Constructal law

Constructal law is a theory of the generation of design (configurations, patterns, geometry) in nature. According to this theory, natural design and the constructal law unite all animate and inanimate systems.[1] The constructal law was stated by Adrian Bejan in 1996 as follows: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it."[2][3] The constructal law is receiving increased acceptance within the scientific community.[4]

"Constructal" is a word coined by Bejan to describe the natural tendency of flow systems (e.g. rivers, trees and branches,[5] lungs, tectonic plates[6] and engineered forms[7]) to generate and evolve structures that increase flow access.[2][8]

1 Introduction

The constructal law was proposed in 1996 as a summary of all design generation and evolution phenomena in nature, bio and non-bio. The constructal law represents three steps toward making "design in nature" a concept and law-based domain in science:[3]

1. Life is flow: all flow systems are living systems, the animate and the inanimate.[1]
2. Design generation and evolution is a phenomenon of physics.[9]
3. Designs have the universal tendency to evolve in a certain direction in time.[10]

The constructal law is proposed as a first principle of physics accounting for all design and evolution in nature. It holds that shape and structure arise to facilitate flow. The designs that happen spontaneously in nature reflect this tendency: they allow entities to flow more easily – to measurably move more current farther and faster per unit of useful energy consumed.[6][11][12][13][14][15][16] Rain drops, for example, coalesce and move together, generating rivulets, streams and the mighty river basins of the world because this design allows them to move more easily.[17]

The constructal law asks the question: Why does this design arise at all? Why can't the water just seep through the ground? The constructal law provides this answer: Because the water flows better with design. The constructal law covers the tendency of nature to generate designs to facilitate flow.[18]

2 Manifestations

The constructal law covers natural phenomena of organization, such as tree-shaped flows, round tubes and bones, scaling laws, etc. The lightning bolts that flash across the sky generate a tree-like structure because this is a good design for moving a current (electricity) from an area (the cloud) to a point (a church steeple or another cloud). The circulatory and nervous systems of biological creatures generate a similar tree-like design because they too are moving currents from a point to an area and from an area to a point.[19]

Although treelike structures are a very common design in nature, they are only one manifestation of the constructal law. In a simple example, logs floating on a lake or icebergs at sea orient themselves perpendicular to the wind which increases the transfer of motion from the moving air body to the water body. A more complex example is the design of animals that have evolved to move mass more efficiently (to cover more distance per unit of useful energy) across the landscape.[20][21][22][23]

This includes the seemingly "characteristic" sizes of organs, the shape of bones, the rhythm of breathing lungs and beating hearts, of undulating tails, running legs, and flapping wings. The constructal law proclaims that all these designs have arisen—and work together—to allow animals, like raindrops in a river basin, to move more easily across a landscape.[24][25] Because human beings are not separate from but a part of nature, their designs are also governed by the constructal law.[21][26][27]

3 Evolutionary design

The constructal law defines the time direction of all evolutionary design phenomena. It states that designs should evolve over time to acquire better configurations to provide more access for the currents that flow through them. It defines in physics terms what it means to be "better", more "fit", to "survive", and to be efficient. Not all changes are improvements, but those that stick measurably enhance flow.[8][28]

Constructal design occurs at every scale. Each component of an evolving flow system—each rivulet, each tree,

and each road—acquires evolving designs to facilitate flow access. As these elements coalesce into larger and larger structures (into evolving river basins, forests and transport networks), a hierarchy emerges such that the multi sized components and channels work together so that everything flows more easily.[17] This is seen in the shape and structure of the neural networks in the brain, of the alveoli in the lung, the size and distribution of vegetation in the forest and of human settlements on the map.[21][27][29]

In the big picture, all the mating and morphing flows on the largest system that surrounds us, the Earth itself, evolve to enhance global flow. For example, trees and other forms of vegetation that move moisture from the ground to the air are components of the larger global system, including forests, river basins and weather patterns, that have the tendency to equilibrate all the moisture on Earth.[18][30] The constructal law states that every flow system is destined to remain imperfect. The direction of design evolution is toward distributing the imperfections of the system, such that the "whole" flows easier (e.g., river basin, animal body, human vehicle).[31]

Evolution never ends. Optimality statements (minimum, maximum, optimum, static, end design, destiny) have only local, limited applicability. The constructal law covers them because it is about the time direction of all the evolutionary design phenomenon.

The constructal law is a law of physics - the law of design generation and evolution in nature. The natural phenomenon is not the elimination but the distribution (better and better over time) of imperfection. The distribution of imperfection generates the geometry (shape, structure) of the system.[13][32][33][34][35][36][36] Today, optimization of many systems arising in thermal engineering such as conductive pathways (fins,[34] cavities [13][35][37][38] and highly conductive inserts), convective channels[33][39][40][41] and radiative systems [42] are inspired by constructal law.

For example, in point-area and point-volume flows, the constructal law predicts tree architectures, such flows displaying at least two regimes: one highly resistive and one with lower resistivity. The constructal-law tendency manifests itself at every scale.[43]

The tree is the natural flow design for achieving flow access between one point and a volume. Alternating trees achieve flow access between two planes. Natural porous media exhibit multiscale flow structures consistent with the multiple scales and performance of alternating trees.

The constructal law provides a unifying theory of evolution. It holds that inanimate and animate phenomena generate evolving configurations to move more easily. The constructal law also provides the physics definition of life, of what it means to be alive. It states that life means flow and the free generation of design. If the flows stop, the system is dead (in thermodynamic equilibrium). The constructal law is the physics law of life, design and evolution.[1][9][19]

4 Constructal thermodynamics

Thermodynamics rests on two laws. Both are first principles: The first law commands the conservation of energy, and the second law commands irreversibility: the tendency of all currents to flow from high (temperature, pressure) to low. These two laws are about systems in the most general sense, viewed as black boxes, without shape and structure.

The two laws of thermodynamics do not account for nature completely. Nature is not made of black boxes. Nature's boxes are filled with evolving, freely morphing configurations—even the fact that they have names (rivers, blood vessels) is due to their appearance, organization, or design. Where the second law commands that things should flow from high to low, the constructal law commands that they evolve in configurations that flow more and more easily over time.[32]

In contrast to fractal models of observed objects in nature, the constructal law is predictive and thus can be tested experimentally.[44][45][46][47] Many natural designs, animate and inanimate, have been explained and unified by the constructal law.[6][16][17][48][49] For example:

5 Criticisms

The main criticism of the constructal law is that its formulation is vague.[63][64] The constructal law states that "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it", but there is neither a mention of what these "currents" are nor an explicit definition of what "providing easier access" means, nor precisely formulating the relationship with math. Without defining the physical quantities or their exact relationships, it is not physical or mathematical.

The related criticism of the constructal law is that there has been no attempt to prove it from first principles. Contrarily to alternative theories of non-equilibrium thermodynamics,[65][66] there is no proof of constructal theory based on simplified systems of statistical physics. The claim that constructal theory is a fundamental principle of thermodynamics itself has also been disputed.[67]

6 Responses to criticisms

Bejan has responded to this criticism [68] by noting that one cannot prove a first principle based on other first principles. The constructal law is not about what flows, but about the physics phenomenon of how any flow system acquires its evolving configuration (design) over time. The constructal law is not about optimality (max, min, opt)—it is the definition of "life" in physics terms, and of the time direction of the changes in flow configuration.[69]

Bejan [68] also noted that the phenomenon governed by the constructal law (design in nature) is macroscopic (finite size, not infinitesimal). It is the birth of design and evolution of design in all the parts together. It is dynamic, not static. The evolution never ends. There is no end design, no destiny (max, min, opt).[70][71]

Bejan and Lorente expanded on this [70] by explaining the difference between a law of physics (e.g., the constructal law) and the many invocations of the law, which underpin many "theories" based on the law. In the section titled "The constructal law versus the second law of thermodynamics" they noted that the constructal law and the second law are first principles. The constructal law is a useful reminder not only of what was missing in physics and thermodynamics (the law of design and evolution) but also of what is present. For example, contrary to the critic's view, the first and second laws of thermodynamics did not require any "proof based on simplified systems of statistical physics."

The constructal law is a statement of a natural tendency—the time direction of the phenomenon. It is as non-mathematical as the original statements of the second law:

Clausius: No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature.

Kelvin: Spontaneously, heat cannot flow from cold regions to hot regions without external work being performed on the system.

A new law does not have to be stated in mathematical terms. The mathematization of the second law statement (and of thermodynamics) came later. The constructal law underwent the same evolution. The 1996 statement was followed in 2004 by a complete mathematical formulation of constructal-law thermodynamics.[72]

Flow leads to better flow. Like any other law of physics, the constructal law is a concise summary of observed facts: the natural tendency of flow systems to evolve toward configurations that provide easier access over time. The word "access" means the ability to move through a confined space such as a crowded room. This is why "finite size" appears in the constructal law statement. This mental viewing covers all the flow design and evolution phenomena, animate and inanimate, because they all morph to enter and to flow better, more easily.[70][73]

7 References

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