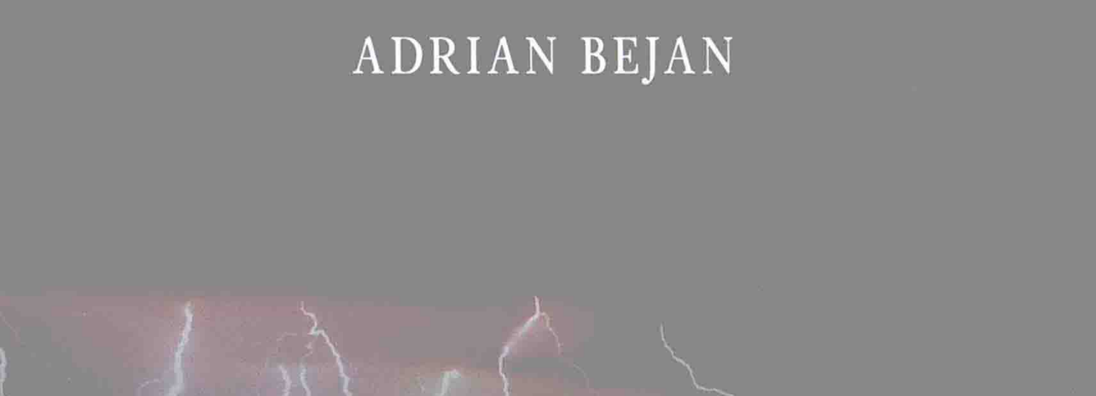
FOURTH EDITION

ADVANCED ENGINEERING THERMODYNAMICS

ADRIAN BEJAN



WILEY

Advanced Engineering Thermodynamics

Fourth Edition

Adrian Bejan
J. A. Jones Distinguished Professor
Duke University
Durham, North Carolina

WILEY

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Names: Bejan, Adrian, 1948- author.
Title: Advanced engineering thermodynamics / Adrian Bejan.
Description: Fourth edition. | Hoboken, New Jersey : John Wiley & Sons Inc., 2016. | Includes bibliographical references and index.
Identifiers: LCCN 2016023367 | ISBN 9781119052098 (cloth : acid-free paper) | ISBN 9781119281030 (epdf) | ISBN 9781119281047 (epub)
Subjects: LCSH: Thermodynamics.
Classification: LCC TJ265 .B425 2017 | DDC 621.402/1—dc23
LC record available at https://lccn.loc.gov/2016023367

Cover Design: Wiley
Cover Images: Lightning storm, Arlington, Arizona © DeepDesertPhoto/Getty Images, Inc.
Lightning, Great Salt Lake, Utah © Scott Stringham photographer/Getty Images, Inc.

This book is printed on acid-free paper. ♾

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Advanced Engineering Thermodynamics

Other books by Adrian Bejan:

The Physics of Life: The Evolution of Everything, St. Martin's Press, 2016.

Design in Nature, with J. P. Zane, Doubleday, 2012.

Design with Constructal Theory, with S. Lorente, Wiley, 2008.

Shape and Structure, from Engineering to Nature, Cambridge University Press, 2000.

Entropy Generation through Heat and Fluid Flow, Wiley, 1982.

Entropy Generation Minimization, CRC Press, 1996.

Thermal Design and Optimization, with G. Tsatsaronis and M. Moran, Wiley, 1996.

Convection in Porous Media, with D. A. Nield, Fourth Edition, Springer, 2013.

Convection Heat Transfer, Fourth Edition, Wiley, 2013.

Heat Transfer, Wiley, 1993

Preface to the First Edition[†]

I have assembled in this book the notes prepared for my advanced class in engineering thermodynamics, which is open to students who have had previous contact with the subject. I decided to present this course in book form for the same reasons that I organized my own notes for use in the classroom. Among them is my impression that the teaching of engineering thermodynamics is dominated by an abundance of good introductory treatments differing only in writing style and quality of graphics. For generation after generation, engineering thermodynamics has flowed from one textbook into the next, essentially unchanged. Today, the textbooks describe a seemingly "classical" engineering discipline, that is, a subject void of controversy and references, one in which the step-by-step innovations in substance and teaching method have been long forgotten.

Traveling back in time to rediscover the history of the discipline and looking into the future for new frontiers and challenges are activities abandoned by all but a curious few. This situation presents a tremendous pedagogical opportunity at the graduate level, where the student's determination to enter the research world comes in conflict with the undergraduate view that thermodynamics is boring and dead as a research arena. The few textbooks that qualify for use at the graduate level have done little to alleviate this conflict. On the theoretical side, the approach preferred by these textbooks has been to emphasize the abstract reformulation of classical thermodynamics into a sequence of axioms and corollaries. The pedagogical drawback of overemphasizing the axiomatic approach is that we do not live by axioms alone and the axiomatic reformulation seems to change from one revisionist author to the next. Of course, there is merit in the simplified phrasing and rephrasing of any theory: This is why a

[†] Abbreviated.

comparative presentation of various axiomatic formulations is a component of the present treatment. However, I see additional merit in proceeding to show how the theory can guide us through the ever-expanding maze of contemporary problems. Instead of emphasizing the discussion of equilibrium states and relations among their properties, I see more value in highlighting irreversible processes, especially the kind found in practical physical systems.

With regard to the presentation of thermodynamics at the graduate level, I note a certain tendency to emphasize physics research developments and to deemphasize engineering applications. I am sure that the engineering student—his[†] sense of self-esteem—has not been well served by the implication that the important and interesting applications are to be found only outside the domain chosen by him for graduate study. If he, like Lazare and Sadi Carnot two centuries earlier, sought to improve his understanding of what limits the "efficiency" of machines, then he finished the course shaking his head wondering about the mechanical engineering relevance of, say, negative absolute temperatures.

These observations served to define my objective in designing the present treatment. My main objective is to demonstrate that thermodynamics is an active and often controversial field of research and encourage the student to invest his creativity in the future growth of the field.

The other considerations that have contributed to defining the objective of the present treatment are hinted at by the title *Advanced Engineering Thermodynamics*. The focus is being placed on "engineering" thermodynamics, that is, on that segment of thermodynamics that addresses the production of mechanical power and refrigeration in the field of engineering practice. I use the word *thermodynamics* despite the campaign fought on behalf of *thermostatics* as the better name for the theory whose subjects are either in equilibrium or, at least, in local equilibrium. I must confess that I feel quite comfortable using the word *thermodynamics* in the broad sense intended by its creator, William Thomson (Lord Kelvin): This particular combination of the Greek words *therme* (heat) and *dynamis* (power) is a most appropriate name[‡] for the field that united the "heat" and "work" lines of activity that preceded it (Table 1.2).

Finally, I view this as an "advanced" course in engineering thermodynamics because it is the natural outcome of my own interaction with the research arena and with students who were previously acquainted with the subject of classical thermodynamics. There are at least two ways in which every subject can be advanced by a second course such as this. One is a "horizontal" expansion into the more remote fields intersected by the subject; the other is a "vertical" expansion, that is, a deepening of our understanding of the most basic concepts that

[†]Masculine pronouns are used throughout this treatment only for succinctness. They are intended to refer to both males and females.

[‡]The appetite for the "thermostatics" nomenclature is stimulated by comparisons with the dynamics/statics differentiation that is practiced in the field of mechanics: I believe that the contemporary mechanics meaning of "dynamics" is being mistakenly viewed as the *origin* of "-dynamics" in "thermodynamics."

define the subject. In the present treatment, I have followed the second approach because I see it as a more effective means of conveying a bird's-eye view of engineering thermodynamics. An exhaustive coverage of the horizontal type already exists in the "handbooks"; and justice to each peripheral domain can be done only in specialized courses such as compressible fluid dynamics, combustion, turbomachinery, refrigeration and air conditioning, cryogenics, etc.

I have followed the vertical approach in order to make a statement of what I consider effective as a pedagogical tool. Although it has become fashionable to associate completeness and volume with "goodness," in this course I have made a conscious effort to focus on the structure of the field. I invite the research student to make his own contributions to this structure. For this last reason, the more applied segments of the present treatment are dominated by the topics that have attracted my own interest as a researcher.

To summarize, the combined research and pedagogical mission of this effort is to take a second look at the field and to make this view accessible in a one-semester course taken by individuals whose initial understanding of the subject is by no means homogeneous. Depth is provided through a comparative discussion of the various ways in which the fundamentals have been stated over the years and by reestablishing the connection between fundamentals and contemporary research trends such as the "exergy" methodology.

ADRIAN BEJAN

Durham, North Carolina
October 1987

Preface to the Second Edition†

In the first edition I urged the student not to regard thermodynamics as finished, but to invest his or her creativity in the future growth of the field. That was a call to action—a manifesto, really—to replace present-day thermodynamics with something better and more useful. I was repeating a call made in my first book (1982), where I noted that we already possess deterministic means with which to attack realistic (irreversible) processes and systems. By sketching Fig. 1, I predicted a merger of thermodynamics with transport phenomena (e.g., heat transfer), to produce a more powerful thermodynamics of irreversible devices by the year 2000.

As I look back at Fig. 1 and the activity published since the first edition (1988), I think it is time to claim a small victory and to accept a new and greater challenge. The victory is that the combined method of thermodynamics and heat transfer has sold itself over the wide spectrum of engineering and physics. Today the method is best known as entropy generation minimization (EGM), thermodynamic optimization, or finite-time thermodynamics. This method brings systematically into thermodynamics both *modeling* and *optimization*. The systems and processes that are analyzed are *realistic*: Their irreversibilities are due to transport processes, which are described in terms of practical (concrete) notions such as materials, shapes, relative positions, and size and time constraints.

The simplest models and the most basic trade-offs (optima) revealed by EGM have enriched the discipline of thermodynamics. These trade-offs are *fundamental*: Since they rule the operation of the simplest model that is still realistic, they are certainly present in the most complex (industrial R & D) models, where they deserve to be identified and exploited.

† Abbreviated.

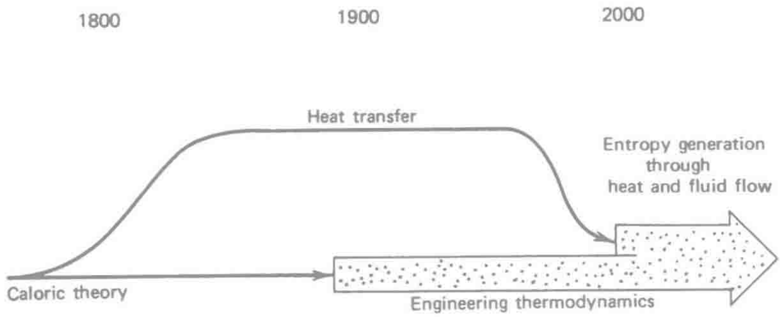


Figure 1 Predicted merger of thermodynamics and heat transfer. (Reprinted from A. Bejan, *Entropy Generation through Heat and Fluid Flow,* Wiley, New York, 1982.)

The newer and greater challenge is to extend our deterministic powers to the class of *naturally organized* systems, living and not living. Such systems are all around us and inside ourselves. Their organization is in space and in time. The networks visible in trees, roots, leaves, lungs, vascularized tissues, dendrites in rapid solidification, axonal arbors, river basins, deltas, lightning, streets, and other paths of telecommunication are spatially organized. Temporal organization is evident in the finely tuned frequencies of respiration, circulation, and pulsating and meandering flows (e.g., rivers, and many other turbulent flows).

My first steps in this new direction were purely by accident, as I now recount in Section 13.1. I saw this direction as a challenge to me (a provocation) only *after* I did the work: It was then that I discovered the voluminous material that physicists and biologists had published on "self-organization," a huge and diverse ensemble of macroscopic phenomena that they consider to be nondeterministic: that is, the result of chance. The challenge was to construct a theory—a deterministic approach—to predict, explain, and in this way *unify* the naturally organized phenomena. There had to be a reason for all the geometric form and similarity that we see in nature.

In Chapter 13 I show that the tree-shaped networks can in fact be predicted in an amazingly simple and direct way, by geometrically optimizing the access between one point and a finite volume (an *infinite* number of points). The existence of at least two access routes (flow regimes) is essential: a slow regime without shape (diffusion, disorganization) placed at the volumetric level, accompanied by a faster flow regime with shape (streams, organization) along channels positioned optimally in assemblies of large sizes. Through this geometric construction and the other results assembled in Chapter 13, configuration, morphing, and time are made a part of our thermodynamics.

To attempt a deterministic theory of organization in Nature is to reach for things sacred: a better understanding of how we fit in this world and how the world holds together. Organization and the beauty that it sets free are at the center of every religion. In science and philosophy, the organization of Nature captivated man's imagination and served as centerpiece in the dispute between randomness and determinism. The subject has experienced a resurgence in physics during the past two decades.

Here is why engineers are the ones who should be developing the thermodynamics of naturally organized systems. The history reviewed in Chapters 1 and 2 shows that the thermodynamics pioneers were engineers, military men, doctors, and amateurs. The physicists contributed later. The reason is that the defining problem of thermodynamics—the heat engine—was a *macroscopic* system with *purpose*. From its very beginning, thermodynamics was formulated and aimed at *irreversible* processes and systems and at ways of *optimizing* (i.e., improving) operation. The tools needed for this work have been developed and used by engineers for the past 200 years. They have been used with enormous success as separate disciplines, but they are now coming together (Fig. 1). Our standard of living today is a measure of this success (e.g., Fig. 8.1).

Now, if we examine closely the problems solved in Chapter 13, we will see that to predict natural organization we do not need thermodynamics. To minimize the resistance to heat or fluid flow was possible in the early 1800s. To minimize the time of travel between a finite area and one point was a problem for the time of Galilei and even earlier. This delay to roughly 150 years after the birth of thermal science (Fourier, Carnot) is due to a coincidence on which I focus next.

The development of principles of engineering science (including thermal science) began with the establishment of the modern engineering schools (Paris, 1795; Prague, 1806; Vienna, 1815; Karlsruhe, 1825). The coincidence is that this was also the era in which differential calculus was beginning to spread as the language of science and engineering. Even though Carnot and the other pioneers were stating their thermodynamics views with reference to macrosystems of arbitrary size and unmentioned internal complexity, the second generation of thermodynamicists sought to make its own contribution by using the newly learned language of infinitesimal calculus.

The infinitesimal and microscopic facets of thermodynamics were almost exclusively the contribution of nonengineers (physicists, chemists, mathematicians), at a time when engineers continued on the geometric and macroscopic (finite-size system) path. The emphasis on the frontier shifted to the differential geometry of surfaces that relate the properties of simple or nearly simple systems at equilibrium. Equilibrium (classical, Gibbsian, or analytical) thermodynamics is one lasting result of this emphasis (Chapters 4–7). The steps made in this century away from equilibrium thermodynamics, in what has become known as irreversible thermodynamics or nonequilibrium thermodynamics (Chapter 12), were also wedded to the infinitesimal, zero-size approach. Unwittingly, these steps were a yearning for a return to the realistic processes and systems targeted by the pioneers.

The 150-year delay to which I referred is the result of a common behavioral trend in science. It takes only one or two truly creative pioneers (e.g., Gibbs) for an entire crowd to form and mimic these pioneers and to start believing in its own material. Next, the even larger group that comes to be educated by the crowd knows nothing—applauds nothing—other than the material regurgitated by Gibbs' epigones. This is why today we read the absurd claim that what we inherited from Carnot and his period is strictly a thermodynamics of reversible processes. We also read that the engineers' interests and abilities are limited to reversible phenomena and that in engineering, irreversibility is regarded as a "nuisance."

Yes, most certainly, irreversibility is to be decreased when the constructor's objective is to improve thermodynamic performance. The giant steps (ideas) illustrated in Figs. 2.1, 8.1, and 10.28, however, did not occur "by chance" to men who had neither interest in, nor an understanding of, irreversibility. On the contrary. From Lazare Carnot, through to our own century (e.g., Stodola, Claude, Keenan), irreversibility minimization has been the main issue. That issue is even better known as efficiency increase, performance improvement, or, simply, good engineering.

It is time that we engineers reclaim our own field—thermodynamics—so that we may expand its deterministic powers in the direction of naturally organized, living and not living systems. We are the ones to do this work because nature is engineered.

ADRIAN BEJAN

Durham, North Carolina
July 1996

Preface to the Third Edition

Thermodynamics has reached an impasse similar to the development of the heat engine two centuries ago. The need is great, the value of research and education is obvious, and valuable improvements are occurring every day. What is missing is a scientific base, a fundamental framework that ties together what is being achieved, and guides us into the future. We all know the headlines: chaos vs. order, darwinism vs. design in nature, globalization, diminishing energy resources, environmental impact, and sustainable development. Confusion and doom prevail in society and academia.

An impasse is a historic opportunity for science. It is the moment to spring into a new direction, and to march loudly against the crowd. Two centuries ago, such a jolt was produced by Sadi Carnot. His vision became the discipline of thermodynamics, which has been serving all our inquiries concerning energy transformations in well specified ("given") fuel resources and configurations surrounded by "infinite" environments: e.g., the transformation of fuel into work in a power plant or in a component, and the transformation of food into work in an animal organ.

Today, thermodynamics has hit a wall. Fuels are not given, environments are not infinite, and energy transformations do not occur in isolation. Furthermore, flow systems are not black boxes with inflows and outflows and no structure internally.

The real world (nature, physics) has structure, organization, pattern. Until now, thermodynamics was not concerned with the architecture (the drawings) of the systems that inhabit its black boxes. It should have been.

The route to historic impact is paved with fundamentals. In the thermodynamics that emerges, the readjustment of fossil and renewable fuel streams (i.e., new equilibria of how to flow) will be predicted and optimized based on principles. In this new science, the shrinking of the environment (i.e., new equilibria between our flows and the external ones) will be predicted and optimized based on principles. Thermodynamic systems will have new properties such as configuration, objective, svelteness and freedom to morph. The new science will be, by its very nature, transdisciplinary—a science of systems of systems.

No flow system is an island. No river exists without its wet plain. No city thrives without its farmland and open spaces. Everything that flowed and lived to this day to "survive" is in an optimal balance with the flows that surround it and sustain it. The air flow to the alveolus is optimally matched to the blood that permeates through the vascularized tissue, and vice versa.

Yes, *vascularized* is a good way to describe the systems that the new science of thermodynamics will cover. The tissues of energy flows, like the fabric of society and all the tissues of biology, are optimized architectures. Not just "any" architectures, as in the black boxes of classical thermodynamics, but the optimal, or the near-optimal architectures. The climbing to this high podium of performance is the transdisciplinary effort—the balance between seemingly unrelated flows, territories, and disciplines. This balancing act—the optimal distribution of imperfection—generates the very design of the process, power plant, city, geography, and economics.

And so, I arrive at the essence of this new edition, which is the union that it forges between physics, engineering science, and life sciences. This union had its start in the second edition, as *the constructal theory of organization in nature*. Now this theory is the basis for the *thermodynamics of nonequilibrium (flow) systems with configuration.*† The news is that there are two time arrows in physics, not one. The old is the time arrow of the second law of thermodynamics, the arrow of irreversibility: every thing flows from high to low. The new is the time arrow of the constructal law, the arrow of how every flowing thing acquires architecture. The "how" is condensed in the *constructal law*: existing configurations assure their survival by morphing *in time* toward easier flowing configurations. The constructal time arrow unites physics with biology and engineering (after all, engineering is the biology and medicine of "man + machine species").

We see this union in Fig. 1, which expresses the vision that I proposed in Fig. 3.16. The earth with its solar heat input, heat rejection, and wheels of atmospheric and oceanic circulation, is a heat engine without shaft: its maximized (but not ideal) mechanical power output cannot be delivered to an extraterrestrial system. Instead, the earth engine is destined to dissipate through air and water friction and other irreversibilities (e.g., heat leaks) all the mechanical power that it produces. It does so by "spinning in its brake" the fastest that it can (hence the winds and the ocean currents, which proceed along easiest routes).

†A. Bejan and S. Lorente, The constructal law and the thermodynamics of flow systems with configuration, *Int. J. Heat Mass Transfer*, Vol. 47, 2004, pp. 3203-3214.
A. Bejan and S. Lorente, *La Loi Constructale*, L'Harmattan, Paris, 2005

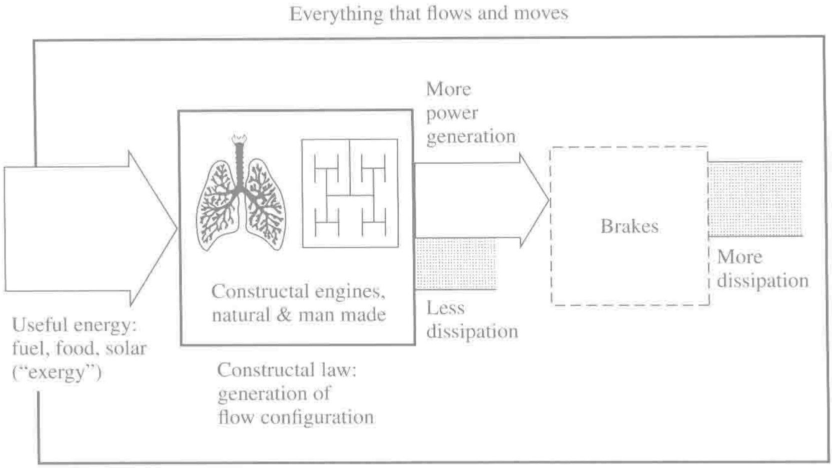


Figure 1 Every nonequilibrium (flow) component of the earth functions as an engine that drives a brake. The constructal law governs "how" the system functions: by generating a flow architecture that distributes imperfections optimally to fill the flow space. The "engine" part evolves in time toward generating maximum power (or minimum dissipation) and, as a consequence, the "brake" part exhibits maximum dissipation. Evolution means that each flow system assures its persistence in time by freely morphing into easier and easier flow structures under finiteness constraints. The arrows proceed from left to right because this is the general drawing for a flow (nonequilibrium) system, in steady or unsteady state. When equilibrium is reached, all the flows cease, and the arrows disappear. Note: this figure is not a "model." It is not a simplified facsimile of something that we see around us. It is not empiricism. It is theory: a purely mental viewing of how things *should be* even when we do not see them.

Because the flowing earth is a constructal heat engine, its flow configuration has evolved in such a way that it is the least imperfect that it can be. It produces maximum power, which it then dissipates at maximum rate. A principle of maximum dissipation is now being invoked ad-hoc in geophysics: all such writings refer only to what goes on in the brake, and are already covered by the constructal law.

The heat engines of engineering and biology (power plants, animal motors) have shafts, rods, legs, and wings that deliver the mechanical power to external entities that use the power (e.g., vehicles and animal bodies needing propulsion). Because the engines of engineering and biology are constructal, they morph in time toward flow configurations that make them the least imperfect that they can be. Therefore, they evolve toward producing maximum mechanical power (under finiteness constraints), which, for them, means a time evolution toward minimum dissipation (minimum entropy generation rate).

If we look outside an engineering or biology engine, we see that all the mechanical power that the engine delivers is destroyed through friction and other irreversibility mechanisms (e.g., transportation and manufacturing for man, animal locomotion and body heat loss to ambient). The engine and its immediate environment (the brake), as one thermodynamic system, are analogous to the whole earth (Fig. 1). After everything is said and done, the flowing earth (with all its engine + brake components, rivers, fish, turbulent eddies, etc.) accomplishes as much as any other flow architecture, animate or inanimate: it mixes the earth's crust most effectively—more effectively than in the absence of constructal phenomena of generation of flow configuration. Irrefutable evidence of this accomplishment is how all the large eddies of biological matter have morphed and spread over larger areas and altitudes, in this sequence in time: fish in water, walking fish and other animals on land, flying animals in the atmosphere, flying man + machine species, and man + machine species in the outer space.

The balanced and intertwined flows that generate our engineering, economics and social organization are no different than the natural flow architectures of biology (animal design) and geophysics (river basins, global circulation). This time, and in this book in particular, we do not copy from nature in order to do engineering. There is no biomimetics here! This time we proclaim engineering as the science that would have made Sadi Carnot proud. With this science we join ranks with biologists, physicists and economists in explaining how to generate better flowing architectures, that is how to construct what will be (i.e., how to predict the future).

* * *

ADRIAN BEJAN

September 2005

Preface

Science, like writing, technology, and the rule of law, is an evolutionary add-on that empowers humanity, from one book to the next.† Thermodynamics is no exception. Its contemporary *evolution* is in full view in the four editions of this book. What in the first edition began as a unification of thermodynamics with heat transfer, fluid mechanics, and thermal design has become thermodynamics endowed with two muscular chapters, entropy generation minimization and the constructal law of evolution as physics (bio, nonbio, geo, socio, techno), Fig. 1.

The constructal law accounts for the human urge to innovate, invent, and create contrivances, which include science and new methods to invent even better and faster. Science is about us, after all. This new edition draws attention to this truth. The growth of the constructal law field, which is documented in this new edition, is an illustration of the much broader phenomenon of how and

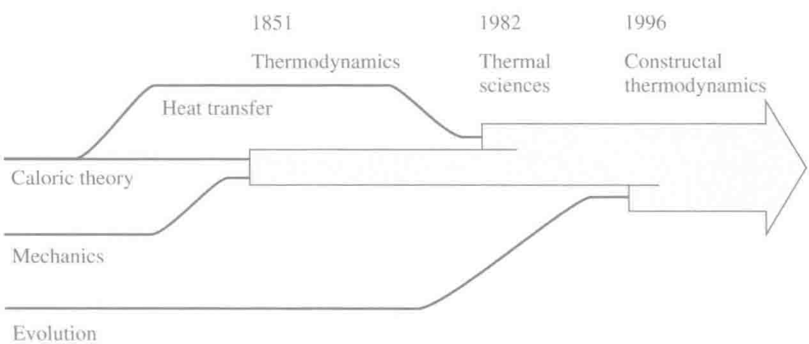


Figure 1 The evolution and spreading of thermodynamics during the past two centuries, as a continuation of Fig. 1 in the Preface to the second edition of this book.

† A. Bejan, *The Physics of Life: The Evolution of Everything*, St. Martin's Press, New York, 2016.