The Constructal Law and the Design of the Biosphere: Nature and Globalization

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"Design in nature" is a topic of growing interest throughout science. The constructal law is the physics law of design generation and evolution in nature: "for a flow system to persist in time (to live), it must evolve such that it provides easier and easier access to its currents." In this paper, we show how the constructal law accounts for the main features of the design of the biosphere: global movement of mass as the action of constructal engines (geophysical, animal, and human made) that dissipate their power into brakes, animal locomotion, vision, cognition, and hierarchy. The architecture and hierarchy of vegetation results from the constructal tendency to generate designs that facilitate the flow of water and "the flow of stresses" (i.e., mechanical strength per unit volume). Natural porous media have multiple scales because their flows are also configured as trees. The paper concludes with the oneness of design in nature, global design, and science and technology evolution—all as manifestations of the natural tendency captured by the constructal law and unified constructal theory of evolution.
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1 The Constructal Law

Nature looks complicated but it is in fact a tapestry weaved in a very simple loom. The designs consist of many flow types and sizes, all governed by a simple law of physics: the constructal law,

> "For a finite-size flow system to persist in time (to live) it must evolve in such a way that it provides easier and easier access to the currents that flow through it" [1].

Even better, the tapestry itself is constituted (woven and sewn) according to the same law. All the designs fit, the animate and the inanimate, the small and the large, and the human made and the not human made [2–5]. They do not fit perfectly and never will. But, they exhibit a universal tendency in spite of their immense diversity. This, coupled with the fact that all the things that flow and move are free to morph, means that every thread and motif of the tapestry will morph so that the whole flows better.

The more we rise above the details, the simpler the tapestry design looks. Taking a bird's eye view is a very good medicine for those sickened by the poison that nature is complicated and random. In this essay, we sketch how the constructal law underpins design in nature and how it can guide our engineering and global design.

2 Winds, Animals, and Vehicles: Engines Connected to Brakes

Here is how the design principle reveals itself if we take a bird's eye view of the whole, which is the whole earth. Begin by imaging the Earth today in a steady state that covers a period longer than one human life. The simplest earth model is a ball with the same temperature all over (Fig. 1). We can predict important features of design in nature even with this extremely simple model.

The sun shoots streams of energy in all directions, radially. Some of these streams are intercepted and absorbed by the earth because the earth is opaque. All together, they represent one current of energy that flows out of the sun and into the earth. This current flows from sun to earth because the sun temperature is higher than the earth temperature. This flow direction (from high to low, always) is demanded by the second law of thermodynamics.

Next, the earth is warmer than the sky and this means that a current of energy must flow from earth to sky. Because the earth in this model is a closed system in steady state, the earth does not store or lose energy. This means that the sun$\rightarrow$earth energy current must equal the earth$\rightarrow$sky current. From this equality follows the conclusion that the earth must have a particular temperature (somewhere between the sun and sky temperatures) and that the earth temperature must be steady. The earth is just an intermediate node along the path of the current from sun to sky.

We see right away that the earth temperature is predictable and steady (i.e., it does not get out of control) as long as the sun $\rightarrow$earth energy current is steady and known. The conclusion then is that the earth is endowed with a property we call "climate" and that climate is predictable if the simple model is correct.

We can predict much more about climate (temperature zones, winds, and day-night variation), because the earth is not a rigid ball [6]. The entire earth is flowing, especially in its spherical shells that house the designs that we observe—the hydrosphere, atmosphere, lithosphere, and biosphere. According to the constructal law, all these flowing things live (i.e., they survive and persist) by generating configurations and by evolving their configurations in time.

How do these flowing things fit inside the big system? The simple model in Fig. 1 is good for answering this question as well. The biggest system is the globe as an intermediate stop for a train of useful energy from the hot sun to the cold sky. The common animal too is an intermediate stop for its own train of useful energy (exergy and food) from meal to excrement.

Every thing that moves on earth does so because it is driven [1,2,7]. The driving is done by very subtle engines, one engine for each flow: muscles for animals, engines for vehicles, and im-

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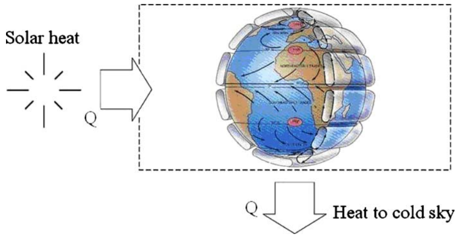

Fig. 1 The solar heat current (Q) that hits the earth and ultimately sinks into the cold universe. The earth temperature settles at a steady level between the sun temperature and the sky temperature. It is as if the current Q passes through the earth as it flows from high temperature (sun) to low temperature (sky).

mense wheels for the circuit executed by water in nature, which constantly puts fresh water upstream of the river basin. No matter how numerous and diverse, all these engines are driven by useful energy (fuel) that comes from high temperature (the sun) in the form of the heat current (Q) intercepted by the earth.

In Fig. 2, we imagine that all these engines are represented by one engine, which uses the heat input Q in order to produce the work W that is needed for driving the movement of all the things on earth. The difference between heat flowing in and work flowing out is Q-W, which is rejected as heat to the cold sky.

This completes the first part of the view, the subtle part, because we do not see "engines" in what moves around us. The winds and the rivers flow *by themselves*, we think. We are used to referring to these flows as "free convection" and "natural convection." These flows are thought to be free and natural because we do not pay for moving them. Yet, they really move and this means that engines drive them.

The second part of the design (animal locomotion, animal organs, and human vehicles) is the movement, which occurs against resistances that constantly try to stop this movement. Without such resistances the masses driven by the work W would be accelerating forever and spin out of control. This is not how nature works. All the driving W is dissipated in the brakes that form between the moving masses and their immediate surroundings. Nature flows in a balanced way: power generation is matched by power dissipation, anywhere and any time.

Key is the observation that all the work W is dissipated into heat (called Q_{diss}, and equal to W), and that Q_{diss} is also rejected to the cold sky. All together, the earth rejects heat to the sky from the engines (Q-W) and from the brakes (Q_{diss}). The sum of these two heat currents is the same as Q, because $Q_{diss}=W$. The total heat current rejected to the sky (Q) is the same as the heat current received from the sun.

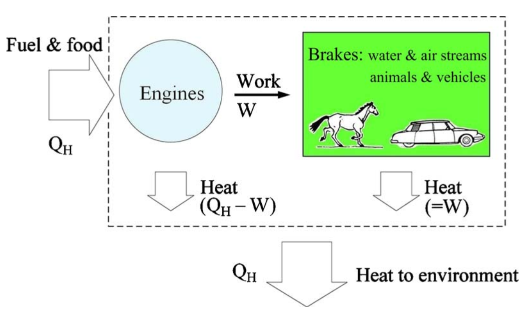

Fig. 2 The biosphere on the move: the two phenomena that the solar heat drives as it passes through the earth [2,7]. First, Q drives flows (natural mechanisms with moving parts) that function as "engines" and produce work W. Second, the work dissipated in the "brakes" that form between these flows and their immediate environments (neighbors). Seen as a whole, the flowing earth (engines+brakes) receives Q from the sun and rejects Q completely to the sky. This is in agreement with the simpler model of Fig. 1.

This comples the bird's eye view of the second model (Fig. 2) and confirms the main feature of the first model (Fig. 1): the continuity of the heat current (Q) through the earth, from the sun to the sky. The material effect of this heat flow is that inside the engine+brake system (Fig. 2), mass has moved to a distance L such that the driving work W always scales as the weight moved (Mg) times the travel (L).

3 The Constructal Law of Evolution

We do not know whether the engines that drive the earth's flows are relatively efficient or not. It does not even matter. They are all imperfect, plagued by irreversibilities. What we know is that all the flows have the tendency to evolve in time (to generate designs) so that they flow more easily. This tendency is the constructal law and it can be restated in different ways depending on which side of the engines+brakes model we discuss.

First, if the flows and moving parts of an engine morph in time so that they move more easily, the engine design has the natural tendency to evolve in time toward producing more work (W) from the fixed heat input (Q). This is the direction of improvements in efficiencies—animal designs that are better fit for moving more animal mass on earth and geophysical currents (river basins and oceanic and atmospheric currents) that move more water and air mass more quickly and farther. The constructal evolution of the engines is in accord with statements we hear in all the evolutionary sciences, in biology and engineering. Improvements can be described thermodynamically as a procession of configurations that offer progressively less dissipation in the engines part, i.e., lower rates of entropy generation and higher efficiencies.

Second, on the brakes side of the earth design, the evolution toward more W from the fixed Q means an evolution toward more Q_{diss}. The brakes evolve toward more dissipation and higher rates of entropy generation. This conclusion sounds confusing (after reading the preceding paragraph), yet it is a statement heard nowadays in geophysics. What geophysicists say (higher dissipation) is the complete opposite of what animal design and engineering scientists say (lower dissipation). The conflict between the two camps is real [8,9] but it is put to rest by the engines+brakes design of Fig. 2. The two camps refer to different parts of the grand design. Both tendencies—toward lower and higher dissipation—are manifestations of the constructal law, which unifies them. Without the evolution of flow configurations in time, there is no evolution toward less dissipation in some flow systems and more dissipation in others.

In sum, the constructal law and the global design sketched in Figs. 1 and 2 constitute a unified theory of evolution. This view is unifying because it explains and predicts evolution in all the diverse domains in which evolutionary phenomena are observed, recorded, and studied scientifically: animal design, river basins, turbulent flow, animal movement, athletics, technology evolution, and global design [1–10]. Some of the most common animate and inanimate examples are sketched in Fig. 3.

Evolution means design modifications, in time. How these changes are happening are *mechanisms* and should not be confused with the constructal law or the constructal theory. In the evolution of biological design, the mechanism is mutations, biological selection, and survival. In geophysical design, the mechanism is soil erosion, rock dynamics, water-vegetation interaction, and wind drag. In sports evolution, the mechanism is training, recruitment, mentoring, selection, and rewards. In technology evolution, the mechanism is liberty, freedom to question, innovation, education, trade, and emigration.

What flows through a design that evolves is not nearly as special in physics as how the flow system generates and improves its configuration in time. The "how" is the physics principle—the constructal law. The "what" are the mechanisms and they are as

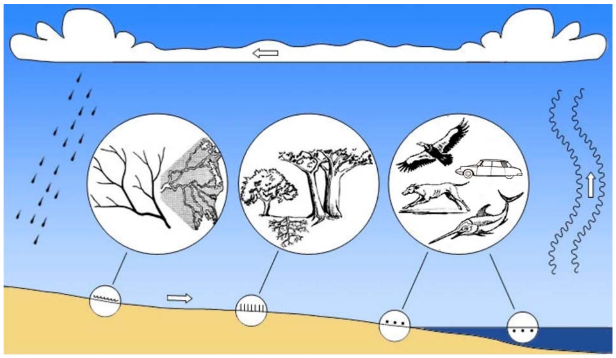

Fig. 3 The physics phenomenon of design generation and evolution facilitates the circuit executed by water in nature: tree-shaped river basins and deltas, vegetation, and all the features of animal design and human and machine species [10]

diverse as the flow systems themselves. The what are many and the how is one. Hierarchy more simple than this does not exist.

Having "impact" on the environment is synonymous with having design in nature. There is no part of nature that does not resist the flows and movements that attempt to penetrate it. Movement means penetration and its name differs depending on the direction from which the phenomenon is observed. To the observer of river basins, the phenomenon is the emergence and evolution of the dendritic vasculature. To the observer of the landscape, the phenomenon is erosion and the reshaping of the earth's crust. No flow on earth is more responsible for the evolution (shaping) of the landscape than the flow of water in rivers.

This mental viewing of design generation and environmental impact as a unitary design in nature is universally applicable. Think of the migration paths for animals, versus the riverlike paths and burrows dug into the ground. Think of the migration of elephants versus the toppling of trees. The same holds for all the movements that define our societal existence. The patterns of social dynamics go hand-in-glove with the impact on the environment.

The effect of life is *measurable* in terms of the mass moved over distances during the life time of the flow system [7]. The work required to move any mass on earth (vehicle, river water, and animal mass) scales as the weight of that mass times the distance to which it is moved horizontally, on the landscape. It is this way with the life of the river basin and the animal and it is the same with the life of man, family, country, and empire. The economic activity of a country is all this movement of mass (people and goods) to distances. Because each movement is proportional to the amount of fuel burned in order to drive it, the entire economic activity on a territory must be proportional to the amount of fuel consumed on that territory. This finally explains the observation [11] that the annual Gross National Product (GNP) of a country is roughly proportional to the amount of fuel burned (i.e., the useful energy generated and dissipated) in that country.

4 Locomotion, Vision, and Cognition

In politics, history, and sociology, one observes and speaks of the increasing speed of everything—faster modes of transportation and communication, the acceleration of technology, social change, and the pace of life. People feel that they are running out of time, even though the technological changes generate more free time for everybody. More time to do what?

In geography, economics, and urbanism, one observes and speaks of humanity generating more space. This continuing phenomenon is known as expansion, globalization, and the spreading of city living in three dimensions, on the landscape and the vertical direction, upward and downward. People complain about lack of space because of all the construction sites, even though the construction technology is generating space for people. More space for what?

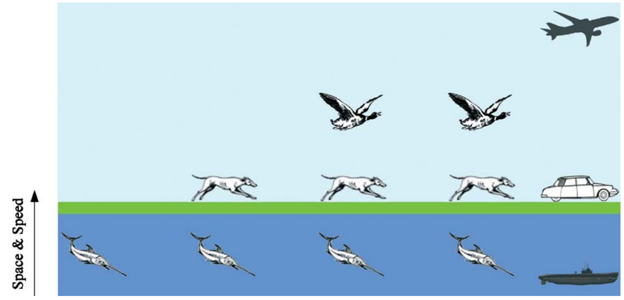

Fig. 4 Space, speed, and time: The evolution of the biosphere from prehistory to today [12]. Animal flow has been spreading vertically in space and toward higher speeds, longer ranges, and better vision. This montage fits on the left plane of Fig. 5.

Better and better language, writing and science also give us more time to think. To think about what? To think about more activity, more movement, more flow of us on the surface of the earth. The same answer holds for the questions of why more time and more space.

With the constructal law, these seemingly unrelated and paradoxical tendencies constitute a universal phenomenon of generation of greater flow access and the evolution of design in nature. They are predictable. They are to be expected because they have been an integral part of design in nature forever.

Increasing speed and spatial expansion are a unitary phenomenon. Animals have been expanding in space, in this unmistakable time direction: from sea to land and later, from land to air (Fig. 4) [12]. The human and machine species are continuing this trend by invading the upper atmosphere, the ocean depths, and the outer space. The same movie (because this is what the occurrence and evolution of design is, a time sequence of images) means that speeds have been increasing in time and will continue to increase. For the same body mass, the runners are faster than the swimmers and the fliers are faster than the runners (Fig. 5). This movie is the same as the evolution of inanimate mass flows, for example, the river basins. Under the persisting rain, all the channels morph constantly to flow more easily.

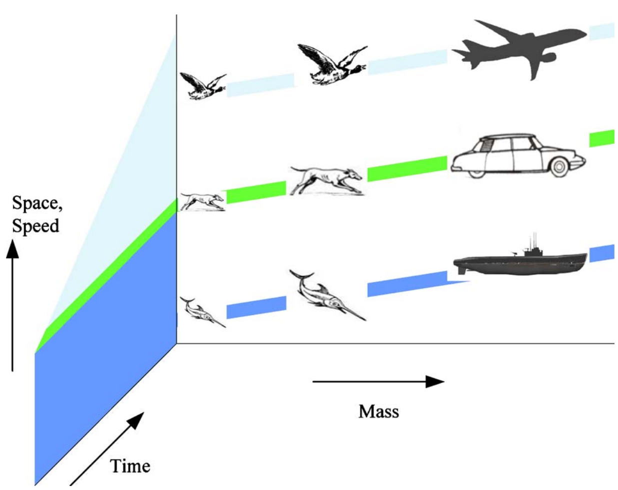

Fig. 5 Space, speed, mass, and time: The third dimension (mass) of the diversity in the flow of animal mass [12]. At any point in time, the biosphere churns itself with a huge *diversity* of animate bodies organized according to a *pattern*. The larger bodies tend to have higher speeds lower body frequencies and larger forces.

Design is the speed governor of nature. None of the changes observed in politics, history, sociology, animal speed and river speed are spinning out of control. None of the expansions feared in geography, economics, and urbanism are slamming into a brick wall.

In accord with the constructal law, all the flow systems evolve their configurations in time toward *equilibrium flow structures* [13] that flow more and more easily through their finite-size (i.e., surviving) environments. Animate design together with inanimate design is a unifying story where increasing speeds represent the same evolution phenomenon as increasing access to space. In the river basins, the slower tributaries move more and more water mass into the faster and bigger channels. The same holds true for animal design. If we imagine body sizes that are roughly the same, then, broadly speaking (compare Fig. 5), runners are faster than swimmers and flyers are faster than swimmers and runners

This is in accord with the constructal law because it is aligned with the time arrow of how life has spread on earth, sea → land → air, and not the other way around. The time direction of this evolution has been toward higher speeds and it is shown qualitatively in Fig. 4, which is a detail of the side plane of Fig. 5. More movement and more mixing of the earth (toward more space) have always been aligned with time, more speed, and more space traveled per unit of animal mass and useful energy consumed.

The big jump in the perfecting of the animal locomotion design was the emergence of the organ for vision (the eye). This has created *guided locomotion*—a flow of animal mass that is much more efficient, faster, and enduring because with vision and cognition the flow of animal mass selects for itself ceaselessly better channels to flow: straighter and safer with fewer obstacles and predators. The time direction of this change in the animal locomotion design is in accord with the constructal law, toward more space, speed, and mixing of the earth's crust. The animal design with vision and cognition came after the animals without vision and cognition, not the other way around.

Vision and cognition are one and they are demanded by the constructal law applied at the scale of the earth. Animal mass and water mass (in river basins) are flow systems with configurations and rhythms that facilitate the flow of mass on earth. From this physics view of the constructal law followed all the scaling rules of animal locomotion [14] and the evolution of speed limits in athletics—running and swimming [15]. The constructal law predicted that larger animals must have higher speeds calculated with complete formulas (slope and intercept) in which speeds are proportional to their body masses raised to the power 1/6 and body movement frequencies (stride, flapping, and fishtailing) are in proportion to body masses raised to $-1/6$. These predictions agree with all the known speed-mass data for flyers, land animals, and swimmers. This is suggested qualitatively in the back plane of Fig. 5. The actual speed-mass data are available in Refs. [2,8,14].

Locomotion design is a manifestation of the constructal law and it has been perfecting itself throughout the history of biological forms and flow systems on earth (i.e., throughout "big history"). Another phenomenon that illustrates this tendency is the human preference for rectangular shapes with aspect ratios that resemble the golden ratio [12]. These 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 all the other configurations that facilitate the same movement, for example, 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. The name of this constructal evolution of brain architecture, every minute and every moment, is cognition—the phenomenon of thinking, knowing, and thinking again, better. "Getting smarter" is the constructal law in action.

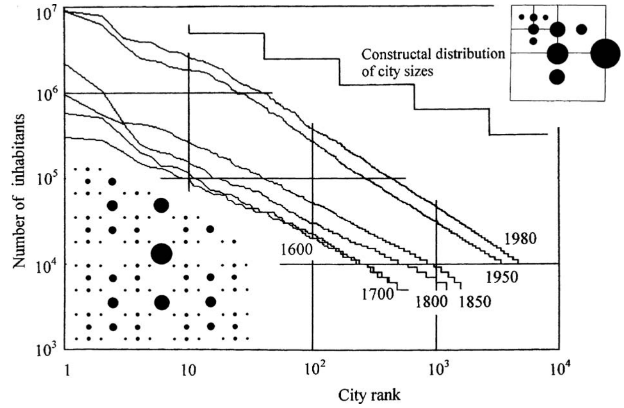

Fig. 6 City sizes versus city rank in Europe during 1600–1980 and the Zipf distribution predicted with the constructal law [17]

5 Natural Hierarchy

Age matters in evolutionary design and it is good for performance. The river basin positions its channels better and better and the channels stay in place. The channels have hierarchy: a few large channels flow in harmony with the many small channels. A sudden downpour is served well by the "memory" built into the old river beds.

From the mental viewing provided by the constructal law, the hierarchies that are visible in all the flow systems that cover the globe can finally be deduced. These architectures form a multiscale weave of point-area and area-point tree flows, all superimposed and all sustaining everything that flows (i.e., everything that lives) on earth. One example is the hierarchy of channel sizes and numbers in all the river basins that have been cataloged. From the constructal law, we deduced that the number of tributaries that feed a larger channel should be 4 [16]. This prediction is in very good agreement with Horton's empirical correlation of river numbers, which states that the observed number of tributaries falls in the range between 3 and 5.

Another constructal hierarchy is the distribution of city sizes and numbers (of cities of the same size) on large areas such as a continent, Fig. 6 [17]. The distribution is linear when plotted log-log. This line with slope in the range between $-1/2$ and -1 is known as a Zipf distribution and it is found empirically in virtually all the natural flow systems that connect discrete points with finite areas or volumes.

The descending line in Fig. 6 was predicted by recognizing the flow access between two populations that live on each area construct (small and large) that covers the landscape. This is suggested by the inset in the upper-right corner of the figure [17]. On every area construct (white) there are two populations that exchange flows: those who live on the area and those who live in a settlement (village, town, and city), which is shown as a black dot. The constructal law also predicts that the straight line must shift upward in time while remaining parallel to itself because of technology improvement and those who live on the area can achieve flow equilibria with larger and larger numbers of people living in the settlement. This too is in agreement with the history of the size-rank distribution of cities over the last 4 centuries.

Another natural hierarchy anticipated with the constructal law is the ranking of tree sizes and numbers in forests (Fig. 7) [10]. The descending bands of size versus rank data were deduced by arranging tree canopies of many sizes on the forest floor such that the entire floor facilitates the flow of water, from the ground to the blowing wind. Two examples of such arrangements (triangular and square) are shown in the upper-right corner. The slope and intercept of the size-rank line is insensitive to the type of arrangement. Important is how the multiscale canopies fill the forest floor area such that the water flow rate from the whole area is greater.

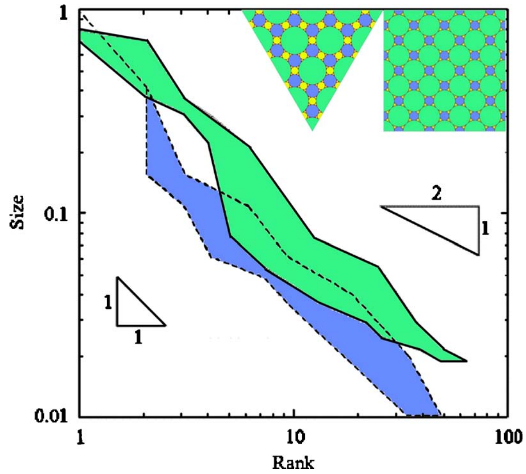

Fig. 7 Distribution of tree canopy sizes versus rank in the constructal design of the forest floor [10]. The Zipf distribution is insensitive to the pattern (e.g., triangular versus square) in which the multiscale tree canopies are arranged on the forest floor.

From this holistic view of design generation come the numerous and seemingly random scales of trees in the forest and the Zipf-type alignment of the size versus rank data.

What the constructal law predicted for multiscale river basins, demography, and forests also applies to the design of societal flow. Science and higher education flow through a natural tissue of universities, each university being connected to the entire globe. The older universities have dug the first channels, which are now some of the largest channels that irrigate the student landscape. "Largest" does not mean largest number of bodies moving in and out of classrooms. Largest are the streams of the most creative, i.e., the channels that attract the *individuals* who generate new ideas and who develop disciples who produce and carry new ideas farther on the globe and into the future. The swelling student population is served well by the "memory" built into the education flow architecture. From this theoretical view followed the prediction that the hierarchy of universities should not change in significant ways [18]. This hierarchy is as permanent as the hierarchy of the channels in a river basin. It is natural because it is demanded by the entire flow system (the globe) in which huge numbers of individuals want the same thing (knowledge).

6 The Flow of Stresses: Vegetation Design

Trees are flow architectures that emerge during a complex evolutionary process. The generation of the tree architecture is driven by many competing demands. The tree must catch sunlight, absorb CO_2, and put water into the atmosphere while competing for all these flows with its neighbors. The tree must survive droughts and resist pests. It must adapt, morph, and grow toward the open space. The tree must be self-healing to survive strong winds, ice accumulation on branches, and animal damage. It must have the ability to bulk up in places where stresses are higher. It must be able to distribute its stresses as uniformly as possible so that all its fibers work hard toward the continued survival of the mechanical structure.

On the background of this complexity in demands and functionality, two flows stand out. The tree must facilitate the flow of water and the flow of stresses (i.e., it must be strong mechanically). The demand to pass water is made abundantly clear by the geographical correlation between the presence of trees and the rate of rainfall (Fig. 3). This correlation is meant "broadly speaking" because the broad view is the key to discovering the pattern, in spite of the obvious and overwhelming diversity (random effects, local geographical variation, winds, and atmospheric humidity). The demand to pass water is also made clear by the dendritic architecture, which according to the constructal law facilitates flow access between one point and a finite-size volume. The demand to be strong mechanically is made clear by features such as the tapered trunks and limbs with round cross section and other designlike features identified in this article. These features of design in solid structures facilitate the *flow of stresses* [4,10]. Avoiding strangulations in the flow of stresses is synonymous with the natural phenomenon of generation of mechanical strength.

We relied solely on the constructal law in order to discover all the main features of vegetation, from root and canopy to forest [4,10]. We took an *integrative* approach to trees as live flow systems that evolve as components of the larger whole (the environment, Fig. 3). We treated the plant and the forest as physical flow architectures that evolve together toward greater mechanical strength against the wind and greater access for the water flowing through the plant. Theoretical features derived from the constructal law are the tapered shape of the root and longitudinally uniform diameter and density of internal flow tubes, the near-conical shape of tree trunks and branches, the proportionality between tree length and wood mass raised to the power 1/3, the proportionality between total water mass flow rate and tree length, the proportionality between the tree flow conductance and the tree length scale raised to a power between 1 and 2, and the existence of forest floor plans that facilitates ground-air flow access, e.g., Fig. 7. The constructal law also predicted that there must exist a characteristic ratio of leaf volume divided by total tree volume, trees of the same size must have a larger wood volume fraction in windy climates, and larger trees must pack more wood per unit of tree volume than smaller trees.

7 Alternating Trees: Multiscale Porous Media

Natural porous flow structures also exhibit multiple length scales that are distributed nonuniformly through the available space. Such multiscale flow structures are anticipated based on the constructal law [19]. We showed this by exploring the flow properties of the dendritic flow architecture proposed in Fig. 8. The idea is to connect two parallel lines (or two parallel planes) with trees that alternate with upside down trees. The resulting dendritic pattern connects the bottom boundary of the flow domain with the top boundary.

This alternating sequence of point-to-line trees constitutes a vasculature between the two parallel boundaries of the porous body. The fluid flows in the same direction through all the trees, e.g., upward in Fig. 8. The flow access between the points of one line and the points of a parallel line can be viewed as a sequence of point-to-line flow access structures. The building block with which Fig. 8 is constructed was proposed by Lorente et al. [20], where it was based on optimally shaped rectangular areas, each area allocated to one channel. We then compared the tree structure (Fig. 8) with a reference architecture: an array of N equidistant parallel tubes perpendicular to the two lines, each tube with diameter D. This reference structure carries the same total flow rate in the same total flow volume and over the same area. The structure has one degree of freedom, the tube diameter D, or the number of parallel tubes. The pressure drop along the reference structure $(\Delta P_{\mathrm{ref}}/\dot{m})$ is derivable analytically. When the d spacing is the same as the spacing between parallel channels the two global flow resistances form the ratio $\Delta P_{\mathrm{trees}}/\Delta P_{\mathrm{ref}} \cong 14/2^n$. When the number of branching levels is four or larger, the tree-shaped architecture offers greater access to the flow that permeates through the porous structure. The superiority of the tree design increases fast as n increases: when $n=7$, the ratio $\Delta P/\Delta P_{\mathrm{ref}}$ is as low as 1/10.

When the available flow scales are sufficiently small (d), the flow architecture should have trees, not parallel channels, i.e., not a single scale. From this follows the prediction of the *multiscale* and *nonuniform* character of natural porous media: large numbers of small pores and few large pores (known as "pipes" in hill slope

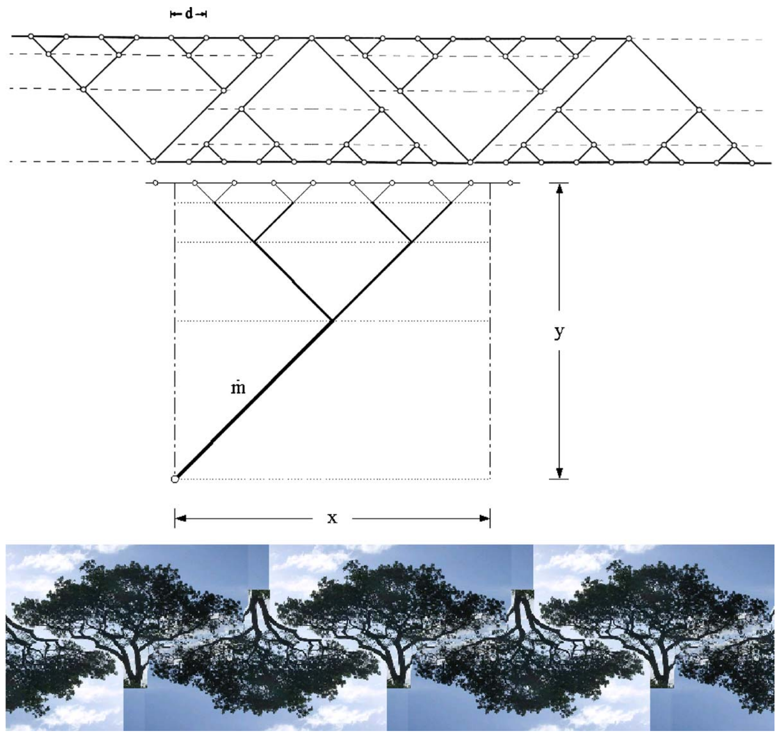

Fig. 8 The origin of multiscale porous media. The flow from plane to plane encounters considerably less resistance through tree-shaped structures than the flow through parallel channels [19].

hydrology). This prediction is crucial because it means that the apparent "diversity" and "randomness" are consistent with and predictable from the constructal law.

The observer who looks from the outside at the porous medium (e.g., from the top of Fig. 8) sees a few large pores surrounded by many small pores. From this viewing position, the porous medium appears to have only two main scales, which is why natural porous media are also described as "bidisperse." The design features uncovered based on the constructal law are qualitatively the same as those of natural porous materials (e.g., the soil of the hill slope in a river drainage basin where two scales dominate: fine porous soil with seepage and larger pores (pipes) embedded in the fine structure). The constructal law also predicts that "vascular" designs must occur in nature and that they must be stepwise more complex as they become larger [21].

8 Globalization Design: Distributed Energy Systems

Seen through the lens of the design law presented in this essay, the future design of globalization is clear. The bulk of future research in the energy area will be devoted to four fronts:

1. the development of fuel resources
2. energy conversion methods
3. the improvement of devices based on current fuels and conversion methods, and
4. the global design of fuel consumption

Most important but least recognized is the fourth front because it resonates in the daily debates about globalization, sustainability, and environmental impact. These global-scale phenomena are important, and they are hotly debated because they happen and because they threaten to happen. Work on the fourth front adds a fundamental component to any energy initiative in government, which has enormous impact on science, education, and industry.

The global energy design is a complex flow system driven by fuels that are consumed. The generated power moves things on the surface of the earth (goods, people, and information), compare Fig. 2. The flow system is a tapestry of nodes of production of power embedded in areas populated by users and environment, all linked and all sweeping the earth with their movement. Constructal design [4] is showing that the whole basin is flowing better (with fewer obstacles globally) when the production nodes and the channels are allocated in certain ways to the covered areas (the environment). This is how the globe becomes a live system—a living tissue—and why its best future can be designed based on principle. With the constructal law, this design can be pursued predictively.

The distribution, allocation, and consumption of power should be considered together on fronts 1–4, as equal partners. This holistic view includes fields, such as housing and transportation, building materials, heating and air conditioning (i.e., the "energy design" of building), lighting, water distribution, etc., (Fig. 9). In the university, it serves as a healthy unifier of mechanical, civil, and electrical engineering with environmental science.

Taken together, all these concerns allow the global design to emerge with balance, or harmony, between the fuel streams that contribute to the global power stream that drives all of our society on earth. How much fossil fuel versus renewables will be a natural feature of the global design, such as the size of the organ on the

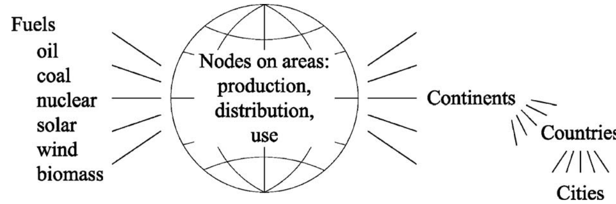

Fig. 9 The global design as a multitude of distributed energy systems of all scales, designed and interwoven in accordance with the constructal law

animal—a result, not assumed, or taken off the shelf. The global design will emerge as a construct from elements (homes) to continents (Fig. 9).

9 Why We Need Engineering Science

In this essay, we showed that with the constructal law, we can explain and predict design in nature—animate, inanimate, and engineered. The law unites.

Why is this important to know? Here are two answers.

First, we can design better vehicles—a more efficient movement of humanity on earth (e.g., Figs. 2 and 3). We can do this more directly, faster, better, and with greater confidence because now we know the law that captures the design evolution, which otherwise would require enormous numbers of designers (chance events in natural evolution and entire armies and industries that develop technologies), this in addition to time and money.

Second, with engineering science, we predict the future. Figure 5 is just one example of how.

(a) The evolution of the flow of animal mass has taken the animal design toward performance levels that persist in time.

(b) The evolution of every vehicle is pointing toward the designs that look more and more animal-like.

Viewed in time, the design of every technology constitutes a movie scripted according to (a) and (b). The movie tape runs in one direction, toward shapes and rhythms that improve in time and make the movement easier and the solid structures lighter, easier to carry.

With the science of engineering, we do not have to labor to see the entire movie. We "get it" from the first few frames and our minds leap to design images that otherwise would have taken an eternity to discover by trial-and-error. With engineering science, we design the future with us in it. The name of this grand evolutionary design is civilization, science, and education.

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