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Luiz A.O. Rocha
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Constructal Law and the Unifying Principle of Design

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Understanding Complex Systems

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Preface

Constructal Law, Design in Nature, and Complexity

This book is about the Constructal Law of design in nature and the state of the field that is growing around this law of physics. It explores the unifying power of the Constructal Law and its applications in all the domains of design generation and evolution, from biology and geophysics to globalization, engineering, sustainability, and security. This growing activity covers the board, from physics and biology to social organization and technology evolution.

The Constructal Law has generated a worldwide movement toward design as science, i.e., design as a physics phenomenon as captured in 1996 by the Constructal Law: "For a finite-size flow system to persist in time (to live), its configuration must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it."

Life is movement and the persistent morphing of the configuration of this movement. The Constructal Law identifies (a) life, design and evolution (changes in configuration) as a physics phenomenon and (b) captures the time direction of design generation and evolution. Reviews of this growing field are available in refs. 1–7.

To place the Constructal Law and its field in the greater framework of scientific inquiry, it is timely to review what we mean by design in nature and by other words that refer to design in nature: complexity, networks, diversity, chance, turbulence, etc. These words are old and numerous because the fascination with the surroundings has inspired human curiosity and creativity throughout history. Science is only the latest and most powerful mental construct that came out of this natural human tendency to understand and use the surroundings in order to move more easily, farther, and more persistently in time through the surroundings.

Design has two meanings in English. The first is the noun, which means shape, structure, configuration, pattern, drawing, figure, rhythm, motif, architecture, and many more words that represent the mental viewing of an image—black lines on a background of a different color. Design in nature is about this. Science began with images: geometry (the science of figures) and mechanics (the science of contrivances made out of moving figures). We think, we create, and we speak in terms of images. Design in nature is about this, the images. The very fact that these images have names—river basin, lung, snowflake—means that we all know what they are individually even though they all look like trees.

The second meaning is the verb "to design," which is about the human activity of creating images and contrivances that are useful. This verb refers strictly to what people do on a design project, for example in engineering, where along with the verb "to design" comes "the designer" as one or many. This second meaning is not the object of this book or of any other application of the Constructal Law. Design in nature is not about "to design" and "the designer."

The Constructal Law is about predicting the design (the flow configuration) and its evolution in time. The Constructal Law is about why geometry happens. Constructal theory is the view that the Constructal Law is correct and reliable in a predictive sense. The use of constructal theory to discover flow configurations that offer greater access is constructal design.

Constructal theory and design are predictive, not descriptive. This is the big difference between the Constructal Law and other views of design in nature. Previous attempts to explain design in nature are based on empiricism: observing first and explaining after. They are backward looking, descriptive, and at best explanatory. They are not predictive theories even though some are called theories. Examples are complexity theory, network theory, chaos theory, power laws (allometric scaling rules), general models, and optimality statements (minimum, maximum, optimum).

The Constructal Law is not about optimality, destiny, or end design. It is about the fact that the generation and evolution of design never ends. With the Constructal Law we anticipate the evolving design and its direction in time. Complexity and scaling rules are discovered, not observed. Complexity is finite (modest), and is part of the description of the constructal design that emerges. If the flows are between points and areas or volumes, the constructal designs that are discovered are tree-shaped networks. The "networks" are discovered, not observed, and not postulated. Networks, scaling rules, and complexity are part of the description of the world of constructal design that emerges predictively from the Constructal Law.

Based on selected papers presented at the 2011 Constructal Law Conference in Porto Alegre, Brazil, this book illustrates the life, vigor, and growth of the research field that is stimulated today by the Constructal Law. The samples selected for presentation cover the broad range of science, from physics and biology to technology and human dynamics. The first part of the book is devoted to fundamentals and how the Constructal Law can be used to predict design in nature, the generation of design and the evolution of design. The second part takes the reader into the world of applications, where the constructal configurations are placed in processes and systems that are useful. Together, the constructal fundamentals and applications are an invitation to new research with the Constructal Law, in new directions that so far are waiting to be brought under the tent of "design as science," which the Constructal Law holds firmly.

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Chapter 3
Leaf Shapes and Venation Patterns

A.H. Reis

3.1 Plant Leaves, Power Generation, and Distribution

Plant life is fuelled by solar radiation through photosynthesis, by processes in which leaves act as power generators, main factories, and dispensers of organic substances. Leaves store energy in organic compounds (mainly carbohydrates) that are redistributed within the plant system, thus keeping all metabolic and transport processes active and maintaining and developing plant structure. Water availability is essential both for metabolic processes and for keeping the sap flowing throughout the whole plant system.

Leaf shape and structure generation have been analyzed from various perspectives, ranging from genetics [1] and auxin sources and signaling [2] to transport of water and carbohydrates [3, 4]. Because leaves display such a startling diversity of shapes and venation structures one hardly conceives that this fact might be understood based on some basic principle.

In this chapter we present an analysis of the shape and venation structure generation of leaves based on a new concept of the process by which water ascends in trees, together with the assumption that plant flow structures have been optimized in time (evolution) in order to "provide easier and easier access to the currents that flow through them" (Constructal Law, Bejan, 1997) [5]. The Constructal Law has been successfully applied to various natural (and engineered) systems (see [6–8]) and is seen more and more as a law of Nature that basically expresses the evolution of flow architectures towards reduction of global resistances to internal flows under the existing constraints.

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3.2 Driving Potential for Sap Flow in Plants

The process by which water ascends up to 100 m height in trees is not well understood yet. Many modern plant physiologists accept Cohesion Theory [9] put forward by Joly (1895) that states that water ascent in trees is achieved by the tension created in the xylem vessels by the transpirational pull. This implies that water flow is not disrupted anywhere and that water can stay liquid and stable under negative pressures of order 0.1 MPa, and higher in the tallest trees. In addition to the fact that water in such conditions would be in a metastable state, there is considerable experimental evidence that Cohesion Theory is not tenable. In result, Multi-force Theory [10] (1995) has been developed to account for a multiplicity of factors such as osmotic pressure [11, 14], gel-supported water lift [12], electrical double layers [13], and Marangoni-streaming [14]. However, it is not clear yet how all these factors might work together (see [14]).

In the following we present a possible very simple mechanism which may provide the adequate driving potential for water ascent in trees. The detailed explanations of this mechanism as well as the experimental evidences that support it are developed in another paper [15]. Here we just summarize its basic features.

The ground is usually electrically negative with respect to the nearby atmosphere, leading to the existence of an electric field directed downwards. Therefore, the ohmic component of the Maxwell current that flows between the ionosphere and the Earth's surface is composed of a downward flux of positive ions, together with an upward flux of negative ions. We put forward the assumption that trees operate as branches of this global circuit by carrying positive atmospheric ions to the ground and absorbing negative ions from the soil. Among the positive ions that are likely absorbed by the tree leaves is hydronium (H_3O^+), which results from dissociation of water ($2H_2O \rightleftharpoons OH^- + H_3O^+$). On the other hand, the negative hydroxide ions (OH^-) that are absorbed in the roots namely in the form of plant nutrients (e.g., KOH, $Zn_5(CO_3)_2(OH)_6$, $Cu_4(OH)_6SO_4$, $Cu_3(OH)_4SO_4$, $Ca(OH)_2$, and $CaMg(OH)_4$) move upwards in plants, where combination with hydronium ions generate liquid water. As the consequence of different concentrations of soluble ions of all kinds, water and nutrients flow within the plant systems (sap flows).

Because plants have much less resistance to ohmic currents than the air, they provide a preferential way for the $OH^- + H_3O^+$ current to flow in the neighborhood of the ground. In this way, the electric potential of leaves is very much close to that of the ground than that of the nearby air, thus enhancing electric fields in the leaves' vicinity. The electric fields are particularly intense in the vicinity of the leaf apex and of the leaf margin, where almost all hydronium ions are expected to be absorbed. This aspect completes the picture put forward for water absorption and, as a consequence, water intake by plants is proportional to the number of leaves times the average length of leaf margins.

Recent work [16] supports the above idea and, namely, that by Koppán and coworkers, [17] which refers "a remarkable correlation between electric potential differences and the water potential of air".