Constructal Law and the Unifying Principle of Design
Springer Complexity

Springer Complexity is an interdisciplinary program publishing the best research and academic-level teaching on both fundamental and applied aspects of complex systems – cutting across all traditional disciplines of the natural and life sciences, engineering, economics, medicine, neuroscience, social and computer science.

Complex Systems are systems that comprise many interacting parts with the ability to generate a new quality of macroscopic collective behavior the manifestations of which are the spontaneous formation of distinctive temporal, spatial or functional structures. Models of such systems can be successfully mapped onto quite diverse “real-life” situations like the climate, the coherent emission of light from lasers, chemical reaction-diffusion systems, biological cellular networks, the dynamics of stock markets and of the internet, earthquake statistics and prediction, freeway traffic, the human brain, or the formation of opinions in social systems, to name just some of the popular applications.

Although their scope and methodologies overlap somewhat, one can distinguish the following main concepts and tools: self-organization, nonlinear dynamics, synergetics, turbulence, dynamical systems, catastrophes, instabilities, stochastic processes, chaos, graphs and networks, cellular automata, adaptive systems, genetic algorithms and computational intelligence.

The three major book publication platforms of the Springer Complexity program are the monograph series “Understanding Complex Systems” focusing on the various applications of complexity, the “Springer Series in Synergetics”, which is devoted to the quantitative theoretical and methodological foundations, and the “SpringerBriefs in Complexity” which are concise and topical working reports, case-studies, surveys, essays and lecture notes of relevance to the field.

In addition to the books in these three core series, the program also incorporates individual titles ranging from textbooks to major reference works.

Editorial and Programme Advisory Board

Henry Abarbanel, Institute for Nonlinear Science, University of California, San Diego, USA
Dan Braha, New England Complex Systems Institute and University of Massachusetts Dartmouth, USA
Péter Érdi, Center for Complex Systems Studies, Kalamazoo College, USA and Hungarian Academy of Sciences, Budapest, Hungary
Karl Friston, Institute of Cognitive Neuroscience, University College London, London, UK
Hermann Haken, Center of Synergetics, University of Stuttgart, Stuttgart, Germany
Viktor Jirsa, Centre National de la Recherche Scientifique (CNRS), Université de la Méditerranée, Marseille, France
Janusz Kačprzyk, System Research, Polish Academy of Sciences, Warsaw, Poland
Kunihiko Kaneko, Research Center for Complex Systems Biology, The University of Tokyo, Tokyo, Japan
Markus Kirkilionis, Mathematics Institute and Centre for Complex Systems, University of Warwick, Coventry, UK
Jürgen Kurths, Nonlinear Dynamics Group, University of Potsdam, Potsdam, Germany
Andrzej Nowak, Department of Psychology, Warsaw University, Poland
Linda Reichl, Center for Complex Quantum Systems, University of Texas, Austin, USA
Peter Schuster, Theoretical Chemistry and Structural Biology, University of Vienna, Vienna, Austria
Frank Schweitzer, System Design, ETH Zurich, Zurich, Switzerland
Didier Sornette, Entrepreneurial Risk, ETH Zurich, Zurich, Switzerland
Stefan Thurner, Section for Science of Complex Systems, Medical University of Vienna, Vienna, Austria
Future scientific and technological developments in many fields will necessarily depend upon coming to grips with complex systems. Such systems are complex in both their composition – typically many different kinds of components interacting simultaneously and nonlinearly with each other and their environments on multiple levels – and in the rich diversity of behavior of which they are capable.

The Springer Series in Understanding Complex Systems series (UCS) promotes new strategies and paradigms for understanding and realizing applications of complex systems research in a wide variety of fields and endeavors. UCS is explicitly transdisciplinary. It has three main goals: First, to elaborate the concepts, methods and tools of complex systems at all levels of description and in all scientific fields, especially newly emerging areas within the life, social, behavioral, economic, neuro- and cognitive sciences (and derivatives thereof); second, to encourage novel applications of these ideas in various fields of engineering and computation such as robotics, nano-technology and informatics; third, to provide a single forum within which commonalities and differences in the workings of complex systems may be discerned, hence leading to deeper insight and understanding.

UCS will publish monographs, lecture notes and selected edited contributions aimed at communicating new findings to a large multidisciplinary audience.

For further volumes:
http://www.springer.com/series/5394
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.

Porto Alegre, RS, Brazil
Luiz A.O. Rocha

Toulouse, France
Sylvie Lorente

Durham, NC, USA
Adrian Bejam

References

Contents

1 The Constructal Design of Humanity on the Globe ............ 1
   A. Bejan and Sylvie Lorente

2 Toward a Quantitative Unifying Theory of Natural Design of Flow Systems: Emergence and Evolution ..................... 21
   A.F. Miguel

3 Leaf Shapes and Venation Patterns .......................... 41
   A.H. Reis

4 Drainage Basins Evolution with Non-erodible Regions ........ 51
   M.R. Errera and C.A. Marin

5 Software Evolution and the Constructal Law .................... 69
   S. Pépin

6 Constructal Design of High-Conductivity Inserts .............. 91
   J.A. Souza and J.C. Ordonez

7 Constructal Design of T-Shaped Water Distribution Networks ................................................................. 113
   P. Bieupoude, Y. Azoumah, and P. Neveu

8 The Constructal Theory of Electrokinetic Transport Through a Porous System ............................... 131
   Sylvie Lorente

9 Constructal Theory Applied to Vascular Countercurrent Networks ................................................................. 143
   Weizhong Dai

10 Constructal Design of Animate and Inanimate Systems: An Answer to Consumerism? ............................. 161
    J.V.C. Vargas
11 Constructal Design of Rectangular Conjugate Cooling Channels ........................................ 177
   T. Bello-Ochende, O.T. Olakoyejo, and J.P. Meyer

12 Flow of Stresses: Constructal Design of Perforated Plates Subjected to Tension or Buckling ...................... 195

13 Equipartition of Joulean Heat in Thermoelectric Generators .................................................. 219
   Achintya Kumar Pramanick

14 Constructal Design of Refrigeration Devices .................. 231
   H. Zhang, X. Liu, R. Xiong, and S. Zhu

15 Constructal Design of Vortex Tubes ......................... 259

16 Constructal Design of Wave Energy Converters ............... 275

17 Constructal Design of Thermal Systems ........................ 295

Index .................................................................................. 323
Contributors

Y. Azoumah LESEE-2iE, Laboratoire Energie Solaire et Economie d’Energie, Institut International d’Ingénierie de l’Eau et de l’Environnement, Ouagadougou, Burkina Faso

A. Bejan Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC, USA

T. Bello-Ochende Department of Mechanical and Aeronautical Engineering, University of Pretoria, Hatfield, South Africa

P. Bieupoude LESEE-2iE, Laboratoire Energie Solaire et Economie d’Energie, Institut International d’Ingénierie de l’Eau et de l’Environnement, Ouagadougou, Burkina Faso

C. Biserni Dipartimento di Ingegneria Energetica, Nucleare e del Controllo Ambientale, Università degli Studi di Bologna, Bologna, Italy

A.L.G. Correia Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil

J.A.V. Costa Escola de Química e Engenharia de Alimentos, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

D.C. Cunha Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul, Campus Rio Grande, Rio Grande, RS, Brazil

Weizhong Dai Mathematics and Statistics, College of Engineering and Science, Louisiana Tech University, Ruston, LA, USA

M.R. Errera Department of Environmental Engineering, Federal University of Paraná, Curitiba, Brazil

F.L. Garcia Departamento de Engenharia Mecânica, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil
M.N. Gomes Departamento de Engenharia Mecânica, Centro Politécnico, Universidade Federal do Paraná, Curitiba, PR, Brazil

L.A. Isoldi Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil

M. Letzow Programa de Pós-Graduação em Modelagem Computacional, Universidade Federal do Rio Grande, Rio Grande, RS, Brazil

X. Liu School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, Jiangsu, China

N. Lopes Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil

Sylvie Lorente LMDC (Laboratoire Matériaux et Durabilité des Constructions), Université de Toulouse, INSA, Toulouse, France

G. Lorenzini Dipartimento di Ingegneria Industriale, Università degli Sudi di Parma, Parma, Italy

B.N. Machado Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil

C.A. Marin Companhia de Saneamento do Paraná–SANEPAR, Curitiba, Brazil

C.H. Marques Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil

J.P. Meyer Department of Mechanical and Aeronautical Engineering, University of Pretoria, Hatfield, South Africa

A.F. Miguel Department of Physics and Geophysics Center of Évora, University of Évora, Évora, Portugal

P. Neveu Laboratoire Procédés Matériaux et Energie Solaire, PROMES-CNRS UPR 8521, Rambla de la thermodynamique, Tecnosud Université de Perpignan, Perpignan cedex, France

O.T. Olakoyejo Department of Mechanical and Aeronautical Engineering, University of Pretoria, Hatfield, South Africa

J.C. Ordonez Department of Mechanical Engineering and Center for Advanced Power Systems, Florida State University, Tallahassee, FL, USA

S. Périn OCTO Technology, Paris, France

Achintya Kumar Pramanick Department of Mechanical Engineering, National Institute of Technology Durgapur, West Bengal, India

M.V. Real Escola de Engenharia (EE), Universidade Federal de Rio Grande (FURG), Rio Grande, RS, Brazil
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.

A.H. Reis
Department of Physics and Évora Geophysics Centre, University of Évora,
Rua Ramalho, 59, 7000-671 Évora, Portugal
e-mail: ahr@uevora.pt
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$_3$O$^+$), which results from dissociation of water (2H$_2$O $\rightarrow$ OH$^- +$ H$_3$O$^+$). 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)$_6$SO$_4$, Cu$_3$(OH)$_4$SO$_4$, Ca(OH)$_2$, and CaMg(OH)$_2$) 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$_3$O$^+$ 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”.