

Design with Constructal Theory*

ADRIAN BEJAN

Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC 27708-0300, USA. E-mail: daldorf@daldorf@duke.edu

SYLVIE LORENTE

Laboratoire Matériaux et Durabilité des Constructions, Institut National des Sciences Appliquées, Département de Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse, France. E-mail: lorente@insa-toulouse.fr

This paper outlines a new 4½-year undergraduate course on the generation of system configuration (geometry, architecture, and drawing) during the maximization of performance of flow systems. The configuration is free to morph. Real systems are destined to remain imperfect because of finiteness constraints. They are plagued by resistances to the flow of fluid, heat, and electricity. The balancing and distributing of resistances (irreversibility) through the available volume is the mechanism that generates the architecture. The course teaches the generation of configuration, multi-scale and multi-objective hierarchical structures for fluid flow and heat flow, tree-shaped networks for collection and distribution, and strategies for reducing the cost of generating the flow configuration.

Keywords: constructal theory; design; flow; mechanical structures

CONCEPT

IN THIS PAPER we describe the development of an entirely new course on the principle-based generation of flow-system architecture. What is new about this approach is the focus on the principle and method of generating geometry (shape, structure, configuration) for energy systems with flows of fluid, heat, electricity and mass. The course is about design discovery—the maximization of global performance subject to global constraints—in engineered systems and in natural systems as well. We believe that this concept is an ideal mechanism for teaching the connection between engineering and nature, and for demonstrating to the student the real-life importance of core courses (fluid mechanics, heat transfer, thermodynamics) in design. It is also an effective vehicle for reviewing mathematical methods, especially the simplest pencil and paper skills, on which the graduating engineer will have to rely in his or her career.

The approach is based on *constructal theory* [1]—the view that flow configuration (geometry, design) can be reasoned on the basis of a principle of maximization of global flow access in systems that are free to morph under global constraints. The generation of flow configuration is viewed as a phenomenon, and the principle that sums up its repeated occurrence in nature and engineering (the constructal law) is deterministic.

Constructal theory provides a broad coverage of 'design' everywhere, from engineering to geophysics and biology [2]. To see the generality of the method, consider the following metaphor, which

we use to teach in the introductory segment of the course. Imagine the formation of a river drainage basin, which has the function of providing flow access from an area (the plain) to one point (the river mouth). The constructal law calls for a configuration with maximum flow access (minimum global flow resistance). The invocation of this law leads to an optimal balancing of all the internal flow resistance, from the seepage along the hill slopes to the flow along all the channels. Resistances (imperfections) cannot be eliminated. They can be 'matched' neighbor to neighbor, and distributed so that their global effect is minimal and the whole basin is the least imperfect that it can be. The river basin 'morphs' en route to its optimal configuration.

The visible and valuable product of this way of thinking is the *configuration*: the river basin, the tree of cooling channels in a package of electronics, etc. The configuration is the big unknown in design; constructal law draws attention to it as the unknown, and guides our thoughts in the direction of discovering it.

In the river basin example, the configuration that the constructal law recommends is a tree-shaped flow, with balances between highly dissimilar flow resistances such as seepage (Darcy flow) and river channel flow. The 'tree' is the theoretical way of providing maximum access between one point (source, sink) and an infinity of points (area, volume). The tree is a *complex* flow structure, which has multiple length scales that are distributed optimally (hence non-uniformly) over the available area or volume. The tree is 'order out of chaos': the order is the stream flow through the tree channels, and the chaos is the diffusion across the interstices between the smallest tree channels.

* Accepted 6 September 2000.

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Table of Contents Design With Constructal Theory Solution Manual

1. Understanding the eBook Design With Constructal Theory Solution Manual
 - The Rise of Digital Reading Design With Constructal Theory Solution Manual
 - Advantages of eBooks Over Traditional Books
2. Identifying Design With Constructal Theory Solution Manual
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Design With Constructal Theory Solution Manual
 - User-Friendly Interface
4. Exploring eBook Recommendations from Design With Constructal Theory Solution Manual
 - Personalized Recommendations
 - Design With Constructal Theory Solution Manual User Reviews and Ratings
 - Design With Constructal Theory Solution Manual and Bestseller Lists

5. Accessing Design With Constructal Theory Solution Manual Free and Paid eBooks
 - Design With Constructal Theory Solution Manual Public Domain eBooks
 - Design With Constructal Theory Solution Manual eBook Subscription Services
 - Design With Constructal Theory Solution Manual Budget-Friendly Options
6. Navigating Design With Constructal Theory Solution Manual eBook Formats
 - ePub, PDF, MOBI, and More
 - Design With Constructal Theory Solution Manual Compatibility with Devices
 - Design With Constructal Theory Solution Manual Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Design With Constructal Theory Solution Manual
 - Highlighting and Note-Taking Design With Constructal Theory Solution Manual
 - Interactive Elements Design With Constructal Theory Solution Manual
8. Staying Engaged with Design With Constructal Theory Solution Manual
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Design With Constructal Theory Solution Manual
9. Balancing eBooks and Physical Books Design With Constructal Theory Solution Manual
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Design With Constructal Theory Solution Manual
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Design With Constructal Theory Solution Manual
 - Setting Reading Goals Design With Constructal Theory Solution Manual
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Design With Constructal Theory Solution Manual
 - Fact-Checking eBook Content of Design With Constructal Theory Solution Manual
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
- Exploring Educational eBooks

14. Embracing eBook Trends

- Integration of Multimedia Elements
- Interactive and Gamified eBooks

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