

## Life and evolution as physics

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### ABSTRACT

What is evolution and why does it exist in the biological, geophysical and technological realms—in short, everywhere? Why is there a time direction—a time arrow—in the changes we know are happening every moment and everywhere? Why is the present different than the past? These are questions of *physics*, about everything, not just biology. The answer is that nothing lives, flows and moves unless it is driven by power. Physics sheds light on the natural engines that produce the power destroyed by the flows, and on the free morphing that leads to flow architectures naturally and universally. There is a unifying tendency across all domains to evolve into flow configurations that provide greater access for movement. This tendency is expressed as the constructal law of evolutionary flow organization everywhere. Here I illustrate how this law of physics accounts for and unites the life and evolution phenomena throughout nature, animate and inanimate.

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### Dead state, live state, evolution

In this article, I present an outline of the unifying power of physics regarding the universal natural phenomenon of life and evolution.<sup>1</sup> The interest in the physics of life is documented regularly in the literature,<sup>2–44</sup> and is growing. The evolution paradigm is shifting seismically toward generality and physics principle.

Life and evolution is the most researched and least agreed upon topic in science today. It seems that every new article in *Nature*, *Science*, *PNAS*, and *Scientific Reports* is dedicated to this topic. The debate is placed without questioning in biology, because *bios* means life in Greek, and the term “evolution” dominates common speech because of Darwin’s enormous impact on modern education. Yet, the physical being of any amount of matter or any region of space (called “system” in thermodynamics) that persists and evolves is accounted for by the laws of physics, in particular by the laws of thermodynamics (Fig. 1).<sup>1–4</sup>

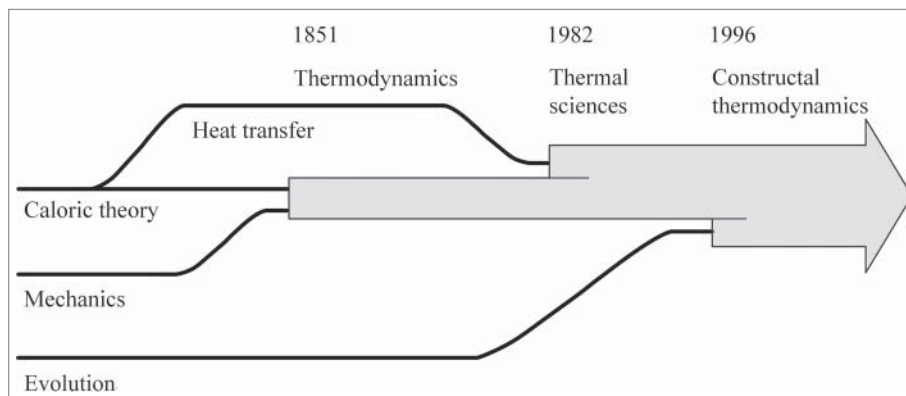
Any system obeys the laws, closed or open, steady or unsteady, animate or inanimate, human made or not human made. The “any” is the key concept from which follows the utmost generality and enormous power of thermodynamics.<sup>4</sup> The laws of thermodynamics that account for observations of life and evolution phenomena are three: the first law, the second law, and the constructal law. Each law accounts for a self-standing tendency in nature, in this order: energy conservation (what goes up must come down), irreversibility (by itself

everything flows one way, from high to low), and evolutionary changes in flow architecture (toward greater flow access over time). The latter is summarized as the constructal law:

“For a finite-size flow system to persist in time (to live) it must evolve freely such that it provides greater access to its currents.”<sup>3–7</sup>

The physics meaning of life and evolution is evident and unambiguous, even though it was not recognized until the formulation of the constructal law. The basis of such clarity is provided by thermodynamics and geometry. Here is how, in three simple steps:

1. The *dead state* is the physical being of a system when nothing flows (nothing moves) inside the system, or between the system and the environment (which is the other system, the rest).<sup>4</sup> In the dead state, nothing changes, not the configuration, and not the system properties. This happens when the system is in complete (unrestricted) equilibrium with its environment. The dead state is the still image of the dead system.
2. The *live state* is the opposite of the dead state. Live is the state of a system with two physical features present at the same time: flow (movement, inside and across its boundary with the environment), and morphing configuration (shape, structure, form, drawing, boundaries, i.e. design) that changes freely while the system flows.<sup>3–7</sup>



**Figure 1.** The evolution and spreading of thermodynamics during the past two centuries, after a drawing made in 1982.<sup>1,2</sup> Caloric theory mated with mechanics to give birth to thermodynamics; more recently, evolutionary design (function, goal-oriented change) mated with thermodynamics to enhance the usefulness and permanence of both (compare Fig. 6).

3. *Evolution* is the sequence of flow configurations that the live system exhibits over time. This is where geometry meets thermodynamics. Two figures are different when, if superimposed, the lines of the first do not match faithfully the lines of the second. Today's flow configuration must be different than yesterday's. The future must be different than the past. Evolution means changes in geometry, which occur one way, in a goal-oriented direction in time (see the next section). Think of evolution as "geometric irreversibility."

Evolution is a concept and word as old as western civilization. Its origin is the Latin verb *evolvo-evolvère*, which means to come forth, to roll out (note the change, and also note the direction of the change). This verb speaks of the same mental image as the noun "nature" (*natura*, from Latin, she who gives birth to everything). Evolution is a phenomenon of everything that happens, which is called nature, or physics (from Greek). Evolution is the "movie" of the live system, and the movie tape runs only forward.

Why is this physics framework of life and evolution important and useful? For at least four reasons:

- First, biology is descriptive,<sup>28</sup> and every description of life, death and evolution from the biology literature fits perfectly in the predictive (physics) frame defined above.
- Second, the concept of function, or goal-directed dimension of evolutionary design is central in physiology, however, the concept itself is not defined in physiology.<sup>33</sup>
- Third, all the advances made in other fields where "evolution" is observed and described are unified under the big tent of physics: the evolutions of animate systems, science, technology, text, language, alphabet, software, warfare, government, rule of law, education, urban design, athletics, and many more.

- Fourth, the unifying power of the physics of life and evolution is the whole point – the usefulness – of science itself. This quote from Henri Poincaré says it best: "The true and only goal of science is to reveal unity rather than mechanism."

As noted above<sup>2-44</sup> and in the next section (points I-IX), in contemporary science a significant publishing volume is being devoted to the search for universal design principles that may explain organization in animate and inanimate systems. The challenge that physicists and biologists face was described in 1993 by Kauffman:<sup>19</sup>

"Imagine a set of identical round-topped hills, each subjected to rain. Each hill will develop a particular pattern of rivulets which branch and converge to drain the hill. Thus the particular branching pattern will be unique to each hill, a consequence of particular contingencies in rock placement, wind direction, and other factors. The particular history of the evolving patterns of rivulets will be unique to each hill. But viewed from above, the statistical features of the branching patterns may be very similar. Therefore, we might hope to develop a theory of the statistical features of such branching patterns, if not of the particular pattern on one hill."

In 1996 the constructal law<sup>4-6</sup> answered the challenge articulated by Kauffman, except that the answer does not involve chance and statistics. This law provides a predictive method and a deterministic foundation for the descriptive world that we all know. Yes, we are living in a period of great excitement in science, and this is why this *review* is timely.

### The time arrow: Evolutionary design

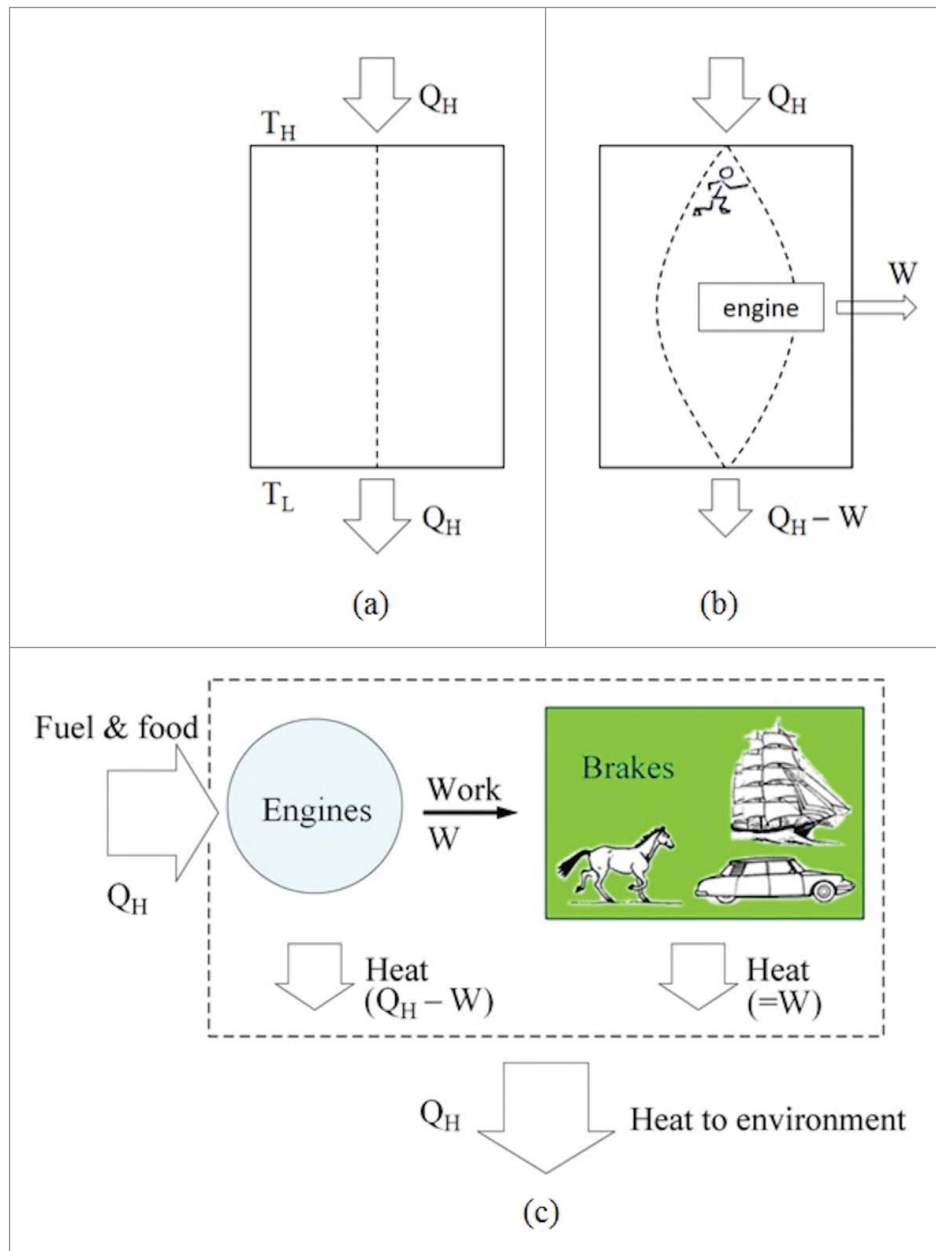
Well known is the arrow of time of the phenomenon of irreversibility. Heat flows from high to low temperature, not the other way around. Like water under the bridge, or over the dam. This natural tendency is captured by

the second law of thermodynamics. We see it in [Figure 2a](#) where the system is defined by the solid line, and the heat flow  $Q_H$  proceeds from high temperature  $T_H$  to low temperature  $T_L$ .

Less known is the time arrow of the phenomenon of evolution, which means design changes that occur in a discernible direction in time. In thermodynamics, design change is discussed commonly when comparing an existing design (e.g. power plant) with a newly proposed one. An early example of design change was Maxwell's demon.<sup>45</sup> Maxwell argued that even though the

temperature is uniform in an isolated system, the molecule speeds are not. He wrote: "Now let us suppose that such a vessel is divided into two portions (A and B) by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B and only the slower molecules to pass from B to A. He will thus, without expenditure of work, raise the temperature of B and lower that of A."

I described the demon in macroscopic terms.<sup>45</sup> Imagine "a being" that can follow the flow of heat and divert



**Figure 2.** Closed system in steady state (heat flows in and out). (a) Without flow organization (design); (b) With flow organization; (c) Every moving body, animate or inanimate, functions as an engine that dissipates its power entirely into a brake during movement. The natural tendency of evolving design is the same as the tendency toward more power (the engine design, animal or machine), and toward more dissipation (mixing the moved with the ambient).<sup>45</sup>

some of it to flow through a contrivance—a design, or machine—that produces power, mechanical or electrical, [Figure 2b](#). This happens everywhere in nature, from the whole earth as a heat engine, to every animal as a vehicle with its own motor, [Figure 2c](#). Without power, nothing moves.

Instead of Maxwell's box, imagine a box filled with a gas of uniform temperature  $T_1$  and pressure  $P_1$ . The gas is moving in the box, with the kinetic energy  $KE_1$  (state 1). Next, partition the box into A and B. The partition is highly conductive to the flow of heat. In one spot on the partition, the designer installed a sensitive instrument that measures the pressure on the two surfaces of the partition. Such a design can be built, operated, recorded, and described.

Time varying pressure differences occur across the partition, at every point, because when jets and eddies hit the wall the fluid stagnates and experiences a pressure rise (the stagnation pressure). The instrument monitors the pressures on the A and B sides of the partition. Whenever the B side is at a higher pressure than the A side, the instrument opens an orifice through which B fluid flows into the A chamber. This process continues until all the motion stops. In that final state the isolated system is isothermal, and the mass and pressure in A are greater than in B.

Key is the system feature that unites the two scenarios, the microscopic and the macroscopic. The partition that opens and closes in accord with measurements of differences between the A and B sides represents *design*, or *organization*—a flow configuration. The system without partition does not have flow configuration. The macroscopic scenario makes the design evident, and much more visible than Maxwell's microscopic argument.

Return to [Figure 2b](#), which shows the most general closed system (not isolated) that underpins this mental viewing. With design, the system generates power ( $W$ ), or work per unit time. With design, the system of [Figure 2b](#) generates less entropy, because the generated entropy [namely,  $(Q_H - W)/T_L - Q_H/T_H$ ] is less than in [Figure 2a](#) (namely,  $Q_H/T_L - Q_H/T_H$ ). Less entropy out makes it appear that more of the inflowing entropy ( $Q_H/T_H$ ) is kept inside the system.

The evolution of flow organization is a universal tendency of flow systems in nature. It happens throughout animate and geophysical systems in accord with the constructal law. In [Figure 2](#), this means that the time arrow points from (a) to (b), or to (c). This tendency is also recognized as self-organization, self-optimization, increasing complexity, order, networks, and scaling. It is also the basis for many disconnected (ad-hoc) and contradictory statements of optimality such as (for reviews see refs. 7,40,41):

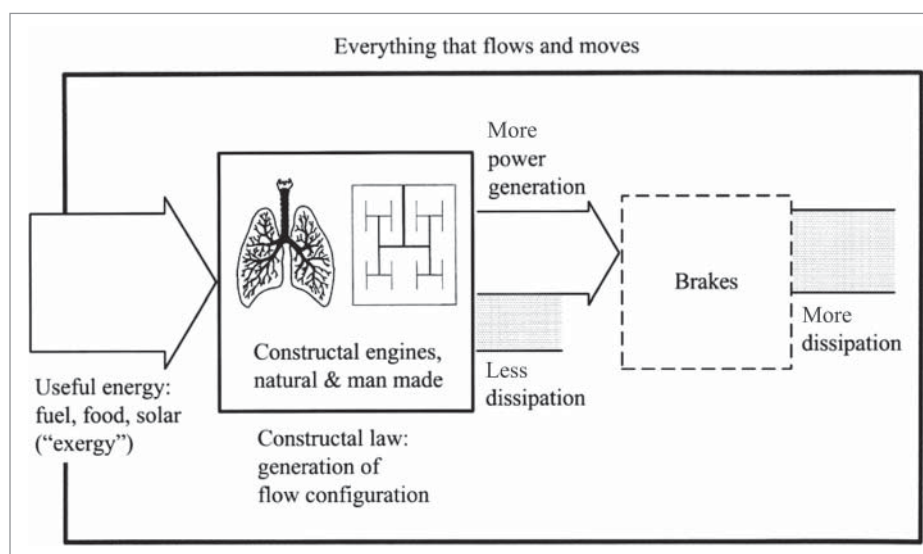
1. Maximum entropy production,
2. Minimum entropy production,
3. Maximum flow resistance,
4. Minimum flow resistance,
5. Animal body-size scaling,
6. Uniform distribution of stresses in loaded solid structures,<sup>46</sup>
7. Maximum growth rate of disturbances in turbulence,
8. Rapid solidification as dendritic design, and
9. Technology evolution (organ size, scaling rules, miniaturization, high density of functionality and minimum weight).

The current literature shows that all these ad hoc statements are reconciled by the constructal law (for example, I and II above, and [Figure 3](#)). These statements represent one phenomenon, which is the time arrow of design change, the time arrow of evolution. We can see the constructal law in snowflakes, Earth's climate, lungs, body insulation, breathing rhythm, city traffic, the shape of the Pyramids, golden-ratio frames of drawings, and many more.

Consider what happens to the produced power ( $W$ ), which is the physical measure of the design. The power is destroyed in the process of moving mass horizontally on land, on water and in the air ([Fig. 2c](#)). Everything that flows and moves does so because it is being pushed. The push comes from the power generated because of design. The dissipation resides in the environment that is displaced (penetrated) by the moving entity. The environment is the “brake” that dissipates the power generated by the “engine.”

People like to say that nature is complicated. Not according to thermodynamics! Nature is the simplest imaginable, because it consists of only two systems, your system (the portion selected by you for contemplation) and the rest (the environment). If your chosen system generates power in order to move through its environment, then the world that you contemplate is an “engine and brake” whole. Other thinkers may contemplate other systems that generate power and move (waterfalls, animals, etc.). For all the thinkers together, the same world as yours is an endless collection of intertwined engine and brake flow systems. The extreme simplicity of nature is revealed by the engine and brake assembly shown in [Figure 2c](#).

The physical effect of evolving design is more movement and greater access for all movers. This is what all the “demons” achieve, including you and I. This is the complete design of all animate or inanimate flow systems, from water flowing in river basins, to animal locomotion and urban traffic, and atmospheric and oceanic circulation.



**Figure 3.** Every non-equilibrium (flow) component of the earth functions as an engine that drives a dissipater (a brake).<sup>4</sup> The constructal law governs 'how' the system functions: by generating a changing flow architecture that provides greater access over time. The 'engine' part evolves in time toward generating more power (or less dissipation) and, as a consequence, the 'brake' part evolves toward more dissipation. Evolution means that each flow part assures its life (persistence, survival in time) by freely morphing in a one-way direction in time.

### Inanimate evolution

Organization in nature is in the eye of the observer. Where many see randomness, chance and nondeterminism, a few see organization and principle. Nowhere is this more evident than in the discussion of turbulence.<sup>39,40</sup> In spite of their obvious irregular appearance, turbulent flows are united by "organization" that makes their behavior expected, predictable, and reliable.

For example, measurements of flow friction inside pipes and on solid surfaces have been lining up on curves that science and technology have used with confidence for more than a century.<sup>47</sup> The large scale structure (i.e., the configuration) of jets and plumes, has become evident when the methods of measuring and visualizing turbulence improved. This empirical body serves as skeleton for the computational models and software packages used today to simulate turbulent flows at all scales, all the way to atmospheric circulation and the weather.

The natural occurrence of organization is an integral part of the phenomenon of turbulence, and has been calling for a physics principle. Progress was made in this direction based on the physics law of design evolution in nature. The constructal law was used to predict and unify the turbulence phenomena, for example, the transition to turbulence, the size of the smallest eddy, the large scale structure of jets and plumes, and the correlations for friction and heat transfer (for reviews see refs. 2, 4, 40, 47).

In Bejan et al. (2014),<sup>48</sup> we drew attention to one of the most common examples of turbulent flow *evolution* that went unquestioned, and showed how to predict it.

The smoke from a row of closely spaced factory smoke stacks (or a brush fire) rises as a curtain, i.e. as a two-dimensional plume. It is only above a certain (predictable) height that the curtain of smoke organizes itself into a round plume that, from a distance, looks like all the other plumes.

Why is this?

The reason is the natural tendency of flow systems to morph into configurations that facilitate the access to what flows. In jets and plumes, it is momentum that flows from the mover (the turbulent column) to the non-mover (the still surroundings). Momentum flows perpendicularly to the flow of fluid. This flow is called "mixing," or momentum transfer. When the lateral flow of momentum has greater access to the stationary environment, the fluid of the column mixes faster with the surrounding fluid, and its longitudinal speed decreases faster. The tendency of the flow is to morph its cross section such that the mixing becomes more effective, and the longitudinal speed decreases faster.

The jet cross section evolves from flat to round, not from round to flat. At bottom, this phenomenon adds to the growing evidence that the tendency toward evolutionary organization in nature is governed by a physics principle. In particular, the tendency toward round cross sections in simple (one stream) configurations unites the animate with the inanimate flow systems. Without exception, the cross sections tend to the round shape: blood vessels, pulmonary airways, subterranean rivers, large pores ("pipes") in the hill slope, underground galleries of



moles and earthworms, tunnels, intestines and many other features of animal design. In river channels, this natural tendency is made visible by the proportionality between depth and width in rivers of all sizes.<sup>4</sup>

Growth is not evolution.<sup>1</sup> Growth is a universal phenomenon that unites the inanimate with the animate, and it is defined by the S-shaped history of areas and volumes swept by spreading flows and collecting flows. Examples of S-curve spreading histories are the growth of populations, the spreading of technologies, and the spreading of news and information, Figure 4. The histories of collecting flows also exhibit S curves: examples are mining and the extraction of minerals, such as the Hubbert peak of oil extraction.<sup>49,50</sup>

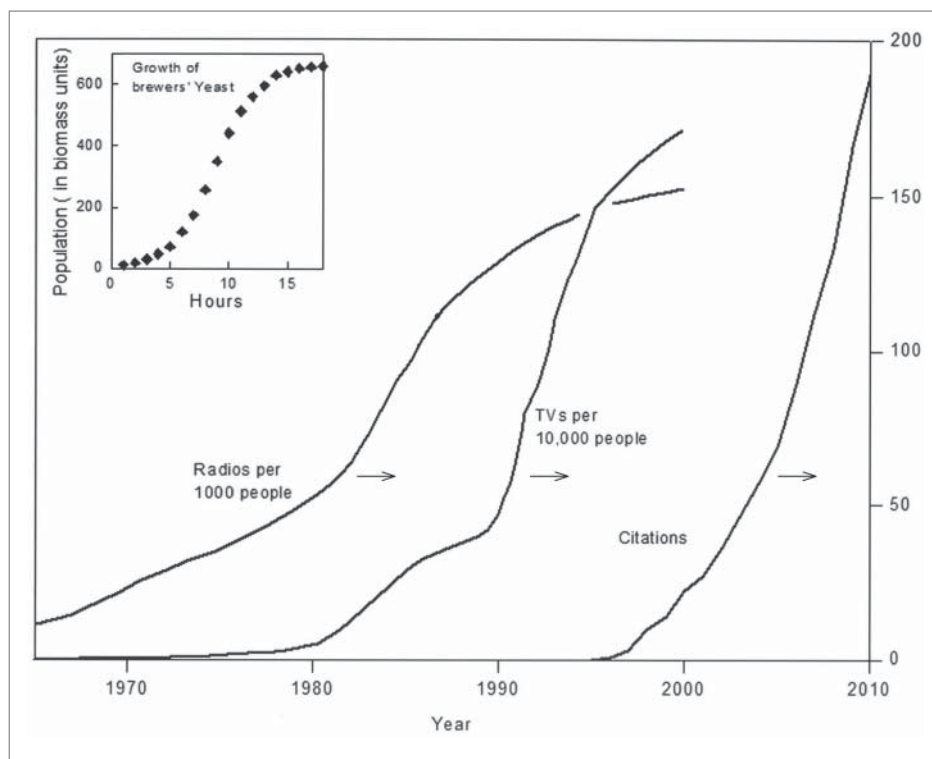
Rapid solidification is another common phenomenon, where the S-curve history is about the growth of solid in a subcooled liquid or gas. This phenomenon is classical textbook material in materials science, and has generated a voluminous body of research dedicated to explaining the S-shaped history. We showed how to predict the S-curve of solidification purely theoretically.<sup>4,51</sup> The starting idea is to see solidification as a “spreading flow” like the flows brought together in Figure 4, and to recognize that this spreading flow has the same natural tendency as all the inanimate and animate flow systems that morph freely into configurations that provide greater access to

what flows, over time. In view of the constructal law, we asked two questions:

First, what flow is spreading during solidification? It is not the solid, because the solid and its subcooled surroundings are motionless. The spreading flow is the flow of heat, which emanates from the solid surface and flows in all directions into the surroundings.

Second, what is the configuration of the heat flow system? We did not postulate the configuration: in fact, in the physics of evolution the configuration is *the unknown*. This runs against current doctrine, where the student is given the governing equations and boundary conditions, and is asked to discover the flow field. In the physics of evolution, the boundaries (the drawings) are to be discovered.

Instead of assuming the configuration, we relied on the physics law that commands that the flow system generates and evolves its flow architecture in order for the solidification process to be the more “rapid” at every stage in its changing history. We showed that although the solidification is triggered as small spheres around nucleation sites, at longer times the greater solidification rate is associated with needles and dendrites, in accord with common observations. Solidification begins at point-size nucleation sites around which the solid grows as tiny spheres. The spherical growth slows down and is replaced by needle-shaped growth, which is faster. The transition



**Figure 4.** Growth, or S-curve phenomena. The growth of brewer’s yeast, the spreading of radios and TVs, and the growth of the readership of scientific publications.<sup>49</sup>

from spherical to needle-shaped growth is in accord with the constructal law, and defines the early part of the S.

Advances in geophysics continue. Recent examples made based on the constructal law include dendritic flow structures,<sup>52</sup> permeable barriers for ground water,<sup>53</sup> beachface slope,<sup>54</sup> climate,<sup>55</sup> climate change,<sup>56</sup> and sub-surface flow networks.<sup>57</sup>

## Animate evolution

Theoretical advances on animal design evolution based on the constructal law appear regularly in the literature.<sup>58-62</sup> For example, it is well known that larger animals live longer:<sup>20-24</sup> the life span ( $t$ ) increases with the body mass  $M$  roughly as the power function  $M^\gamma$ . For mammals, observations show that the  $\gamma$  values are around 0.2 and 0.22, with considerable scatter around the  $t \sim M^\gamma$  curve. This information is empirical. The purely theoretical prediction<sup>63,64</sup> is based on the view that animals are not the only moving bodies for which the larger size translates into a longer life span. Inanimate systems such as rivers, atmospheric currents, rolling stones and turbulent eddies persist longer in time when they are larger. They also travel farther during their lifetimes, and this unveils a second aspect of animal design that is not nearly as well known as the body size effect on life span: the bigger travel farther during their lives than the smaller.

According to the constructal law, “life” is defined as a flow system that morphs freely over time toward easier movement and access to the available space. This definition of life makes the life span vs. body size a problem of *physics*, i.e., of everything, not just biology. The same size effect on life span and distance traveled holds for the other flows that move mass on earth: atmospheric and oceanic jets and plumes, river basins, animals and human operated vehicles. The physics is the same for all flow systems on the landscape: the scaling rules that suggest “design” are expressions of the natural tendency of all flow systems to morph so that they facilitate flow access. Larger bodies are more efficient movers of mass on the landscape: because this evolutionary design is predictable, the phenomenon of “economies of scale” is physics,<sup>1,65</sup> i.e., a manifestation of the constructal law.

In Bejan (2012),<sup>63</sup> three theoretical steps were made. First, a theoretical framework unified the movement of inanimate mass flow (fluid jets, rivers) with the movement of animate mass flows (human transportation, animals). This unifying theory showed that inanimate and animate mass flows exhibit the same size effect on life span and territory covered by movement: larger bodies move to greater distances during longer life times.

Second, this unifying theory predicted the size effect on animal life span, namely  $t \sim M^{1/4}$ . This scaling has the same constructal-law origin as the speed-mass scaling of all locomotion (land, sea, air, sports).<sup>66-70</sup>

Third, the theory predicted that larger bodies should cover larger distances during lifetime. Although obvious intuitively, the size effect on distance traveled is not documented and correlated in biology. Most interesting is that the size effect is essentially the same in inanimate and animate flow systems.

Vision, cognition and locomotion are features of a single design for movement of animal mass with easier and easier access in time, all over the globe. The golden-ratio phenomenon and its constructal-law prediction<sup>71</sup> illuminate the oneness of the integrative design of the movement of biological mass on earth. Shapes that resemble the golden ratio facilitate the scanning of images and their transmission through vision organs to the brain. The speeding up of this flow goes hand-in-hand with the dendritic architectures of the nervous system in the eye and the brain. Dendrites maximize the rate of point-volume flow of information inside finite volumes, and the rate at which new point-volume connections can occur naturally in the brain.

## Modularity and vascular evolution

What works is kept—this is the formula for evolution as a universal phenomenon. We see this everywhere, yet, one place where its manifestation has been intriguing (and frequently in the news) is the brain.<sup>72</sup> The brain, like the lung and the muscle, is a vascular design, a flow architecture that connects a whole volume to innumerable discrete points that fill the volume. The intriguing design that emerges naturally is modularity: organization at the real (system) scale appears to be a collage of the same design from smaller scales. This is an appearance, but its basis is in physics, and it has nothing to do with fractal geometry. It has everything to do with flow and the free morphing of architecture toward greater access. We showed that the modular design emerges naturally as one stream bathes a volume (e.g., living tissue) and then it leaves the volume as one stream.<sup>4,73,74</sup> The constructal law architecture that must be in place turns out to be modular, with flow constructs wrapped into larger constructs.

The cerebral vascular network has evolved in such a way so as to minimize transport time and power expenditure.<sup>72</sup> This is accomplished by a subtle combination of the arrangement of arteries, arterioles and capillaries and the transport mechanisms of convection and diffusion. Elucidating the interaction between cerebral vascular architectonics and the latter physical mechanisms can catalyze

progress in treating cerebral pathologies such as stroke, brain tumors, dementia and targeted drug delivery. Brain microvascular organization is predicated on commensurate intracapillary oxygen convection and parenchymal diffusion times. Cross-species gray matter results for the rat, cat, rabbit and human reveal very good correlation between the cerebral capillary and tissue mean axial oxygen convective and diffusion time intervals. These findings are in accord with the constructal law.

## Human and machine evolution

Our bonfires are shaped as cones and pyramids, as tall as they are wide at the base.<sup>1</sup> Why is this human preference for burning piles that look the same? Why do we build the same “edifice” of burning fuel every time? Why do we do it instinctively, without having to learn it in school or steal the idea from the neighbor?

The reason is that fire is good for power (movement, life), and because it is good it was adopted. The adoption of fire in human civilization was a design change (a transition) of the same nature as the emergence of organs for vision in animal design, the emergence of turbulence in laminar flow, the emergence of terrestrial animal locomotion from swimming, and the emergence of flying later on. This step occurred in an unmistakable direction, from no fire to fire, not the other way around. Why?

The answer is the same for all the transitions: to facilitate movement and mixing on earth. For us, fire means ultimately more movement for humanity on the landscape, in accord with the constructal law. Fire accounts for many empowering features that enable the human mass to move more easily and for greater access. Controlled fire is a human contrivance for instant and portable shelter, which is good for the continuity of movement. With fire the early humans did not depend on caves for warmth, dryness and safety.

The hottest pile of burning fuel occurs when the height of the pile is roughly the same as its base diameter.<sup>1,75</sup> Future studies may address the shape effect of wind, material type, and packing. Key is why humans of all eras have been relying on this design of fire “unwittingly.” The reason is that the heat flow from fire facilitates the movement and spreading of human mass on the globe.

The same physics provides the scientific foundation for sustainability.<sup>76</sup> The need to have sustainability is about the flow of energy and the flow of water through the inhabited space. All the flows needed for human life (transportation, heating, cooling, water) are driven by the purposeful consumption of fuels. This is why the wealth of a country (the GDP) is directly proportional to the annual consumption of fuel in that country.<sup>7</sup>

This organization happens, it is natural. Sustainability is the one-word need that covers all the specific needs. Sustainability comes from greater freedom in changing the organization—the flow architecture—that sustains life. Greater freedom to change the design (from water and power to laws and government) leads to greater flow, wealth, life and longevity, i.e. sustainability.

Fuel that drives human flows is wealth (Fig. 5), because it sustains the movement of people and goods, in accord with the tendency of all natural flow organizations to morph to move more easily. The physical relation between fuel use, wealth and sustained movement is also responsible for the relation between wealth, life expectancy, happiness, and freedom.<sup>1</sup> With the evolutionary principle that underpins these trends, biology and economics become like physics—law-based, exact, and predictable.

The current literature shows that a scientific framework for human and machine evolution is emerging.<sup>6,39,42,77-84</sup> Wealth is power, literally, the power used to drive all the currents that constitute the economic activity. They are manifestations of the greater need to have life (sustainability), freedom, advancement, and staying power. These changes are spreading naturally, cf. Figure 6.

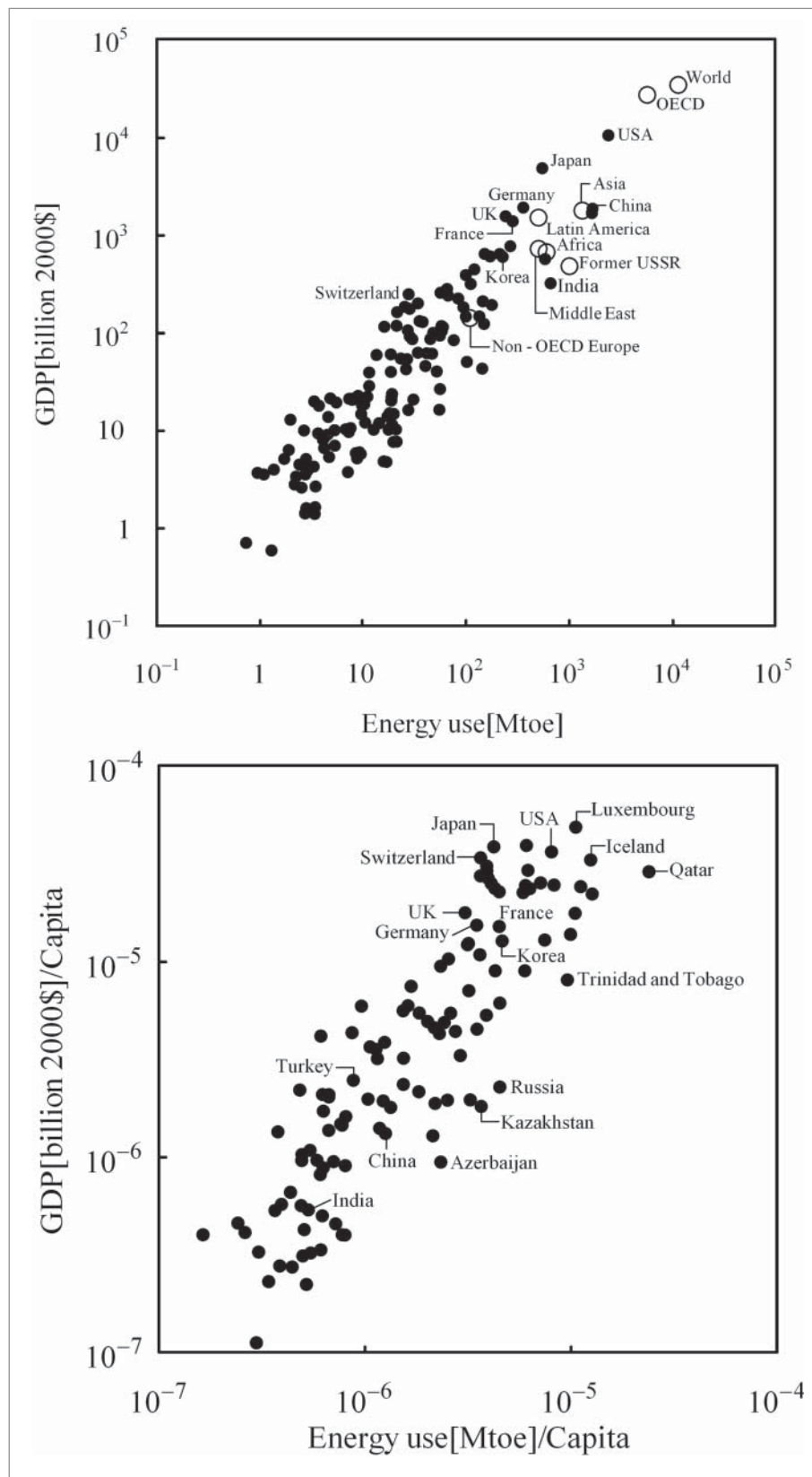
The burning of fuel and the resulting movement are not the only streams that represent wealth. There is also the creation and spreading of knowledge (science, education, information), technology and paths of communication (cf. Fig. 6). These morphing flow architectures happen because they are integral parts of the design of moving people and goods more effectively. They guide the process of changing and improving the design, to flow better. The flow of knowledge is an integral part of the material flow architecture on the globe, and it also means wealth—more, farther, more efficiently, all measurable in physics.

## One phenomenon, one law, many theories

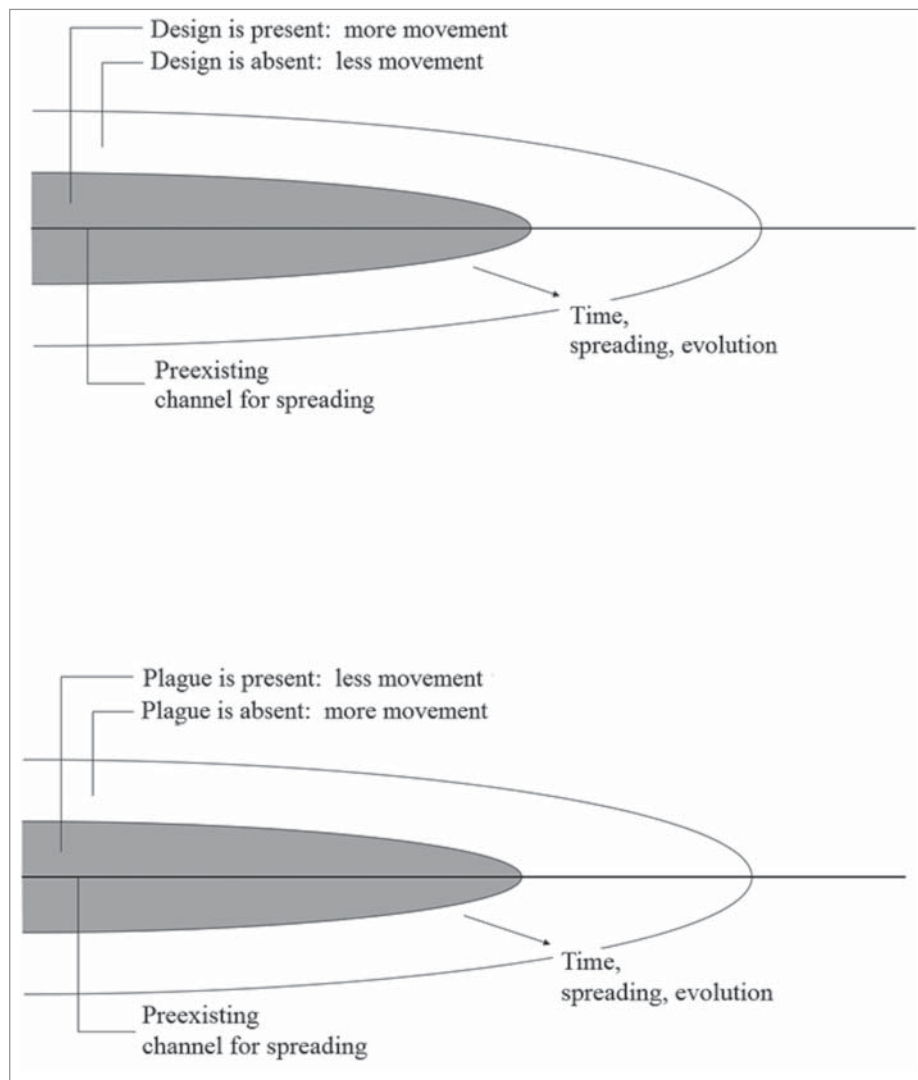
The field reviewed in this article provides concrete answers to Ellis and Silk’s question of what is a scientific theory.<sup>85</sup> To see how, we must first review the concepts that lead to and underpin any theory:

1. The human observation that certain things (images, events) happen the same way innumerable times represents one natural tendency, i.e., one universal *phenomenon* of nature (physics).
2. The *law* of physics is the compact statement (text, or formula) that summarizes the innumerable observations of the same kind everywhere. One law, for one distinct universal phenomenon.





**Figure 5.** Wealth is movement. Economic activity means fuel that is being burned for human use: the GDP (Gross Domestic Product) of regions and countries all over the globe versus their annual consumption of fuel.<sup>7</sup> The data are from the International Energy Agency, Key World Energy Statistics, 2006.



**Figure 6.** Knowledge is the spreading of the ability to effect design changes that facilitate greater and more lasting movement over the covered territory.<sup>45</sup>

3. To rely on the law (i.e., to invoke it) in order to experience a purely mental viewing of how things *should be* in a particular set of circumstances (i.e., to predict observations for that setting) is the *theory* that became available for that setting because the law is known to the thinker.

In sum, the phenomenon is one, the law is one, and the theories that spring from the law are as many as the circumstances in which the thinker contemplates the phenomenon, i.e., the manifestations of the law. The constructal law is one and the constructal theories are many, covering the board from *bio* to non *bio*, for example, lung structure, rhythm (respiration, heartbeat), animal locomotion, river basin structure, river channel cross sections, aircraft evolution, turbulent structure evolution, snowflake evolution, and many more.

Ellis and Silk<sup>85</sup> concluded their defense of physics this way: “the issue boils down to clarifying one question:

what potential observational or experimental evidence is there that would persuade you that the theory is wrong and lead you to abandoning it? If there is none, it is not a scientific theory.” I agree, and so does my physics colleague Ron Metzner,<sup>86</sup> who put it this way: “Take a prediction of the constructal law, then look at nature to see if the prediction is observed.” Sure, here are a few of the many predictions documented in this article:

1. A flat plume or jet should evolve into a round plume or jet, never the other way around.<sup>48</sup>
2. Solid bodies that grow during rapid solidification (e.g., snowflakes) should be tree-like, not spherical.<sup>4,51</sup>
3. The bigger movers (animals, rivers, vehicles, winds, rolling stones, eddies) should live longer and travel farther, not live less and travel less.<sup>63,64</sup>
4. The human lung should be a tree flow architecture with 23 levels of branching.<sup>61</sup>

5. All animal speeds (swimming, running, flying) should be proportional to the body size raised to the power 1/6, and for a given body size should increase from swimmers to runners and then flyers.<sup>87</sup>

The examples go on and on, and every single one is evidence in answer to questions of falsifiability.<sup>85,86</sup>

There is more to this than meets the eye. Some readers may be tempted to argue that the evidence has long been available in the past, and that the theory cannot predict “future” observations. This argument is incorrect, in two ways:

- To predict existing observations that were not recognized as a universal tendency (a phenomenon) is theory indeed. Think of Galilei’s law of gravitational fall, and Clausius’ law of irreversibility (the second law). Observations that everything on earth has weight (from which the word “gravity”) and everything flows from high to low (from which “irreversibility”) are phenomena that were not brought into physics before Galilei and Clausius questioned them and summarized them with two laws.
- Throughout this article, there are plenty of predictions that refer to *future* observations, such as no. 1 and no. 2 above, and many more evolutionary designs that occur at short time scales that are comparable with our life time, for example, technology evolution<sup>1</sup> and sports evolution.<sup>1,66</sup>

This should come as no surprise, because all science is an artifact (an add-on) that empowers humans to predict the future. This is why I end this article with a true story that illustrates the predictive power that a scientific theory brings to us. When Charles and I discovered how to predict that the winners in sprint and swimming will be bigger and taller at the 2008 Olympics,<sup>66</sup> we submitted our “constructal theory of athletics evolution” as a Letter to Nature. That was two months before the Beijing Olympics. Unfortunately, Nature editors declined to review our paper. Yet, the 2008 Olympics and every other world competition since 2008 proved the theory correct across the board (running, swimming, male, female) and unified the evolution of athletics with the evolution of animal locomotion, which was another constructal theory: the constructal theory of all animal locomotion.<sup>87</sup>

Such is science. If its power to predict the future is not clear enough, then here is how we concluded our constructal theory of sports evolution:<sup>66</sup>

“In the future, the fastest athletes can be expected to be heavier and taller. If the winners’ podium is to include athletes of all sizes, then speed competitions might have to be divided into weight categories. This is not at all unrealistic in view of the body force scaling (...), which

was recognized from the beginning in the structuring of modern athletics. Larger athletes lift, push and punch harder than smaller athletes, and this led to the establishment of weight classes for weight lifting, wrestling and boxing. Larger athletes also run and swim faster.”

The exact time when the change will happen is not the prediction. The prediction is the time direction of the change, from flow design X to flow design Y. Sports in which the size has become so big that it injures the athlete, as in American football, will change. The current movie hit “Concussion” (2016) was released *after* our 2008 prediction,<sup>66</sup> and changes in the rules of the sport will surely follow.

In conclusion, the constructal law is the law of physics of life<sup>1,3</sup> and evolution everywhere, animate and inanimate, and at all scales, from vascular tissues<sup>72</sup> to celestial bodies.<sup>88</sup>

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## References

- [1] Bejan A. The Physics of Life: The Evolution of Everything. New York: St. Martin’s Press, 2016; PMID: 26883787.
- [2] Bejan A. Entropy Generation through Heat and Fluid Flow. New York: Wiley, 1982.
- [3] Basak T. The law of life: the bridge between physics and biology. *Phys Life Rev* 2013; 8:249-52; <http://dx.doi.org/10.1016/j.plrev.2011.07.003>
- [4] Bejan A. Advanced Engineering Thermodynamics, third edition. Hoboken: Wiley, 2006.
- [5] Bejan A. Constructal-theory network of conducting paths for cooling a heat generating volume. *Int J Heat Mass Transf* 1997; 40:799-816 (published on 1 November 1996); [http://dx.doi.org/10.1016/0017-9310\(96\)00175-5](http://dx.doi.org/10.1016/0017-9310(96)00175-5)
- [6] Bejan A. Shape and Structure, from Engineering to Nature, New York: Cambridge University Press, 2000.
- [7] Bejan A, Lorente S. The constructal law and the evolution of design in nature. *Phys Life Rev* 2011; 8:209-40; PMID: 21683663; <http://dx.doi.org/10.1016/j.plrev.2011.05.010>
- [8] Kováč L. Bioenergetics. *Commun Integr Biol* 2008; 1:114-22; <http://dx.doi.org/10.4161/cib.1.1.6670>
- [9] Baluška F, Mancuso S. Deep evolutionary origins of neurobiology. *Commun Integr Biol* 2009; 2:60-5; <http://dx.doi.org/10.4161/cib.2.1.7620>
- [10] De Loof A. From Darwin’s On the Origin of Species by Means of Natural Selection to The evolution of Life with Communication Activity as its Very Essence and Driving

- Force (=Mega-Evolution). *Life Excit Biol* 2015; 3:153-87; [http://dx.doi.org/10.9784/LEB3\(3\)DeLoof.01](http://dx.doi.org/10.9784/LEB3(3)DeLoof.01)
- [11] Baluška F. Evolution in Revolution. A paradigm shift in our understanding of life and biological evolution. *Commun Integr Biol* 2011; 4:523-5.
- [12] Baluška F, Witzany G. At the dawn of a new revolution in life sciences. *World J Biol Chem* 2013; 4:13-5.
- [13] Noble D. Evolution beyond neo-Darwinism: a new conceptual framework. *J Exp Biol* 2015; 218:7-13; PMID:25568446; <http://dx.doi.org/10.1242/jeb.106310>
- [14] Noble D. Physiology is rocking the foundations of evolutionary biology. *Exp Physiol* 2013; 98:1235-43; PMID:23585325; <http://dx.doi.org/10.1113/expphysiol.2012.071134>
- [15] Pigliucci M. Do we need an extended evolutionary theory? *Evolution* 2007; 61:2743-9; PMID:17924956; <http://dx.doi.org/10.1111/j.1558-5646.2007.00246.x>
- [16] Pookottil R. B.E.E.M. Biological Emergence-based Evolutionary Mechanism: How Species Direct Their Own Evolution. London: Fossil Fish Publishing, 2013.
- [17] Shapiro JA. *Evolution: A View from the 21st Century*. Upper Saddle River, New Jersey: FT Press Science, 2011.
- [18] Shapiro JA. Rethinking the (im)possible in evolution. *Progr Biophys Mol Biol* 2012; 111:92-6; <http://dx.doi.org/10.1016/j.pbiomolbio.2012.08.016>
- [19] Kauffman SA. *The Origins of Order. Self-Organization and Selection in Evolution*, New York: Oxford University Press, 1993.
- [20] Schmidt-Nielsen K. *Scaling (Why is Animal Size so Important?)*, Cambridge, UK: Cambridge University Press, 1984.
- [21] Vogel S. *Life's Devices*, Princeton, NJ: Princeton University Press, 1988.
- [22] Weibel ER, Taylor CR, Bolis L. *Principles of Animal Design*, Cambridge, UK: Cambridge University Press, 1998.
- [23] Weibel ER. *Symmorphosis, On Form and Function in Shaping Life*, Harvard, MA: Harvard University Press, 2000.
- [24] Ahlborn BK. *Zoological Physics*, Berlin: Springer, 2004.
- [25] Pramanick AK. *The Nature of Motive Force*, Heidelberg: Springer, 2014.
- [26] Turner JS. *The Tinkerer's Accomplice, How Design Emerges from Life Itself*, Harvard, MA: Harvard University Press, 2007.
- [27] Fodor J, Piattelli-Palmarini M. *What Darwin Got Wrong*, New York: Picador, 2010.
- [28] Torday JS. A central theory of biology. *Med Hypoth* 2015; 85:49-57; <http://dx.doi.org/10.1016/j.mehy.2015.03.019>
- [29] Lewins J. Bejan's constructal theory of equal potential distribution. *Int J Heat Mass Transfer* 2003; 46:1541-3; [http://dx.doi.org/10.1016/S0017-9310\(02\)00441-6](http://dx.doi.org/10.1016/S0017-9310(02)00441-6)
- [30] Mazur S. *The Origin of Life Circus: A How to Make Life Extravaganza*, New York: Caswell Books, 2014; 2016.
- [31] Mazur S. *The Paradigm Shifters: Overthrowing 'the Hegemony of the Culture of Darwin'*, New York: Caswell Books, 2015.
- [32] Queiros-Conde D, Feidt M, Eds. *Constructal Theory and Multi-scale Geometries: Theory and Applications in Energetics, Chemical Engineering and Materials*. Paris: Les Presses de L'ENSTA, 2009.
- [33] Roux E. The concept of function in modern physiology. *J Physiol* 2014; 592:2245-9; PMID:24882809; <http://dx.doi.org/10.1113/jphysiol.2014.272062>
- [34] Lorenzini G, Moretti, S, Conti A. *Fin Shape Optimization Using Bejan's Constructal Theory* San Francisco: Morgan & Claypool Publishers, 2011
- [35] Bachtá A, Dhombres J, Kremer-Marietti A. *Trois Études sur la Loi Constructale d'Adrian Bejan*. Paris: L'Harmattan, 2008
- [36] Chen L. Progress in study on constructal theory and its applications. *Sci China Technol Sci* 2012; 55:802-20; <http://dx.doi.org/10.1007/s11431-011-4701-9>
- [37] Miguel AF. The physics principle of the generation of flow configuration. *Phys Life Rev* 2011; 8:243-4; PMID:21795127; <http://dx.doi.org/10.1016/j.plprev.2011.07.006>
- [38] Miguel AF. Natural flow systems: acquiring their constructal morphology. *Int J Design Nat Ecodyn* 2010; 5:230-41; <http://dx.doi.org/10.2495/DNE-V5-N3-230-241>
- [39] Bejan A, Lorente S. Constructal theory of generation of configuration in nature and engineering. *J Appl Phys* 2006; 100:041301; <http://dx.doi.org/10.1063/1.2221896>
- [40] Bejan A, Lorente S. The constructal law of design and evolution in nature. *Phil Transact Royal Soc B* 2010; 365:1335-1347; <http://dx.doi.org/10.1098/rstb.2009.0302>
- [41] Bejan A, Lorente S. Constructal law of design and evolution: Physics, biology, technology, and society. *J Appl Phys* 2013; 113:151301; <http://dx.doi.org/10.1063/1.4798429>
- [42] Reis AH. Constructal theory: from engineering to physics, and how systems flow develop shape and structure. *Appl Mech Rev* 2006; 59:269-82; <http://dx.doi.org/10.1115/1.2204075>
- [43] Green S. Revisiting generality in biology: systems biology and the quest for design principles. *Biol Philos* 2015; 30:629-52; <http://dx.doi.org/10.1007/s10539-015-9496-9>
- [44] Conway Morris S, Hoyal Cuthill JF, Gerber S, eds. *Hunting Darwin's Snark: which maps shall we use?* *Interf Foc* 2015; 5:20150078; <http://dx.doi.org/10.1098/rsfs.2015.0078>
- [45] Bejan A. Maxwell's demons everywhere: evolving design as the arrow of time. *Sci Rep* 2014; 4:4017; PMID:24510201.
- [46] Lorente S, Lee J, Bejan A. The "flow of stresses" concept: the analogy between mechanical strength and heat convection. *Int Heat Mass Transfer* 2010; 53:2963-8; <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.03.038>
- [47] Bejan A. *Convection Heat Transfer*, 4th ed., Hoboken, NJ: Wiley, 2013.
- [48] Bejan A, Ziaei S, Lorente S. Evolution: why all plumes and jets evolve to round cross sections. *Sci Rep* 2014; 4:4730; PMID:24756029.
- [49] Bejan A, Lorente S. The constructal law origin of the logistics S curve. *J Appl Phys* 2011; 110:024901; <http://dx.doi.org/10.1063/1.3606555>
- [50] Bejan A, Lorente S. The physics of spreading ideas. *Int J Heat Mass Transf* 2012; 55:802-7; <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2011.10.029>
- [51] Bejan A, Lorente S, Yilbas BS, Sahin AZ. Why solidification has an S-shaped history. *Sci Rep* 2013; 3:1711; <http://dx.doi.org/10.1038/srep01711>
- [52] Miguel AF. Dendritic structures for fluid flow: Laminar, turbulent and construal design. *J Fluids Struct* 2010; 26:330-5; <http://dx.doi.org/10.1016/j.jfluidstructs.2009.11.004>
- [53] Kacimov AR, Klammler H, Il'yinskii H, Hatfield K. Constructal design of permeable reactive barriers: groundwater - hydraulics criteria. *J Eng Math* 2011; 71:319-38; <http://dx.doi.org/10.1007/s10665-011-9457-5>

- [54] Reis AH, Gama C. Sand size versus beachface slope—an explanation based on the constructal law. *Geomorphology* 2010; 114:276-83; <http://dx.doi.org/10.1016/j.geomorph.2009.07.008>
- [55] Reis AH, Bejan A. Constructal theory of global circulation and climate. *Int J Heat Mass Transf* 2006; 49:1857-75; <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.10.037>
- [56] Clause M, Meunier F, Reis AH, Bejan A. Climate change, in the framework of the constructal law. *Int J Global Warm* 2012; 4:242-60; <http://dx.doi.org/10.1504/IJGW.2012.049449>
- [57] Band LE, McDonnell JJ, Duncan JM, Barros A, Bejan A, Burt T, Dietrich WE, Emanuel RE, Hwang T, Katul G, et al. Ecohydrological flow networks in the subsurface. *Ecohydrology* 2014; 7:1073-8.
- [58] Hoppeler H, Weibel ER. Scaling functions to body size: theories and facts, special issue. *J Exp Biol* 2005; 208:1573-769; PMID:15855388; <http://dx.doi.org/10.1242/jeb.01630>
- [59] Bejan A, Morega A, West GB, Brown JH. Constructing a theory for scaling and more. *Phys Today* 2005; 58:20; <http://dx.doi.org/10.1063/1.2012444>
- [60] Miguel AF. Constructal pattern formation in stony corals, bacterial colonies and plant roots under different hydrodynamics conditions. *J Theor Biol* 2006; 242:954-61; PMID:16839570; <http://dx.doi.org/10.1016/j.jtbi.2006.05.010>
- [61] Reis AH, Miguel AF, Aydin M. Constructal theory of flow architecture of the lungs. *Med Phys* 2004; 31:1135-40; PMID:15191302; <http://dx.doi.org/10.1118/1.1705443>
- [62] Kasimova R. Optimal shape of anthill dome: Bejan's constructal law revisited. *Ecol Model* 2013; 250:384-90; <http://dx.doi.org/10.1016/j.ecolmodel.2012.11.021>
- [63] Bejan A. Why the bigger live longer and travel farther: animals, vehicles, rivers and the winds. *Sci Rep* 2012; 2:594; PMID:22924107; <http://dx.doi.org/10.1038/srep00594>
- [64] Bejan A. Rolling stones and turbulent eddies: why the bigger live longer and travel farther. *Sci Rep* 2016; 6:21445; PMID:26883787; <http://dx.doi.org/10.1038/srep21445>
- [65] Lorente S, Bejan A. Few large and many small: hierarchy in movement on earth. *Int J Des Nat Ecodyn* 2010; 5:254-67; <http://dx.doi.org/10.2495/DNE-V5-N3-254-267>
- [66] Charles JD, Bejan A. The evolution of speed, size and shape in modern athletics. *J Exp Biol* 2009; 212:2419-25; PMID:19617435; <http://dx.doi.org/10.1242/jeb.031161>
- [67] Bejan A, Jones EC, Charles JD. The evolution of speed in athletics: why the fastest runners are black and swimmers white. *Int J Des Nat Ecodyn* 2010; 5:199-211; <http://dx.doi.org/10.2495/DNE-V5-N3-199-211>
- [68] Charles JD, Bejan A. The evolution of long distance running and swimming. *Int J Des Nat Ecodyn* 2013; 8:17-28; <http://dx.doi.org/10.2495/DNE-V8-N1-17-28>
- [69] Majumder PP, Choudhury SR. Reasons for success in competitive swimming among various human races. *J Sport Phys Educ* 2014; 1:24-30; <http://dx.doi.org/10.9790/6737-0132430>
- [70] Bejan A. The constructal-law origin of the wheel, size, and skeleton in animal design. *Am J Phys* 2010; 78:692-9; <http://dx.doi.org/10.1119/1.3431988>
- [71] Bejan A. The Golden Ratio predicted: vision, cognition and locomotion as a single design in nature. *Int J Des Nat Ecodyn* 2009; 4:97-104; <http://dx.doi.org/10.2495/DNE-V4-N2-97-104>
- [72] Hadjistassou C, Bejan A, Ventikos V. Cerebral oxygenation and optimal vascular brain organization. *Interface* 2015; 12:20150245; PMID:25972435.
- [73] Kim S, Lorente S, Bejan A, Miller W, Morse J. The emergence of vascular design in three dimensions. *J Appl Phys* 2008; 103:123511; <http://dx.doi.org/10.1063/1.2936919>
- [74] Cetkin E, Lorente S, Bejan A. Natural constructal emergence of vascular design with turbulent flow. *J Appl Phys* 2010; 107:114901; <http://dx.doi.org/10.1063/1.3430941>
- [75] Bejan A. Why humans build fires shaped the same way. *Sci Rep* 2015; 5:11270; PMID:26053318; <http://dx.doi.org/10.1038/srep11270>
- [76] Bejan A. Sustainability: the water and energy problem, and the natural design solution. *Eur Rev* 2015; 23:481-8; <http://dx.doi.org/10.1017/S1062798715000216>
- [77] Bejan A, Charles JD, Lorente S. The evolution of airplanes. *J Appl Phys* 2014; 116:044901; <http://dx.doi.org/10.1063/1.4886855>
- [78] Bejan A, Merx GW, eds. *Constructal Theory of Social Dynamics*. New York: Springer, 2007.
- [79] Kalason P. *Épistémologie Constructale du Lien Culturel*. Paris: L'Harmattan, 2007.
- [80] Takac MT. *Scientific Proof of Our Unalienable Rights*. Los Gatos, CA: Robertson Publishing, 2015.
- [81] Amoozegar C. Constructal theory of written language, Chapter 16 in Ref. [76]
- [82] Weinerth G. The constructal analysis of warfare. *Int J Design Nat Ecodyn*, 2010; 5:268-76; <http://dx.doi.org/10.2495/DNE-V5-N3-268-276>
- [83] Lorenzini G, Biserni C, Garcia FL, Rocha LAO. Geometric optimization of a convective T-shaped cavity on the basis of constructal theory. *Int J Heat Mass Transfer* 2012; 55:6951-6958; <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.07.009>
- [84] Lorenzini G, Biserni C. A vapotron effect application for electronic equipment cooling. *J Electronic Packaging* 2003; 125:475-479; <http://dx.doi.org/10.1115/1.1615796>
- [85] Ellis G, Silk J. Defend the integrity of physics. *Nature* 2014; 516:321-3; PMID:25519115; <http://dx.doi.org/10.1038/516321a>
- [86] Metzner R. Private communication. 11 January 2016.
- [87] Bejan A, Marden JH. Unifying constructal theory for scale effects in running, swimming and flying. *J Exp Biol* 2006; 209:238-48; PMID:16391346; <http://dx.doi.org/10.1242/jeb.01974>
- [88] Bejan A, Wagstaff RW. The physics origin of the hierarchy of bodies in space. *J Appl Phys* 2016; 119:094901; <http://dx.doi.org/10.1063/1.4941986>