References

1. S. Glasstone, P. J. Dolan, *The Effects of Nuclear Weapons, Third Edition*, US Department of Defense and US Department of Energy, Washington, DC (1977), p. 101.
2. P. D. Zimmerman, in *Physics, Technology and the Nuclear Arms Race*, D. W. Hafemeister, D. Schroeer, eds., American Institute of Physics, New York (1983), p. 71.

Peter D. Zimmerman
Kings College, London

Eden responds: I accept Peter Zimmerman's apology and explanation for misstating the yields and burst heights in the first chapter of *Whole World on Fire*. My own figures, however, strengthen my case, not his, as readers of the book will readily see. I also appreciate Zimmerman's statement that "perhaps" he should not have called my book a "diatribe" nor indicated that I saw a "conspiracy"—themes that run throughout much of his original review, but that do not figure in my book. Finally, I did not write about heroes or scoundrels but about how professionals in organizations, in focusing on certain problems, can undermine their own ability to see and solve other problems that can prove highly consequential.

Lynn Eden

Constructing a Theory for Scaling and More

The developments that Geoffrey West and James Brown review in their article "Life's Universal Scaling Laws" (PHYSICS TODAY, September 2004, page 36) are important, but they fit into a much greater theoretical framework. West and coauthors' first paper appeared in April 1997.[1] I published the basic idea behind their approach to the modeling of tree flows one year earlier[2] as part of the constructal theory of organization in nature. Constructal theory, reviewed in my 1997 book *Advanced Engineering Thermodynamics*, 2nd edition (Wiley) and more recently,[3] is now a growing field, with articles appearing regularly, including in physics journals.[4]

Constructal theory is about the generation of shape and structure in nonequilibrium thermodynamic systems—flow systems—in general. Simply put, the constructal law states, "For a finite-size flow system to persist in time (to live), it must evolve in such a way that it provides easier access to the currents that flow through it."[2,3] The constructal law is not about *what* flows—fluid, energy, momentum, goods, or people—but about how the flow system generates its architecture. The three key assumptions that West and coauthors stated in 1997 and that West and Brown reviewed in their PHYSICS TODAY article are present in constructal theory, not as convenient assumptions to make a model work, but as invocations of the constructal law. In particular, a space-filling tree architecture can be deduced from the constructal law. Constructal trees are not fractal objects.

In a constructal tree there are at least two flow modes. The slow mode, which describes low-conductivity, low-permeability, high-unit-cost processes such as diffusion or walking, corresponds to interstices in the tree architecture. The fast mode, which describes high-conductivity, high-permeability, low-unit-cost processes such as flowing water and moving vehicular traffic, corresponds to channels in the architecture. Interstices and channels optimally connect to form a "tree," in which the resistance across interstices is balanced against the resistance along channels.

Because West's three assumptions are consequences of constructal theory, every successful derivation of an allometric law that West and coworkers make is an affirmation of the validity of that theory.

In return, every successful invocation of the constructal law in domains far removed from the living flow systems of West and coauthors is an indication not only that their model is correct but that it is an integral part of a theoretical framework that unites biology with physics and engineering. In addition to allometric laws, constructal theory covers many phenomena that fall well outside the biological scaling reviewed by West and Brown. Some examples are turbulent flow structure in various flow configurations, cracks in shrinking solids, the structure of animal hair, refraction in geographical economics, flight, atmospheric and oceanic circulation, and the structure of power plants and refrigeration plants—that is, the architecture of "human-plus-machine" species.

West and Brown conclude by asking, Is all life organized by a few fundamental principles? According to constructal theory, the answer is yes.

References

1. G. B. West, J. H. Brown, B. J. Enquist, *Science* **276**, 122 (1997).
2. A. Bejan, *J. Adv. Transportation* **30**, 85 (1996).
3. A. Bejan, *Shape and Structure: From Engineering to Nature,* Cambridge U. Press, New York (2000).
4. L. Ghodoossi, N. Egrican, *J. Appl. Phys.* **93**, 4922 (2003); S. M. Senn, D. Poulikakos, *J. Appl. Phys.* **96**, 842 (2004).

Adrian Bejan
(dalford@duke.edu)
Duke University
Durham, North Carolina

Adrian Bejan, in his book, *Shape and Structure: From Engineering to Nature* (Cambridge University Press, 2000), sums up work that started well before Geoffrey West and James Brown's early paper in 1997. Bejan discusses the emergence of shape and structure that derive from the purposes of animate and inanimate systems, which must deal with limited resources and other constraints. Animate systems must survive; inanimate systems—for example, engineered ones—must meet specific objectives.

In particular, the ¾ exponent in the relationship between metabolic rate and body size is proven on the basis of pure constructal theory (see section 10.6 of Bejan's book), which avoids the ad-hoc assumption of the tree architecture. Logically, any animal correlation that West and Brown derived in 1997 is evidence that the constructal law is valid.

Alexandru Morega
(amm@iem.pub.ro)
Politehnica University of Bucharest
Bucharest, Romania

West and Brown reply: The theory we developed with Brian Enquist on the origins, implications, and ramifications of universal scaling laws in biology, and which we reviewed in our article in PHYSICS TODAY, is predicated on the idea that life at all scales is sustained by optimized, space-filling, hierarchical branching networks whose terminal units are invariant. The theory not only explains quarter-power scaling but leads to detailed quantitative calculations and predictions of many biological phenomena.

We suggested that the generic underlying principles of the theory are derived from natural selection. Adrian Bejan suggests, however, that they follow from his constructal theory and that our idea was already implicit in his 1996 paper in which he investigated the special case of traffic flow through a network of streets. Although there are clearly qualitative areas of overlap, particularly concerning modeling trees and his specific version of optimization and space-filling, it is difficult for us to see any explicit connection to our work. He did not consider allometric scaling in biology, nor is there any mathematical derivation of the three major principles underlying our theory.

It is true, as Alexandru Morega points out, that in Bejan's 2000 book, published three years after our original paper, he does consider biological systems and presents a derivation of the ¾ power law for metabolic rate. The derivation is based on the special case of the role of blood flow in dissipating heat. Even if correct, that derivation is not general and is relevant only for warm-blooded mammals and birds. The vast majority of animals and plants are ectothermic, having body temperatures that mirror their environment, so heat dissipation is unimportant and consequently has not been a major target of natural selection. Nevertheless, ectothermic organisms also exhibit quarter-power scaling, which we claim is because their distribution networks have been selected to optimize the distribution of energy and materials.

We agree that there appear to be general principles of flow network and design that have crafted, and are exhibited by, a wide variety of biological and human systems. Bejan's book is a serious attempt to address this intriguing and very important observation. It remains to be seen, however, whether constructal theory is sufficiently general, detailed, and mechanistic to describe these systems in a quantitative, predictive, and analytic way. A significant contribution would be to have a convincing derivation from more fundamental principles of our assumptions that much of life is sustained by optimized, space-filling, hierarchical branching networks whose terminal units are invariant.

Geoffrey B. West
(gbw@santafe.edu)
Santa Fe Institute
Santa Fe, New Mexico
James H. Brown
(jhbrown@unm.edu)
University of New Mexico
Albuquerque ■