It's easy to talk about how exciting biomimicry is, and how we'll see more of it in the future, but it's another thing to actually design and built things that are **biomimetic**. Most designers, engineers, architects, and other people who build things just don't know that much about biology and the natural world; and even when they do, there's often a gap of capability in available materials, manufacturing methods, and economic systems. Some of these obstacles are out of the designer's hands, and you just have to move on to things that are more feasible. (But don't forget your ideas; maybe ten years from now the technology will be there.) Even with existing technology, however, an enormous realm of possibilities is feasible, it just requires the right approach. Here is my attempt to describe the biomimetic approach, with a comprehensive list of principles. It combines lessons from **Janine Benyus, Kevin Kelly, Steven Vogel, D'Arcy Thompson, Buckminster Fuller, Julian Vincent**, and my own limited experience. I also mention at the end where biomimicry will *not* help you, a subject often glossed over, as well as further resources (books and schools).

The Direct Method: Find an Example

- Define the problem and its context.
- Find organisms with a similar problem & context, see what they do. Find many divergent organisms to see which has the best / most relevant strategy.
- Translate the best strategy to a buildable thing; if necessary, find an expert to help.

The direct method is what you usually hear about--where the designer / engineer can point to an organism and say "it's like that". Janine Benyus and Dayna Baumeister have published a nice tutorial on it. The value of this method is that even the most creative people still get stuck thinking along certain lines. In fact, a method called TRIZ which has been developed to catalog and analyze problem-solving techniques, claims there are just 40 methods that people have ever used to think up new inventions. Since evolution works differently from our brains, nature has used many more. Julian Vincent at University of Bath has been working on extending TRIZ to biology, cataloging and analyzing the ways other organisms have "invented" new solutions to problems. But so far the best way to find ideas in nature is to go look for yourself; arguably it always will be.

Defining the problem well is always a challenge in design, but then finding organisms that have relevant strategies is a trick in and of itself. Some examples are easy to find just by going for a walk and paying attention; other examples are more obscure, and require research--online, in books & academic journals, or even by hiring a biologist to consult. It's especially useful to find many examples from wildly divergent sources (e.g. for structures don't just look at animal bones, but also insect exoskeletons, the branches of trees, the stems of grasses, etc.) so that you have design alternatives. Just because a certain strategy evolved in one place doesn't mean it's the best solution; the power of biomimicry is that you can find many different solutions that you've never thought of. The process of collecting several examples will also help you analyze the principles involved--if many different organisms use variations of a common strategy, you know that approach is promising.

Translating the best strategy to a buildable thing is often the hardest part. If you are doing long-term R&D it is feasible to try developing new technology that works like the strategy you found, but if you are a normal architect or engineer trying to kick out a product for a client, this luxury is usually unavailable. At this point you may need to settle for part of your idea, or better, abstract it a bit further until you reach something that is doable. Remember, good biomimicry is inspiration from nature, not slavish imitation of it.

The Indirect Method: Use General Principles

Many people have abstracted principles of how nature designs. The following list is what I consider the distilled combination of those enumerated by Janine Benyus, Michael Braungart and William McDonough, Kevin Kelly, Steven Vogel, D'Arcy Thompson, Buckminster Fuller, Julian Vincent, Dee Hock, and my own limited experience. Explanations and attributions follow the main list.

- **Waste = Food**
- **Self-assemble, from the ground up**
- **Evolve solutions, don't plan them**
- **Relentlessly adjust to the here & now**
- **Cooperate AND compete, not just one or the other**
- **Diversify to fill every niche**
- **Gather energy & materials efficiently**
- **Optimize the system rather than maximizing components**
- **The whole is greater than the sum of its parts--design for swarm**
- **Use minimal energy & materials**
- **"Don t foul your nest"**
- **Organize fractally**
- **Chemical reactions should be in water at normal temperature & pressure**
- **Vogel's mechanical-engineering-specific principles (summarized):**

- Nature's factories produce things much larger, not smaller, than themselves.
- We use metals, nature never does
- Nature makes gradual transitions in structures (curves, density gradients, etc.) rather than sharp corners.
- We make things out of many components, each of which is homogeneous; nature makes things out of fewer components but they vary internally.

- We design for stiffness, nature designs for strength and toughness.
- Our mechanisms have rigid pieces moving on sliding contacts, nature bends/twists/stretches.
- Nature often uses diffusion, surface tension, and laminar flow; we often use gravity, thermal conductivity, and turbulence.
- Our engines are mostly rotary or expansive, nature's are mostly sliding or contracting.
- Nature's engines are isothermal.
- Nature mostly stores mechanical work as elastic energy, sometimes as gravitational potential energy. Explanations of the above points:

Waste = Food: This is the biggest one. Use waste as a resource, "close the loops" as they say, build industrial ecologies instead of landfills and mines. Michael Braungart and William McDonough have the best developed model for this, with their concept of biological nutrients and technical nutrients. Strictly speaking, as Janine Benyus points out, modern industry does act like some ecosystems in nature--"type 1" systems, the weeds that colonize an area after a disturbance. However, type 1 ecosystems aren't sustainable, they eventually give way to type 2 and type 3 ecosystems, which have increasingly greater interdependencies, with increasingly closed-loop resource flows (such as rainforests). Creating type 3 industrial ecosystems has historically been tricky to implement because the pace at which products change, and markets change, are often rapid--industry has so far always been in a "disturbed" state as new technologies change the rules of the game; natural ecosystems, by contrast, transform from type 1 to type 3 over thousands of generations of the species involved. How can we help push industry forward? This has been covered in depth elsewhere (designing for long life, reuse, recycling, biodegradability, etc.), but there are a couple points I feel are under-recognized. The adoption of open standards can help here, so that components are more interchangeable between products and industries--this helps manufacturing systems develop the long-term stability needed for building webs of interdependencies. Likewise less dependency on new cutting-edge technologies makes it easier to fit into existing webs.

An important corollary of "waste = food" that Janine Benyus makes is "don□t draw down resources, live off the 'interest'." It is a financial analogy, describing how mature ('type 3') ecosystems don't need new income, they are living off of the interest from the great biological wealth they have. Mining or harvesting too much of the world's existing resources is like spending the capital that you're trying to live off the interest of, and it will eventually catch up to you.

Self-assemble, from the ground up: The most important stuff happens at the smallest scales. This can work on many levels: On the material level, instead of having a block of stuff that you cut away, have small parts that combine to form the whole. This reduces waste and increases design flexibility. On the system level, design networks, not pyramids. The nodes should create the overall structure by their interrelations, because this method is more robust, scaleable, and flexible than a system with an overarching plan that must have certain nodes in certain places.

The second part of this, "most important stuff happens at the smallest scales", refers to the fact that the most complex, detail-filled aspects of biological designs are at the smallest scales: at first, a bone looks like a stick; look closer, and you see its porous structure; look closer, and you see the material is a composite; look closer, and you find that composite has three or four deeper levels of substructure; look closely enough and you get to the DNA, which is complex enough to contain the blueprints for the whole bone and the rest of the animal besides. Sometimes designing for the most minute detail can cause the whole overarching design to be determined.

Evolve solutions, don't plan them: As Kevin Kelly put it, "letting go, with dignity". This means design without authorship--not the traditional process of artists and *their* works, but creating the right context for possibilities to emerge from. The most direct example is genetic algorithms, and their huge success has proven the usefulness of the technique. A more clumsy (but much easier and still useful) example is iterative design. Iterative design is making multiple prototypes, user-testing them to find the favorites, then mixing and matching elements to create another generation of prototypes which are in turn user-tested, ad infinitum. Incidentally, this is the method advocated by IDEO, the most successful design firm in the world.

Relentlessly adjust to the here & now: True evolution means never saying you're done, it is only one means of adaptation. As Janine Benyus says, effective adaptation requires organisms to be information-driven, with local expertise. It also requires timely expertise. Species that range across dramatically different habitats must adjust themselves to the new locales, and those that stay in the same place but whose habitat changes (say, from summer to winter) adjust as well. In the product world this means customizability for different users and different circumstances, to extend product lifecycle. In more advanced implementations, it means the products adjust themselves without need for user intervention.

Cooperate AND compete, not just one or the other: Biologists of the 19th century usually described Darwinism as a dog-eat-dog world; today's biologists highlight the cooperative interdependencies of different creatures in their ecosystems. Both are true, and both are useful in their own ways. Dee Hock , the creator of the VISA system, coined the word " chaord " to describe the partly-chaotic, partly-ordered system that he designed to mimic nature's ecosystems, where the interdependencies are sometimes both cooperative and competitive at the same time. This concept also appears in software and hardware with "open standards":

cooperatively-chosen arenas (such as a file format or broadcast spectrum) that allow companies to compete on the same playing field.

Perhaps a useful note about this is that in nature, each species tends to have a certain niche and stick to it, therefore cementing who is a competitor and who is not. In industry, companies often shift niches or try to operate in several at once. Being clearer about your own niche can help you decide where to cooperate or compete, and seeing opportunities for cooperation can help you shift into more profitable or safer niches.

Diversify to fill every niche: Traditional industry already does this on the market level; on the product level, mass-customization does a similar thing. However, the green-design lesson here ties in with Waste = Food: it is to find untapped niches where waste is being created, where it could instead be used as a resource. Smart manufacturers close their own resource loops; smart entrepreneurs close other peoples' loops.

Gather energy & materials efficiently: A point most often mentioned by Benyus. You don't need to study nature to get the importance of this, but it has a cornucopia of strategies you've never tried. Ants have been studied to improve shipping schedule algorithms, plant leaves have been studied for solar energy absorption, mollusks have been studied for building shells out of seawater without even moving. The list goes on.

Optimize the system rather than maximizing components: This is general systems-thinking advice, but Benyus points out its ubiquitousness in biology. Creatures always have to balance multiple cost/benefit dimensions, there are no single-minded goals (like being bigger, faster, etc.) A quick rule of thumb here is perform as many functions with as few components as possible. It is a good exercise to explicitly lay out all the factors you are trying to balance. For instance, Amory Lovins' method of "tunneling through the cost barrier" is a system-optimization technique where one variable can be made slightly worse--say, spend more money on insulation--to make the whole system better--a heater is no longer necessary, thus saving more money than the extra insulation cost. (Lovins got his method from general systems-thinking, not biomimicry explicitly, but it's all of a piece.)

The whole is greater than the sum of its parts--design for swarm: To keep things simple, people tend to design one function at a time, creating separate elements for each task and then creating the product by assembling all the pieces. There are many advantages to this, but in these products the whole will only be the sum of its parts. One of the hallmarks of complex systems (which include everything alive) is "emergent phenomena", the fact that the whole is greater than the sum of its parts. Kevin Kelly most memorably describes this with his example of how an individual bee has a small brain and simple behavior, but a swarm of bees is like an organism all its own. Emergent phenomena are hard, if not impossible to predict, and in the built world mostly happen by accident (a simple invention like the automobile end up causing traffic and sprawl). However, designing with emergent phenomena in mind can not only help avoid unintended consequences, but can open new opportunities--the democratizing force of the internet, for example. The key to this principle is designing lots of little, simple things that together can do sophisticated things; this can be a green design tool because it lets you build robust systems without infrastructure, build smaller stuff, and built smarter stuff without super-high technology. This can also be a great tool for leapfrog design, for the same reasons.

Use minimal energy & materials: Another principle where you don't need nature to tell you this, but it has great examples. Plants and animals always try to use material and energy efficiently, because for them energy & material costs are the only costs. Successfully minimizing mass and energy use requires thorough optimization to the problem at hand, so organism structures are highly information-driven. On the other hand, industry's costs are primarily financial, so it usually finds it easier to simply use more material or energy than spend the extra time researching how to use it well. But minimalist designs can be successful and cost-effective in industry. Buckminster Fuller was the rock star of this principle, constantly driving to "dematerialize" objects by using more brains and less mass. The main strategy he found used universally in nature was what he called " tensegrity "--the use of both tension and compression for structural integrity. (Supporting things with tension requires less mass, because buckling is not an issue.) His geodesic domes are the most famous implementation of this, but he also used it in many other inventions. It is a sorely underused strategy, particularly in architecture, where it usually only sees use in tents and bridges. One contemporary architect who has used tension to great effect--in particular, with inflated structures --is Axel Thallemer. There are many other methods of dematerializing--too many to list here, but much of it comes down to stripping away artifacts of form that are not related to the object's function.

"Don't foul your nest": This is another Benyus principle, in the grand scheme meaning don't use or build with harmful materials or effluents. Do you really want to live in a home that offgases formaldehyde or dioxins? This sounds simple and obvious (again, not something you need biomimicry for to know its importance), but if engineers, architects, and other builders actually started following this principle alone, it would cause a revolution.

Organize fractally: self-similarity is a way of planning for several different scales at once. Fibonacci spirals don't occur all over the place in nature because they're pretty, they occur all over because they're an algorithm that allows perpetual growth to any size without having to readjust or plan ahead. Fractal structures do not have to be as "smart" as other structures which require different planning for different scales. Fractal forms are also pretty. Other biomorphic shapes ("blobjects") are also popular these days for their prettiness; this doesn't count for anything in terms of green design, unless it provides some psychological affinity like " biophilia " does, but it can help product adoption.

Chemical reactions should be in water at normal temperature & pressure: This principle (from both Benyus and Vogel) is fairly self-explanatory. Most industrial chemistry is petroleum-based, uses many toxics, and happens at high temperatures and pressures; this makes chemistry highly energy-intensive, hazardous to health & safety, and dependent on non-renewable resources. Biological chemistry has so far been much harder for researchers to understand and use, but the biotech industry is making great strides, and in the long run it should allow chemistry to become cheaper as well as greener, because of the reduced energy-intensity, reduced safety hazards, and plentiful (renewable) raw materials.

Finally, the following is an engineering-specific list from Steven Vogel's book Cats' Paws and Catapults. It is slightly paraphrased and edited to avoid overlapping with points mentioned elsewhere here, but his is the best single list for a mechanical engineer or architect to reference. (For the full list & details, read the book.)

- **Nature's factories produce things much larger, not smaller, than themselves.**
- **We use metals, nature never does--we use the ductility of metals to avoid crack propagation, nature uses foams & composites to do so.**
- **Nature makes gradual transitions in structures (curves, density gradients, etc.) rather than sharp corners, to avoid stress concentrations.**
- **We make things out of many components, each of which is homogeneous; nature makes things out of fewer components but they vary internally.**
- **We design for stiffness, nature designs for strength and toughness.**
- **Our mechanisms have rigid pieces moving on sliding contacts, nature bends/twists/stretches.**
- **Nature often uses diffusion, surface tension, and laminar flow; we often use gravity, thermal conductivity, and turbulence.**
- **Our engines are mostly rotary or expansive, nature's are mostly sliding or contracting.**
- **Nature's engines are isothermal.**
- **Nature mostly stores mechanical work as elastic energy, sometimes as gravitational potential energy; we also store work electrically or kinetically.**
- **We make dry things, nature makes wet things.**

Where Biomimicry Will Not Help

As much as a proponent of biomimicry as I am, I think it's important to be realistic about where nature's strategies will and won't help you, rather than glossing anything over. There are definitely some drawbacks to the way life designs, which you probably don't want to imitate (unless you can somehow turn them to your advantage). Mostly pointed out in Kelly and Vogel's works, there are three main stumbling blocks.

First, evolution can only find local optima, not global optima. Put another way, evolution requires every generation to have an immediate advantage--when transitioning from one strategy to another, you cannot get worse for a few generations, knowing that in the end you'll get better than you could have with the original strategy. Thus nature shuts out many design possibilities that we humans can find.

Second, natural products need continual maintenance and/or rebuilding. This can easily be turned into an advantage for products meant to biodegrade or planned to obsolesce. But most often it is simply a reminder to not imitate too slavishly.

Finally, organisms can't borrow designs from others, they have to evolve from what they have now. Human designers, however, can mix and match freely from different products in whole other genres. There's nothing wrong with making a building whose walls insulate like penguin feathers but are structured like crab shell. Some companies are doing things like this in biology with genetic engineering (gene-splicing crops, etc.), but the law of unintended consequences has frequently shown it to be a bad idea.

Resources (books, courses, networks)

Here's a short list of what I consider the handiest books for designers and engineers (probably also architects) interested in doing biomimicry. Some of them are good to read through for theory/philosophy, others are useful as reference books (catalogs of ideas). They are listed roughly in order of their usefulness for design ideas--the top one is just a picture-book of neat examples, which is all some people will need. If this beginner / intermediate list doesn't satisfy you, you'll find there are dozens of books on the subject, many specializing in particular fields (like medical technology, fluid dynamics, and many others.)

- The Way Nature Works , edited by Robin Rees
- Cats' Paws and Catapults , by Steven Vogel
- On Growth and Form , by D'arcy Thompson
- Out of Control , by Kevin Kelly
- Biomimicry , by Janine Benyus
- Cradle to Cradle , by William McDonough and Michael Braungart
- Structural Biomaterials , by Julian Vincent

If you want interactive instruction, you may be surprised how many places can help you. Janine Benyus and Dayna Baumeister teach two different kinds of green-design oriented short courses for professionals. There are scores of universities worldwide that have relevant engineering courses, but most (such as Berkeley and Stanford) aren't particularly green-oriented in their biomimicry, instead focusing on robotics, medical devices, and such. ...But you never know when normal engineering research will come up with a technology having amazing green potential, like gecko tape . To find schools that specifically teach biomimicry for green design or architecture, I recommend the BIONIS and Biomimicry Guild resource lists. BIONIS's list also has links to other networks, though it may be the most extensive biomimicry network.

Jeremy Faludi