and yet rarely named, as many everyday items that people use have been created using the methods of biomimicry.

Plants and animals in nature are constantly producing products vital to their survival; many of these humans would love to imitate. The spider makes silk that is much stronger than steel by weight. The mussel creates glue as powerful as any we create, and it works underwater. The mollusk produces a shell underwater strong enough to withstand being run over with a car. All of these have the potential for application in human technology.

Two questions that have been pondered by many for a very long time are the lotus' ability to always remain clean and dry and the gecko's ability to stick to walls and ceilings. Until the last half-century or so both of these questions remained unanswered, with countless theories, both scientific and spiritual, for how living things can have these abilities. However, due to our limited scope of vision, the mechanisms governing the abilities of the lotus and gecko remained a mystery. In a 1959 talk to the American Physical Society, Richard Feynman stated:

“ Unfortunately, the present microscope sees at a scale which is just a bit too crude. Make the microscope one hundred times more powerful, and many problems of biology would be made very much easier.” (Feynman)

The phenomena behind many of the unique abilities in nature have finally become understood due in great part to the invention of the scanning electron microscope along with other breakthroughs in observational technology and research methods. With this technology in hand, it is now possible to inspect objects in much finer detail.

What is Biomimicry?

A definition

As found in the preface the 1997 book Biomimicry (Benyus), the definition of biomimicry is as follows:

“1. Nature as model. Biomimicry is a new science that studies nature’s models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf. 2. Nature as measure. Biomimicry uses an ecological standard to judge the “rightness” of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts. 3. Nature as mentor. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it.“

It is currently 14 years since the book was published, and the “new science” of biomimicry is becoming more recognized within the scientific community as a model for how we can create new things to improve our lives.

Why should we care? (in short)

A few of the primary arguments for studying biomimicry are environmental: currently, the manufacture of many of our material staples involves extremely high energy use, harsh solvents, and the production of waste far in excess. In contrast, nature uses only sunlight and other natural resources, including using only enough energy to achieve its specific goal. All things in nature are recyclable, breaking down after their usefulness

has expired. (Benyus) If we are going to continue to produce items at the current rate, we must change some of the methods of production to be more like nature.

A short example

Biomimicry often occurs on accident when a researcher is looking for an answer to a problem seemingly unrelated to nature. Many of the problems we try and solve have already been solved in some form by nature. For example, in the 1940's George de Mestral was looking for a better fastener, having become frustrated every time he had to help his wife fasten the large hook-and-loop fasteners on the back of her dress. One fateful day he returned from his walk with his dog when he noticed that his dog was covered in burs. He was in awe at the ability of these burs to stick to the dog's fur so easily, and so he decided to study them under a microscope. It was here that he discovered the many tiny hooks on the burs that allow the burs to stick. A few years later, when nylon became available for public consumption, he was able to reproduce these hooks on a flat surface. He patented his hooks and the methods for producing them in 1951. Perfected over the next couple years, the initial product entered the market in 1955, the children of which are now colloquially called 'VELCRO®' (which is actually the name of a company and trademark that produces hook-and-loop fasteners). (Forbes)



Figure 1: Photos of Velcro hooks (OLIVEPIXEL, VELCRO HOOKS) and loops (OLIVEPIXEL, VELCRO LOOPS).

And a few more examples

People may not realize it, but biomimicry truly is all around us. While Velcro is used by people everywhere, there are many other examples of Biomimicry in use around the world. In Harare, Zimbabwe there is a high-rise building that makes use of the same principles that termite mounds use in order to maintain a comfortable, constant temperature. This is done by imitating the way the termites open and close vents throughout the mound in order to regulate convection currents. A company called WhalePower has developed turbine blades with little bumps called tubercles on the front edge to mimic flippers from humpback whales. These bumps result in a noticeable drop in drag and increase in lift. One last example became well known during the past summer Olympics: Michael Phelps' swimsuit. It was made by Speedo and manipulates boundary layer flow in order to reduce drag; this idea came from observing the skin of a shark. The same effect helps keep animals from growing on ships when applied to the

hull of the ship. Biomimetic products like these will continue to make their way into the public eye, bringing the importance of this science to light. (Brainz.org)

How the lotus emerges clean from the swamp

A religious symbol

The leaf of the lotus plant has always been venerated for its powers of self-cleaning. Because of this ability, the lotus has played a large role throughout the world both culturally and religiously. For example, Buddhists noticed how the lotus flower emerges clean from a dirty swamp. The Lotus Sutra (Encyclopædia Britannica) is an early Mahayana Buddhist text, proclaimed to be the embodiment of truth by certain Buddhist sects in eastern Asia. Others around the world see the Lotus Sutra as a traditional, religious work of great beauty. It remains to be one of the most popular texts in the Mahayana tradition. Within the book, Buddha is divine and undying, having achieved enlightenment. Those who follow the religion are called to do the same. This is because of the great meaning that the people put on the lotus' purity.

The only clean swamp dweller

The "lotus" that has been greatly studied in biomimicry comes from the flower often found in Asian and North American swamps. The genus this comes from is the *Nelumbo*, a set of aquatic plants with large flowers that are very similar to water lilies. Of these there are the Egyptian lotus, the blue lotus, and sacred lotus, and the American lotus. (Encyclopædia Britannica)



Figure 2: The flower of the Nelumbo Nucifera (PERIPITUS)

It is known that like many other plants, the leaves of the lotus are covered in a substance similar to wax in order to help prevent water and nutrient loss. This surface is called the cuticle and is already hydrophobic in nature (Andreas Solga). However, the waxy film alone is not enough to fully account for the “superhydrophobicity” that the lotus exhibits. Superhydrophobicity is a term given to surfaces on which the contact angle of the water is very high and the sliding angle is very low. FIGURE 3 shows a representation how contact angle is defined:

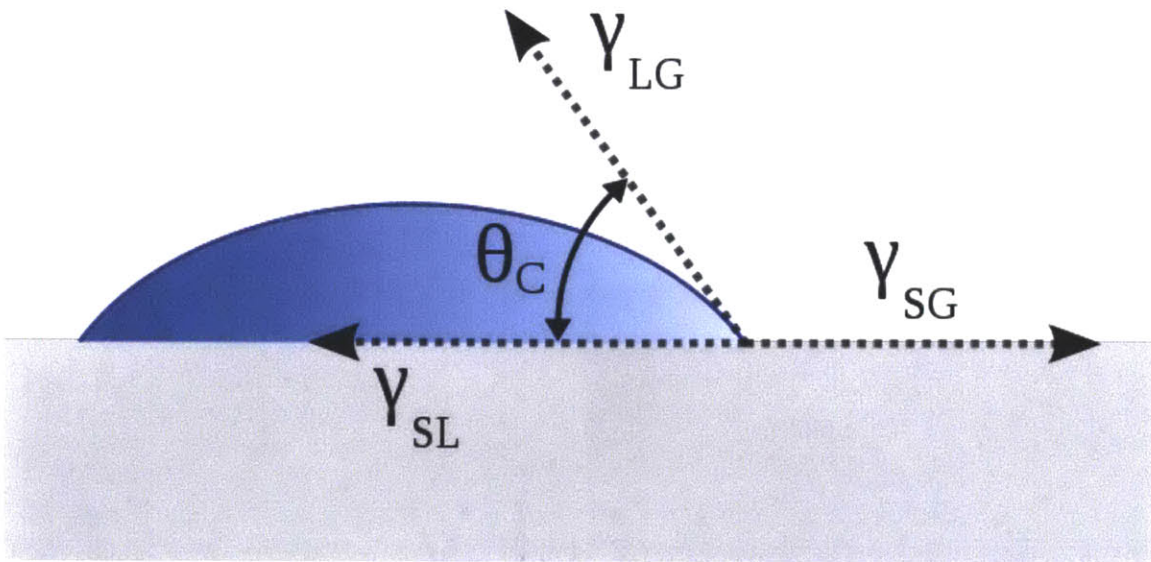


Figure 3: A cartoon showing how contact angle is defined. Interfacial energy shown is solid-liquid (γ_{SL}), liquid-gas (γ_{LG}), and solid-gas (γ_{SG}). The contact angle is θ_C .

(SETRESET)

Discovering its secrets

Unfortunately, the other secrets of the lotus leaf remained a mystery until the electron scanning microscope was put into common use. This allowed for the ability to see incredible detail at microscopic levels. This resolution is possible because the SEM utilizes a focused beam of low energy electrons to probe the surface of the object to be scanned in a regular fashion. It then receives high-energy scattered electrons and low energy secondary electrons back from the surface. Using the form of the returned electrons, a picture can be formed. The entire process could be made analogous to echolocation in bats. One caveat is that it is quite favorable that the specimen to be examined be electrically conducting to allow for the sharpest image. Since its original

invention, the SEM has been combined with other technologies in order to create still superior scanning methods. (Encyclopædia Britannica)

Being an object of much controversy, the lotus leaf was one of the first things looked at under the new microscope. FIGURE 4 shows a simulated image of what was found:

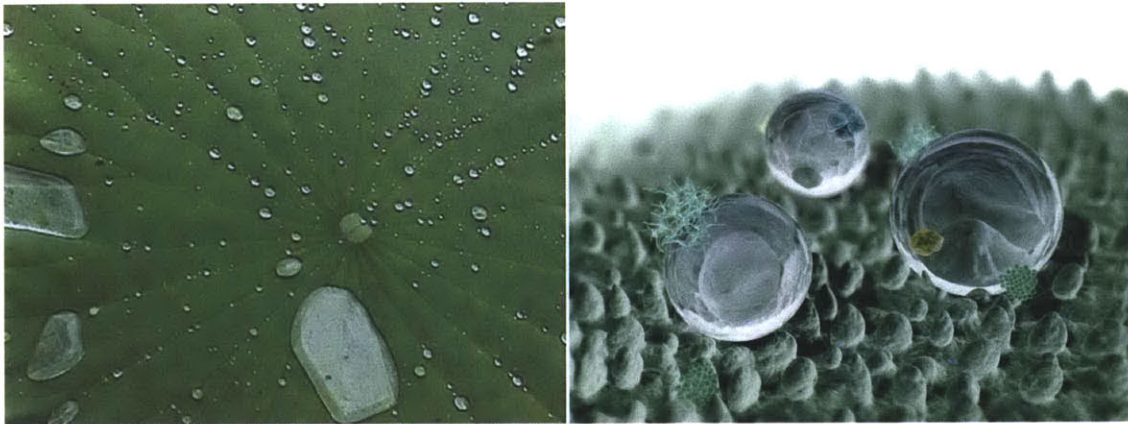


Figure 4: An unzoomed photograph of a lotus leaf (BUTCHER) and a representation of what the leaf actually looks like on the microscopic level. (SENTERRA)

The surface of the lotus is actually very rough on the nano-level. Before this discovery, two sets of equations were proposed concerning the wettability of solid surfaces that would help account for the behavior of droplets, one by Robert Wenzel and another by Cassie and Baxter (Ball). In 1936, Wenzel argued that the droplets would become impaled on the tiny microstructures, increasing the surface's resistance to wetting. Then, in 1944, Cassie and Baxter proposed that the wettability of a surface is greatly decreased by microstructures due to the air that is getting trapped beneath the liquid. The surface tension of the water keeps it spherical, so it sits on the points of the microstructures and air is left under it, helping to suspend it. Some newer studies have begun to disagree with

Wenzel's and Cassie and Baxter's theories, however they still serve as a basis for why roughness on the nano-level leads to superhydrophobicity.

So water rolls off, but why does dirt?

A 1997 article in *Planta* by W. Barthlott and C. Neinhuis summarized their study of how contamination is avoided in certain plants (W. Barthlott). Several plants were studied by simulating what they presumed to be normal contamination. They started by discussing the wettability of the plants. The wettable plants that they tested exhibited a smaller contact angle and no real microstructures. On the other hand, all the water-repellant leaves had some sort of microscopic surface sculptures, typically in the form of wax crystals. Water on these leaves experienced contact angles of at least 150 degrees. When water was dropped on these leaves it formed spheres and quickly rolled off with little help from the angle of the leaf.

Barthlott and Neinhuis further discovered that any contamination particles on the water-repellant leaves were easily removed when subjected to rain regardless of the type or origin of the particles, granted the microstructure of the plant was not damaged. In their discussion, they asserted that contamination particles had a very small area in which they interfaced with the leaves because they were suspended on the microstructures. This resulted in very weak adhesion to the surface, allowing the water droplets to easily 'grab' the particles and roll away with them. FIGURE 5 is from their article and easily summarizes this phenomenon:

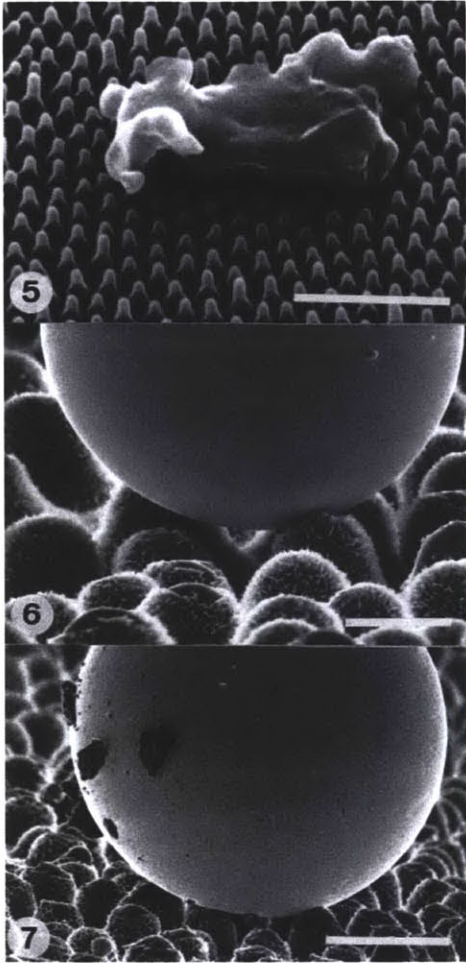


Figure 5: 5) Shows a contaminating particle with reduced contact area between it and the rough surface; 6) Mercury droplet enclosing air between it and the leaf; 7) Mercury droplet with particles sticking to it rather than the surface (numbering based on their article) (W. BARTHLOTT)

The Lotus Effect

Soon after Barthlott and Neinhuis published their paper, a patent was filed for production of “Lotus-effect” products, a trademark that Barthlott had coined in 1992. The first truly successful enactment of this technology was in a paint from the company Ispo,

adequately called Lotusan. As one could imagine, this paint contained particles on the micro-scale that, combined with the chemistry at work in the paint itself, created a superhydrophobic effect. This paint is easily cleaned using only water, and therefore has the potential to last much longer on the buildings and projects that it has been used on.

Pilkington Activ Glass

Pilkington, a glassmaker based in St. Helens, Lancashire, has developed a glass coating that exhibits self-cleaning properties. Pilkington became successful when Alastair Pilkington (not a member of the original family but a distant relative) rediscovered the idea of creating float glass on top of molten metal. Having taken out patents, much of Pilkington's resources were poured into this new process, resulting in a method of producing nearly flawless, uniform thickness glass sheets. Since then, Pilkington has branched out and has become a major producer of glass throughout the world. (Barbour)

Pilkington's Activ glass is made using a patented method of coating the float glass during the initial production. It exhibits self-cleaning properties while being robust enough to endure normal cleaning; the coating is also said to last for the lifetime of the frame.

However, this Activ glass works quite the opposite way the Lotus Effect works: instead of being superhydrophobic and causing water to bead and roll off with the dirt, the glass is extremely hydrophilic, causing water to form sheets and wash away the dirt. The dirt itself comes off easily because of a photocatalytic process in which sunlight reacts with the titanium dioxide and causes dirt and organic materials to break down. This process is not expressly related to Biomimicry, but shows a way to use self-renewing materials (the TiO_2 is activated by UV light after all). (Pilkington Glass)

Wrap-up: Other possible applications

There is a beetle in the Namib Desert of southern Africa that combines elements of hydrophobicity and hydrophilicity in order to harvest water from the fog. The Namibian Darkling beetle has warty wing covers that have bumps of which the tips are hydrophilic, causing the water to stick to them. However, the rest of the bumps are hydrophobic due to their bumpy shapes on the nanoscale. Water droplets form on the tips of the bumps and combine, eventually growing large enough to detach from the tips and roll down the back of the beetle into its mouth. In addition to this water gathering ability, the beetle somehow thrives in possibly the hottest desert on earth. This ability comes from heat reflection surfaces on its body, which were being studied when its water gathering ability was discovered. This is yet another example of nature's amazing yet simple. It is these discoveries that will lead to new inventions that will improve human lives throughout the world. (Forbes)

The Spiderman dream: How the gecko defied our laws of physics

The wondrous wall-crawler

The name “gecko” is given to any lizard in the family Gekkonidae (Encyclopædia Britannica). They are usually between 1.2 and 6 inches long, possessing a flat body, a large head, and digits on each limb covered in adhesive pads. There are many different types, all of which live in quite different environments. The Tokay gecko is the largest of them, growing to an adult length of 10 to 14 inches. Typically nocturnal, geckos sustain themselves mostly on insects. In the United States, the two native species are the banded gecko and the leaf-fingered gecko (Gecko). On average, geckos grow to be about 4 inches long. The leaf-fingered gecko is generally the one that people know of, due to their climbing abilities and the many areas they inhabit.



Figure 6: A gecko you might see clinging to the side of a North American household. (ENCYCLOPÆDIA BRITANNICA)

Man's assumptions, how they've changed

Since geckos have been studied, the secret behind their ability to walk on walls and ceilings as been pondered by many. In the past it was believed that geckos had small discs on their feet that acted like suction cups, enabling them to walk on walls (Gecko). However, this simplistic approach was invalidated because the gecko was then able to remove itself from where it has stuck. Further down the line, it was theorized that capillary adhesion was what allowed geckos to scale walls. This type of force is used by many insects and frogs, and requires that the surface be both wet and hydrophilic in order to provide a strong, stable force. This did not explain why the gecko could stick to any surface, including hydrophobic ones. It was finally discovered, with the advent of more precise methods of inspection (i.e. SEM), that the pads of the gecko's toes are actually

covered by tiny plates that are covered by tiny, hair-like threads called seta that split and end in spatulas.

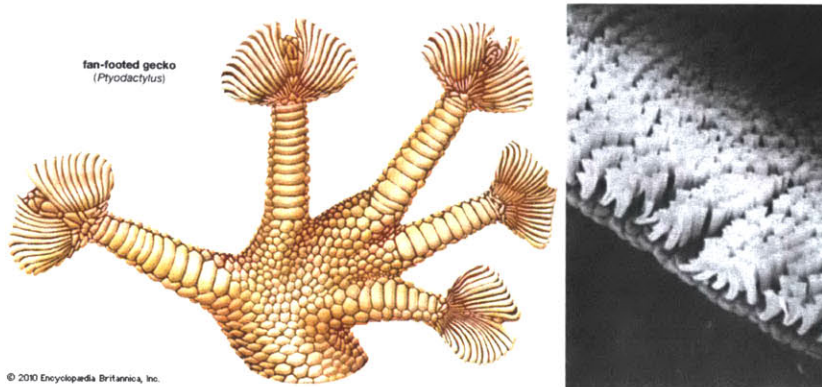


Figure 7: A drawing of a gecko's foot and a picture of the seta on it taken by a scanning electron microscope. On each seta are a bunch of smaller fibers, each ending in a spatula. (ENCYCLOPÆDIA BRITANNICA)

Van der Waals forces

The mechanism of the dry attraction that geckos create with the surfaces they walk on makes use of van der Waals forces. These are weak electric forces attracting one neutral molecule to another. There are three ways this happens (Encyclopædia Britannica): molecules are permanent dipoles, the presence of permanent dipoles causes the electron charges in nearby molecules to line up, or electric charges in adjacent non-polar molecules will randomly line up, resulting in a force. No matter the cause however, van der Waals forces rely on molecules being very close together in order to produce the effect. That is where the seta and spatulae come in. Because the seta and fibers leading to the spatulae are flexible (while being stiff enough to not stick to each other), they are

able to make contact with almost any surface at the nano-level. The reason we cannot do this is because our skin is extremely rough in comparison, resulting in very little actual interface between us and whatever we're touching. Each time a spatula meets the surface, van der Waals forces are created. Because the spatulae are so tiny, each gecko has countless number of them. Furthermore, the thinner / more fine each spatula is, the greater force it can create per area. Using force sensors, researchers were able to calculate that the radii for individual spatula the bundles of a tokay gecko are approximately 0.13 μm to 0.16 μm . (Kellar Autumn)

Attempts to imitate

The team lead by Kellar Autumn not only lead the research to prove that the van der Waals forces were the primary driving force, but they created artificial setal tips that stuck almost exactly in the same way the gecko's did. Using silicone rubber methylsiloxane and polyester resin, the team crafted two sets of synthetic setal tips from hydrophobic materials. Using an Atomic Force Microscope-based manufacturing technique, the synthetic spatulae were made to be as much like the gecko spatulae as possible. The synthetic spatulae were able to produce nearly identical force when compared with the organic spatulae of the gecko. Given this success, test pieces of "gecko tape" were produced, demonstrating the potential for commercial application i.e. when dry adhesion is necessary. The successes at producing gecko-like dry adhesion will likely lead to a real product coming to market in the near future.

Now what? (Why should we care?, continued)

So far, many papers have been published and many products have been invented that involve the creation of products that mimic traits of plants and animals in nature.

However, these products are often created using our common-practice production methods. As such, they share the same downfalls that non-biomimetic products share: a reliance on often hard to find materials, huge overhead energy usage, and large amounts of waste. However, if we imitate the way that nature creates things, then we could instead rely on simple, abundant, and non-toxic materials. We could also find ways to use only the energy needed to perform the task in order to process the materials. Finally, the waste of processing the materials could then be recycled into creating more product or disposed of in an environmentally-friendly way.

A study published in 2005 explored what happens when we try and mimic the mechanics and benefits of nature without mimicking the production methods (John Reap). Three products that were created using research in biomimicry were compared to their non-biomimetic counterparts. The research involved to create the products focused only on the physics they were imitating to obtain the function they wanted; they did not focus on how the organism they studied creates their version of the product. Surprisingly (or not surprisingly, depending on point of view), the products invented using biomimicry did not necessarily result in a lower environmental effect. The assertion was then made that in order to correct this we must focus on holistic biomimicry, not reductive biomimicry.

The document goes on to discuss how we could truly mimic the way that nature creates things. There are seven specific descriptions of life's characteristics: 1) Life builds from the bottom-up, 2) Life fits form to function, 3) Life depends on water, 4) Life is cyclic and recycles, 5) Life is locally attuned and resourceful, 6) Life adapts and evolves, and 7) Life coexists within a cooperative framework. This list, adapted from Benyus and Baumeister of The Biomimicry Guild, can be adapted to pertain to our human manufacturing processes (Janine Benyus). We must focus on things like mass customization (building from the ground up); general design theory (fitting form to function, limiting materials and energy used); and recycling, remanufacturing, design for disassembly (making our product lives cyclic and recyclable). By focusing on imitating nature all the way through the process of creation, we can greatly reduce the environmental impact of living on this planet.

Conclusions

In performing this review, it became obvious that the information and research opportunities are all out there; they're just waiting for action to be taken on them. A quick Internet search for the word "Biomimicry" yields about 341,000 results in 0.14 seconds. The primary limiting factor in using nature's expertise to better the way our society interacts with the planet is people being educated. In order for policy changes to be made or for companies to actively strive for sustainability people must know about the possibilities; they also must let the government and big corporations know that they want actions taken that will lead to a better earth in the future.

The current wave of biomimicry products mostly mimic dry physics, creating materials and structures similar to those found in nature. The next step is to learn to mimic how nature creates these structures and other remarkable objects, such as spider silk and mussel glue. This research should be done with the mindset that the production of these new products will be from the ground up, waste-free, and will result in recyclable material when the use stage of the product passes. If these ideas are kept in mind, there is no reason humanity cannot stop and eventually reverse the destructive effects that it is having on the planet. All things in nature before humans had a natural balance, and we must strive for that now and for the future.

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