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CONSTRUCTAL LAW, TWENTY YEARS AFTER

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The Constructal law has come a long way since its enunciation in two 1996 papers [1, 2], which were followed by a book [3] and five more papers in 1997 [4–8]. In Bucharest on 15–16 May 2017, we celebrated the 10th international conference dedicated to the emerging Constructal law field. The preceding conferences were held in the USA (2006, 2007), Portugal (2008), Italy (2008), France (2009), Italy (2010), Brazil (2011), China (2013) and Italy (2015).

As shown in Ref. [9], a law of physics is a concise statement that summarizes a phenomenon that occurs in nature. The Constructal-law field started from the realization that design is a universal physics phenomenon. It unites the animate with the inanimate over an extremely broad range of scales, from the tree design of the snowflake, to animal design and the tree design of the Amazon river basin. The river delta and the human lung are just two examples of the same volume-point flow architecture, one inanimate and the other animate, to which one could add many more relatives (e.g., lightning, vascularized living tissues, city traffic, the spreading of new ideas on the globe). Nature has evolution (Fig. 1).

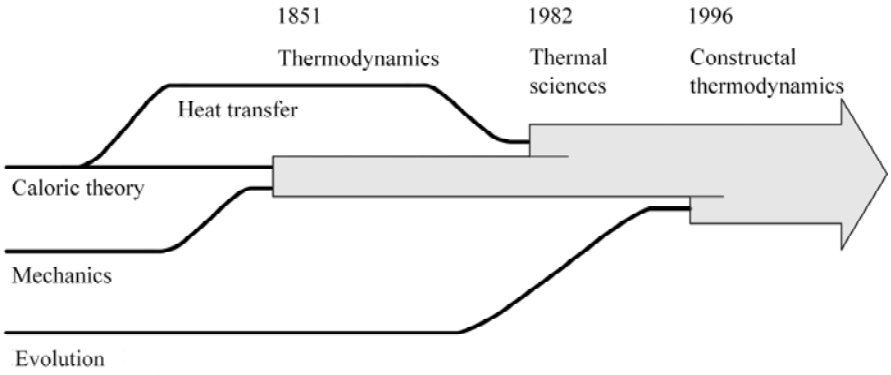

Fig. 1 – The evolution and spreading of thermodynamics during the past two centuries.

The concepts of life, design and future (evolution) were placed firmly in physics by the Constructal Law, stated in 1996 [1, 2]:

"For a finite-size flow system to persist in time (to live), its configuration must evolve freely in such a way that provides greater and greater access to the currents that flow through it."

According to the Constructal Law, a live system is one that has two universal characteristics: it flows (i.e., it is a nonequilibrium system in thermodynamics), and it morphs freely toward configurations that allow all its currents to flow more easily over time. Life and evolution are a self-standing physics phenomenon, and they belong in physics [10].

The Constructal Law is a field that is expanding rapidly in physics, biology, technology and social sciences. The field is expanding rapidly. Books on the Constructal Law appear regularly [11–23]. Today, on Google Scholar the word constructal yields 5,700 articles and books.

To see the position of design in nature as a universal phenomenon of physics, it is necessary to recall that thermodynamics rests mainly on two laws, which are both first principles. The first law commands the conservation of energy in any system. The second law commands the presence of irreversibility (i.e. the generation of entropy) in any system: Irreversibility means that, by itself, any stream flows naturally one way,

from high to low. The permanence and extreme generality of the two laws are consequences of the fact that in thermodynamics the any system is a black box. It is a region of space, or a collection of matter without specified shape and structure. The two laws are global statements about the balance or imbalance of the flows (mass, heat, work, entropy) that flow into and out of the black box.

Nature is not made of boxes without configuration. The systems that we discern in nature have shape and structure. They are macroscopic, finite size, and recognizable as images-sharp lines on a diffuse background. They have configurations, maps, rhythms and sounds. They are simple: their complexity is modest, because if it were not modest we would not be able to discern them and to question their existence. The very fact that they have names (river basins, blood vessels, trees) indicates that they have appearances that the observer recognizes.

The constructal-law literature draws attention to the fact that the laws of thermodynamics do not account *completely* for the systems of nature, even though scientists have built thermodynamics into thick books in which the two laws are just the introduction. The body of thermodynamics is devoted to describing, designing and optimizing things that seem to correspond to flow systems found in nature, or to devices that can be used by humans to make life easier. Nowhere is this more evident than in engineering, where the method of Entropy Generation Minimization [24–26] is recognized as thermodynamics even though neither of the two laws accounts for the natural occurrence of design or optimization phenomena.

The Constructal law is not a statement of optimization, maximization, minimization, or any other mental image of end design or destiny. The Constructal law is about the direction of evolution in time, and the fact that the design phenomenon is not static: it is dynamic, ever changing, like the images in a movie at the cinema. Evolution never ends. This is important to keep in mind, because there is a growing list of *ad hoc* proposals of optimality (end-design), but each addresses a narrow domain, and, as a consequence, the body of optimality statements that have emerged is self-contradictory, and the claim that each is a general principle is easy to refute [9, 27]:

(i) Minimum entropy generation (production) and maximum efficiency are used commonly in engineering and biology.
(ii) Maximum entropy production (MEP) is being invoked in geophysics.
(iii) Maximum fitness and adaptability (robustness, resilience) are used in biology.
(iv) Minimum flow resistance (fluid flow, heat transfer, mass transfer) is invoked in engineering, river mechanics and physiology.
(v) Maximum flow resistance is used regularly in physiology and engineering, e.g. maximum resistance to loss of body heat through animal hair and fur, or through the insulation of power and refrigeration plants, the minimization of fluid leaks through the walls of ducts, etc.
(vi) Minimum travel time is used in urban design, traffic, transportation.
(vii) Minimum effort and cost is a core idea in social dynamics and animal design.
(viii) Maximum profit and utility is used in economics.
(ix) Maximum territory is used for rationalizing the spreading of living species, deltas in the desert, and empires.
(x) Uniform distribution of maximum stresses is used as an axiom in rationalizing the design of botanical trees and animal bones.
(xi) Maximum growth rate of flow disturbances (deformations) is invoked in the study of fluid flow disturbances and turbulence.
(xii) Maximum power was proposed in biology, physics and engineering.

The optimality statements are contradictory and disunited, yet they demonstrate that the time for placing the ‘evolution’ phenomena in science is now. The progress made with the Constructal law [9, 27–29] shows that the diversity of phenomena addressed with the *ad hoc* statements (i) – (xii) are manifestations of the single natural tendency that is expressed by this law of physics. For example, the contradiction between (i) minimum and (ii) maximum entropy production (MEP) was resolved based on the Constructal law: both (i) and (ii) are covered by the Constructal law.

The Constructal law can be used to fast-forward design in engineering and social organization. This is useful, but the imagined end design (min, max) is neither reachable in nature, nor is it to be confused with

the phenomenon and the law of physics, which is the natural tendency (the direction in time) that points to it. The time direction is the natural phenomenon, and the law of physics that governs this natural phenomenon is the Constructal law.

Science is an evolutionary design [30] in which what we know – what is true, what works – becomes simpler, more accessible, and easier to teach. The Constructal law is a new law of physics that broadens significantly the reach of thermodynamics (Fig. 1).

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Constructal law states that any system tries to maximize flow. Flow just means transporting important things, such as fuel or water, from one place to another. This is the driving force behind three disparate categories, evolution, engineering, and design. Mechanical engineering professor Adrian Bejan discovered constructal law in 1996. It dawned on him while he was designing the cooling system for laptop computers, which has tree branch-like channels in the architecture.Â Two years later, he noticed that his designed resembled the limbs of trees and constructal law started to take shape. It was the branching pathways in the cooling system that got him thinking about flow and how it influences all kinds of systems.