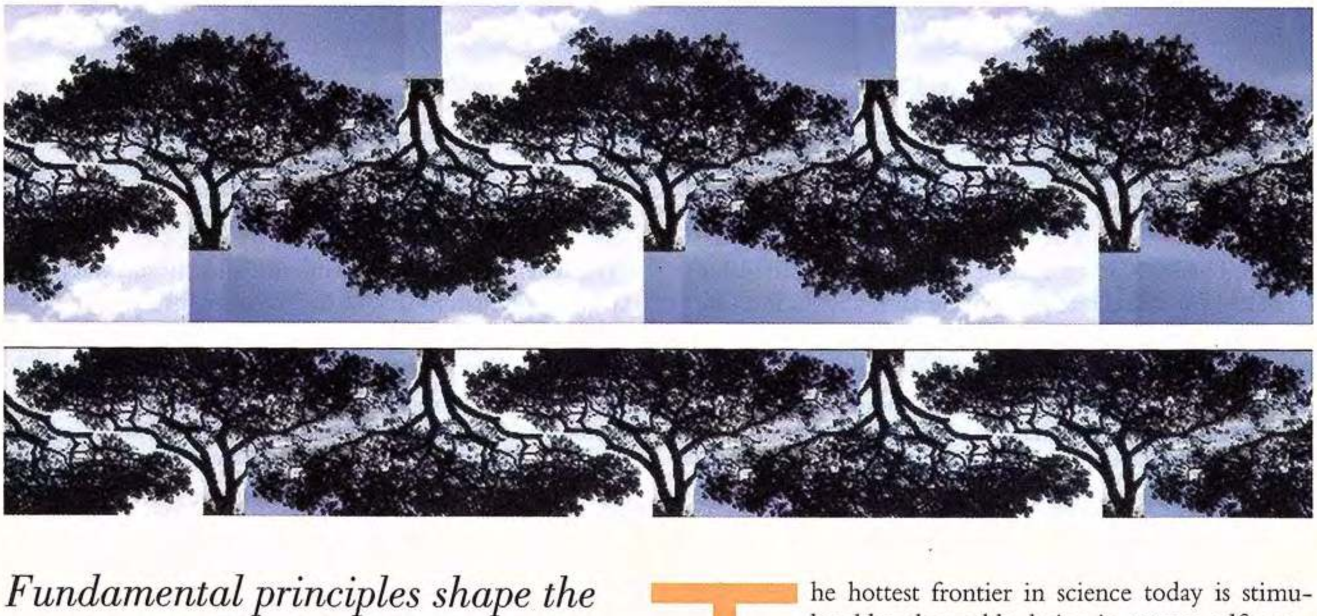
NATURAL DESIGN WITH CONSTRUCTAL THEORY



Fundamental principles shape the patterns of nature; they can guide the engineer, as well.

By Adrian Bejan and Sylvie Lorente

The hottest frontier in science today is stimulated by observable design in nature: self-organization, self-optimization, animal design rules, and the many scaling relations in geophysics, biophysics, social dynamics, and technology evolution. Design in nature has always provided central and highly stimulating images for scientific inquiry. Images are what

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The line-to-line trees (bottom image) illustrate the two sides of constructal theory. One is the prediction that alternating trees are the natural design for providing flow access between two lines or two planes. The other is the strategy for how to bathe a body volumetrically, with a single stream flowing in and out. Natural porous media (e.g. soil) exhibit multiscale (hierarchical) flow structures consistent with the scales and performance of the line-to-line architecture.

gave birth to science, as "geometry" in ancient Greece. Michelangelo Buonarroti said it this way: "Design ... is the fount and body of painting and sculpture and architecture ... and the root of all sciences."

Design in nature is captivating, useful, and misunderstood. "Design" in this article means discernable configurations, images, patterns, rhythms, and motifs that we see and hear all around us. This is the original meaning of the word (disegno = drawing, outline, in Italian), and it is universal and unifying.

All nature, from rivers to lungs, flows in patterns and rhythms. The occurrence of visible and audible designs is a natural phenomenon, which must not be confused with the human activity represented by the verb "to design." Science is the search for the principle that captures the natural phenomenon. Science is not the search for the designer.

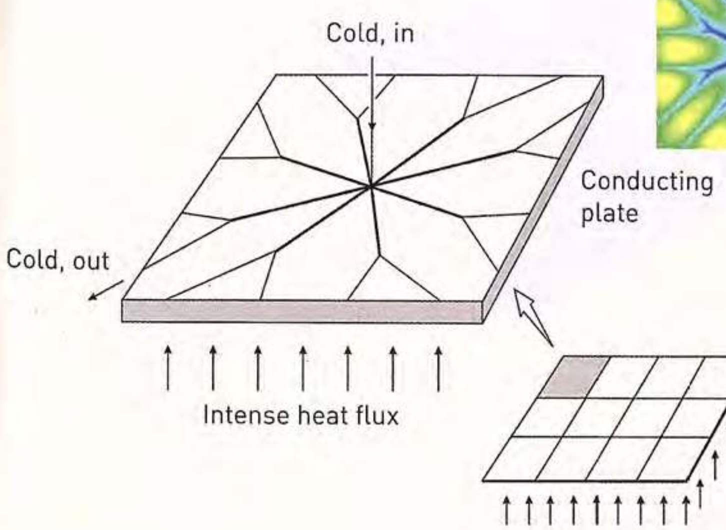
Engineering is the science concerned with developing scientific knowledge for practical uses. This is a key observation because the modern diversification of science and education has produced the impression that science and engineering are different, so different that "engineers" just implement the ideas generated by "scientists." This is not true, as the names Carnot, Gibbs, and Prandtl testify. These giants were engineers by training (mechanical engineers, in modern terminology), yet their contributions to physics have been so great that centuries later they are thought to have been physicists, not engineers. The engineering student needs to know that we are all scientists, or scientists by other names: geometrists, designers, and trackers (hunters) of form.

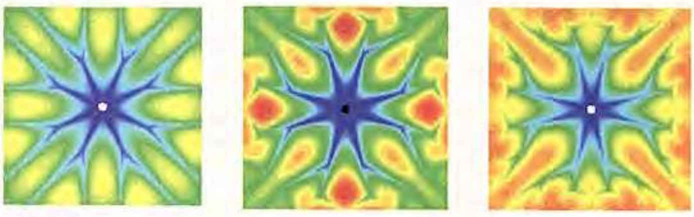
The configuration of a useful process or device is essential to its performance. The common approach to configuring fluid flows and solid components in a working whole is by hunch, talent, and trial and error. Images occur in the mind, and later they are tried in practice. This approach is so common that we do not question it, and most of us equate it with the activity of designing.

The alternative to this approach is to "see" the useful configurations because the principle that accounts for their occurrence in nature is known. For example, we know now that the easiest way to flow between one point (source, sink) and an infinite number of points (area, volume) is to flow dendritically, in a tree pattern. Not just any tree, but a particular tree drawing, with the right dimensions, numbers of channels, hierarchy, layout, and finite complexity. This alternative is to pursue design as a scientific activity.

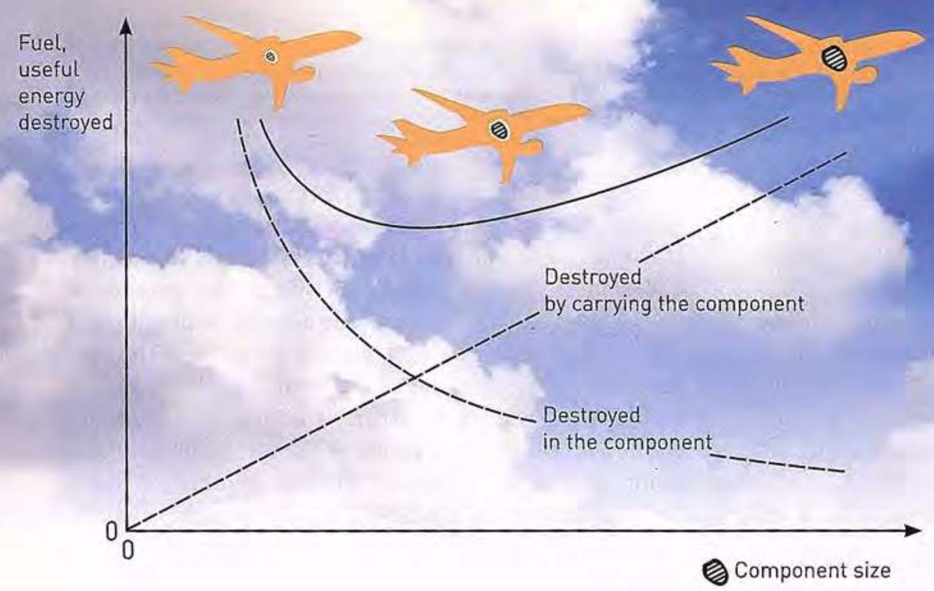
The design as science paradigm is spreading fast. With colleagues from many campuses all over the world, we have developed it into a new design course and book (*Design with Constructal Theory*, Wiley, 2008). Constructal theory is the view that the generation of design (configuration, rhythm) in nature is a universal phenomenon, which is covered by a law of physics known as the constructal law, articulated by Adran Bejan in 1996: "For a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it." In constructal terms, everything that flows and keeps on flowing is a "live" system, river basins and animal migrations alike. This view is in accord with that of Leonardo da Vinci, who wrote, "Movement is the cause of every life."

The constructal law is about direction in time. Imagine the evolution of a river basin under persistent rain. The channels swell and rearrange themselves into a bet-





Square slabs cooled by embedded tree-shaped flow channels. The intense heating is uniform and perpendicular to the figure. The coolant enters through the center and exits through ports on the square perimeter. The vascular architecture has the ability to distribute the hot spots more evenly over the available surface or volume. From left to right, the dendritic designs have one, two, and three levels of pairing.



The integral design of a vehicle or animal is an assembly of components of "characteristic" finite size. Each component introduces two losses in the global design. The sum of the two losses is minimum when the component has a certain optimum size.

ter and better tree on the landscape. Watching this tree emerge is like watching a movie. The constructal law is about the direction in which the movie tape runs. Existing flow configurations are replaced by globally easier flowing configurations.

The evolution of the dendritic structure is toward easier flowing, not toward maximum complexity, or greatest contact surface with least material. The lung, for example, is not ramified into smaller and smaller air passages solely to maximize surface-air contact. Yes, a large contact surface is necessary because it poses a low resistance to mass transfer (O_2 and CO_2). Equally necessary is an air distribution network with minimal flow resistance from point (mouth) to volume (thorax), and back.

The constructal law provides a broad coverage of "designedness" everywhere, from engineering to geophysics and biology. To see its generality, imagine the formation of a river drainage basin. The constructal law calls for configurations with successively smaller global flow resistances in time. This is achieved through a balancing of all the internal flow resistances, from the seepage along the hill slopes to the streams in all the channels. Resistances that are overcome by flows represent thermodynamic losses, or irreversibilities. Resistances cannot be eliminated.

The cross-sectional area of a duct with fluid flow, or the surface for heat transfer in a heat exchanger must be finite, not infinite. The losses due to resistances can be reduced by distributing the resistances through the available space such that their global effect is minimal. This distributing act is the phenomenon of emergence of configuration. In the river basin, this is achieved when the resistance to seepage down the hill slope is the same as the resistance to flowing along the channels. The emerging design is completely analogous to the lung: in the river basin, the role of the alveoli (the flow by diffusion) is played by the hill slopes, and the smallest rivulets play the role of the smallest air passages.

The most valuable product of this way of thinking is the configuration: the river basin, the lung, the tree of cooling channels in an electronics package, the city traffic pattern, and so on. The configuration is the big unknown in design. The constructal law draws attention to it as the unknown and guides our thoughts in the direction of discovering it.

THE VASCULARIZATION REVOLUTION

In the river basin evolution, the constructal configuration is a tree-shaped flow, with fine balances between high resistivity (diffusion, seepage) and low resistivity (channel flow). The tree-shaped flow is the constructal design of providing effective flow access between points and areas and volumes. The tree has finite complexity, i.e. a certain way of allocating flow channels and distributing them nonuniformly through the available area or volume. This entire architecture is deducible from principle.

Vascularized is a good name for complex flow systems. Vascularization is everywhere, in the animate, the inanimate, and the engineered, from the muscle and the river basin to the cooling of high-density electronics. The tissues of energy flows, like the fabric of society and all the tissue of biology, are designed (that is, patterned and purposeful) architectures. The climbing to this high level of performance is the transdisciplinary effort: the balance between seemingly unrelated flows, territories, and disciplines. This balancing act—the optimal distribution of imperfection—generates the very design of the process, power plant, city, geography, and economics.

Think of the flow that enters and exits a permeable body, such as the coolant that bathes a chip, or the rain falling on soil. Which is the architecture that provides the easiest access to the flow? One cannot "learn from nature" by looking through soil. The most that nature could reveal (for example, in a cut made with a shovel) is a seemingly random distribution of pores of many sizes, a few of them so large that they can be called "pipes."

From heat exchangers to microelectronics, the classical view of how to configure the plane-to-plane (or line-to-line) flow is by using the simplest drawing: an array of identical parallel channels across the porous body, i.e. a uniform porous medium. With the constructal law, the student has the freedom to change the drawing, and the first step in this direction is to discard the off-the-shelf solution.

With constructal design the student discovers (with pencil and paper) that the better line-to-line flow architectures should be configured as trees that alternate with upside down trees—a double-dendritic structure. It was demonstrated analytically that these vasculatures are dramatically superior to parallel channels and homogeneous porous structures. This discovery also accounts for the apparent multi-scale structure of soil and other naturally occurring porous media.

The future belongs to the vascularized. This is evident in the current race toward smart materials with new volumetric functionalities (self-healing, self-cooling), which require the distribution of fluids continuously, uniformly, and on demand throughout the material volume.

The same vascularized configuration can be used in cooling the skin of a vehicle under intense heating attack. The coolant bathes the skin as a patchwork of point-area tree flows. Each patch is cooled by a stream that enters through the center and exits through the periphery. Dendritic structures are currently under active study, and work is proceeding toward building and testing them for aerospace applications.

Understanding these designs also sheds light on the origin of their occurrence in animal design, where blood streams are distributed to vascularized volumes and surfaces in order to cool, i.e. to collect and dissipate heat. Examples are the blood circulation in the brain, the ear of the elephant, and the discharge of body heat during running.

Nature impresses us with many designs that are tree-shaped. Many of the flow architectures predicted from the constructal law are tree-shaped. Books on fractal geometry display tree-shaped drawings among many frizzy drawings. The tree image unites, but it also confuses.

Tree does not mean theory. The constructal law is theory because it is a purely mental viewing of how phenomena *should be* in nature. Fractal geometry is, at best, a descriptive method of things observed in nature, i.e. empiricism. None of the configurations of nature are fractal.

A fractal drawing is imaginable by choosing an *ad-hoc* algorithm and repeating it an infinite number of times. Such a drawing cannot be made, shown, or seen. If the configurations of nature were truly fractal, then all that we would be seeing would be blurs and shades of gray, i.e. no pattern whatsoever, and nothing to comprehend, remember, and discuss.

DESIGN FOR COMPACTNESS

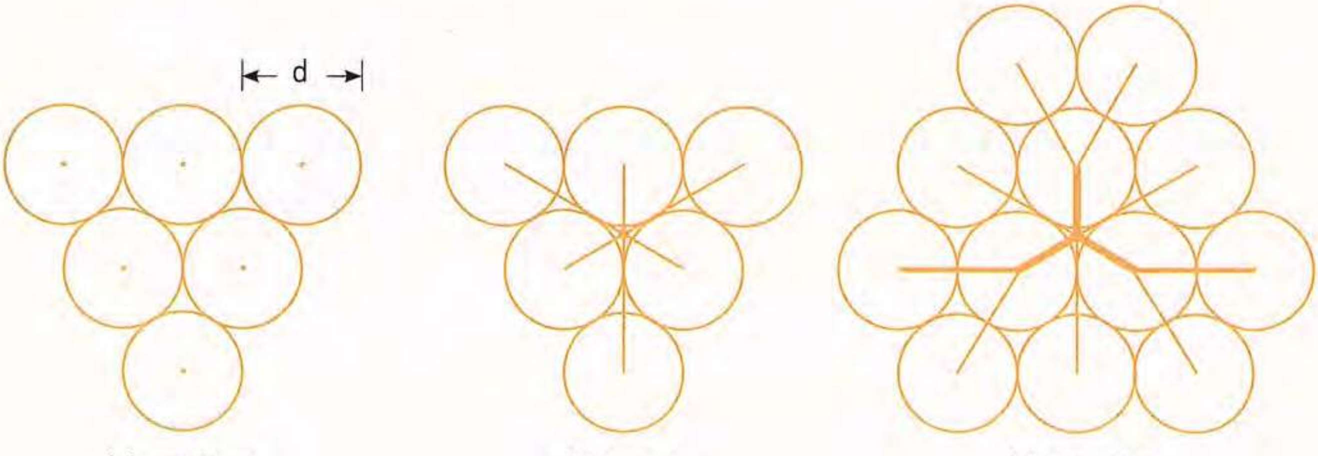
The design of entire vehicles is evolving toward the integration and distribution of thermal fluid and mechanical strength functionalities throughout the vehicle structure. We see it in every kind of vehicle, especially as we look at the past hundred years of development in automobiles, submarines, and aircraft.

With constructal theory and design, we conceptualize the vehicle structure as a molding solid with flow spaces to be allocated to the spots and subvolumes that need the fluids and heat currents that must flow. This way of thinking is about the two aspects of any drawing:

(1) The proportions (the aspect ratios, the shapes), and

(2) The actual dimensions of the design (the sizes of components).

▼ **How hot water is produced and distributed to users spread on a territory. Distributed energy systems emerge as a balance between central losses (at nodes, sources) and distributed losses, along the lines of the distribution network. The balance reveals the proper size for the territory allocated to one source. The proper territory increases as the individual use of hot water increases. In time, the network changes (stepwise) from radial to dendritic, and continues to morph toward larger and more complex tree-shaped flow architectures.**



(a) Individual (b) Radial (c) Dendritic

Imagine the sizing of a flow component such as a duct, pump, or heat exchanger. Larger components operate more efficiently because their streams of fluid or heat encounter smaller constrictions. So, if the component is designed alone, then a larger size is better.

Integrative design, however, is about the whole animal, not about the organ. This view reveals the rising curve, which accounts for the fact that a larger component induces a fuel penalty that is proportional to its weight. Added together, the two penalties reveal the principle that has been generating "characteristic sizes" for organs and components in every body that moves—animal or vehicle. The most appropriate organ has a certain optimum size: larger organs on larger vehicles.

Optimum size means optimum weight and compactness. By itself, the optimum-size organ is not as close to the Carnot ideal as would be a larger version of itself. The constructal-size organ along with the other constructal-size organs makes the best functioning whole. Along this route, the mind sweeps the vehicle searching for the right balances between the sizes of flow components and the global performance of the vehicle.

Engineers know most of these things already. To do more with less, to strive for efficiency and functionality, are qualities that define our work. This is one more reason why it is important to know how to fast forward the design evolution. This can be done as science, not art, based on the principle that governs the evolutionary process, the constructal law.

The flow of stresses goes hand-in-glove with the flow of fluid and heat. This integrative view is important because mechanical structural members are components for the flow of stresses. Their proper sizes and shapes come from the same principle. Larger is better when designed alone (stresses are lower, materials cheaper, manufacturing easier). Smaller is better when it is to be carried on board. The clash between the two trends determines the right weights and volumes.

The current trend to globalization can be viewed, in part, as the spreading of our technology-based society as new flow structures on areas swept by existing flow structures: vegetation, animal movement, river basins, etc. The existing structures are being affected by the pressures to build infrastructure all over the globe, not only in the developing world. Much earlier, the equilibrium of the natural flow structures was achieved because each movement and stream found its proper size on the area that was available to it.

This constructal-law tendency is also the key to sustainable development. The challenge is to allocate our streams to areas such that the entire global flow structure flows easily (fast, low cost, close to every potential user). The emerging global vasculature consists of distributed energy systems: flow structures allocated to areas and connected in ways that benefit the whole.

An illustration is the production and delivery of heating for human use. Say that hot water is produced in installations that serve as sources at nodes in a network that distributes the heating to users on the landscape, which could be an apartment building or a university campus.

This arrangement is accompanied by two kinds of heat losses: central, from the installation that produces hot water, and distributed, from the insulated ducts that distribute the hot water. These losses compete against each other, because when the area (or number of users) increases, the central loss per kilogram of hot water decreases, while the distributed losses increase. Their combined effect is minimal when the central is best allocated to the distributed. This is achieved when the node and the distribution network are allocated to an area that has the right size.

Most interesting is that the "right size" increases with the individual use of hot water, i.e. with the standard of living, in time. Consequently, the vascular design must change stepwise (that is, suddenly) as the right-size territory served by a single node increases. It changes from one node for every user, to radial ducts connecting the node to several users, and finally to dendritic designs that become larger and more complex stepwise as they serve larger and larger numbers of users on larger territories.

DESIGN AS SCIENCE

The central idea is that design (configuration, pattern, rhythm) can be deduced from a principle of physics, deterministically. Along this route, we discover the better configurations, the physics meaning of "better," and we also predict the images that are found (or will be found) in nature. The direction of this route is the exact opposite of mimicking nature (biomimetics), i.e. the opposite of copying what cannot be predicted.

The constructal law provides the student with strategy for how to pursue and discover design—the configurations or patterns—in both space and time. Constructal theory pushes design thinking closer to science and away from art. It tears down the walls between engineering and natural sciences.

Because the configuration-generating phenomenon of "design" has scientific principles that are now becoming known, it is possible to learn where to expect opportunities for discovering new, more effective configurations. How to pursue these discoveries with less effort and time (i.e., with strategy) is the chief merit of the constructal law and learning design generation as a scientific subject. ■

To Learn More

Design with Constructal Theory by Adrian Bejan of Duke University and Sylvie Lorente of the University of Toulouse (John Wiley & Sons, 2008) provides a course approach to design using the constructal law, the principle of configurations in nature and engineering.

See also the Web portal to constructal theory at www.constructal.org.