Preface to the Second Edition

The publication of this *Second Edition* of *The Dynamics of Heat* has given me the opportunity to make some major and, I hope, useful changes to the book. The character of the conceptualization of thermal processes—the direct approach to entropy as what in lay terms would be called "heat" and temperature as the corresponding potential—has been retained and much has been taken directly from the *First Edition*, but I have completely changed the structure of this text and I have added new material on thermal processes, chemical dynamics, and explicit dynamical modeling. The original goals of a unification of foundations and applications in general, and of thermodynamics and heat transfer in particular, have been the guiding principles for this revision. As such, *The Dynamics of Heat* continues to be a text that can help students of the applied sciences, engineering, and medicine to take the steps from the simplest beginnings in thermal and chemical physics all the way to more demanding and formal treatments of modern continuum thermodynamics. Students of physics can find an introduction to the foundations of a dynamical theory of macroscopic thermal phenomena that will complement modern treatments of statistical physics.

The book is now divided into four parts. Part I, *Processes, Energy, and Dynamical Models*, is an extensive revision of the Introduction of the *First Edition*. I have simplified the original brief description of the material and I have added explicit system dynamics modeling of laboratory experiments. Part II, *Thermal and Chemical Processes*, takes the introductory elements of the four main chapters of the previous edition and transforms them into an introduction to the dynamics of heat and substances suitable to a first college course on the subject. It builds upon the description of fluid, electrical, and mechanical phenomena introduced in Part I and essentially provides a uniform dynamical systems approach to models of thermal and chemical processes. Part IV, *Special Processes and Systems*, is the least changed from the previous text and contains the more advanced applications of the four large chapters of the *First Edition*. The Epilogue of the *First Edition* has been converted into Part III, *A Dynamical Theory of Heat*. which now offers a formal conclusion to Part II and an introduction to continuum thermodynamics and radiative transfer useful for the applications in Part IV. The Interlude of the First Edition which had the character of a historical and formal introduction to the thermodynamics of spatially uniform systems, has been omitted. For a direct approach to the dynamics of heat I now prefer the formalism of uniform processes developed in Part III over the classical treatment of cycles. Parts III and IV can be the foundation of an advanced course. Last but not least, the new *Introduction* is a brief outline of cognitive and historical aspects of human conceptualizations of nature in general and of thermal phenomena in particular.

A number of aspects of the text have been changed and some elements have been added. Here is a list of the most important of these changes and additions:

- There are descriptions including actual laboratory data for thermal and chemical phenomena in some key chapters. Many of the phenomena have subsequently been modeled with the help of simple system dynamics tools, providing explicit and detailed dynamical models. Additional experiments and models can be found on a Website for inquiry based learning (see below).

- Time dependent thermal and, especially, chemical phenomena have been given more space than in the previous edition. They can be found in Part II.
- A discussion of thermoelectricity has been added both in the introduction to thermal processes (Chapter 4) and in a more in-depth study of conductive processes (Chapter 13). This is another demonstration of the ease with which some subjects can be treated that are usually considered advanced material in standard texts.
- To strengthen the didactic approach to introductory continuum physics, I have added a brief development of equations of balance and constitutive relations for the life and migration of locust in a single spatial dimension in Chapter 11.
- Short conceptual and review questions have been added to most of the chapters of the book. They should require no more than a pencil and a piece of paper, and maybe not even that. Answers to these questions are provided in the Appendix.
- There are short answers to many of the end-of-chapter problems in the Appendix. A solutions manual will accompany the book.
- I have changed the sign convention for fluxes. Previously, I had chosen to go with the tradition of electromagnetic field theory where an outward flux is given a positive sign. Now, I prefer to count a flow *into* a system as a *positive* quantity. This leads to two changes: (1) in the laws of balance, the rate of change of a fluidlike quantity equals the sum of the currents (rather than the negative sum); (2) a flux as the surface integral of a current density obtains a minus sign. The convention adopted here should be more convenient for engineering students.

Many of the new aspects and elements have been inspired by a didactics of inquiry based learning which I have been privileged to build up with Georges Ecoffey of the University of Applied Sciences of Western Switzerland and Edy Schütz (Bildungszentrum Uster),[1] partially under a grant made available by the Eduard Job Foundation for Thermal and Chemical Dynamics in Hamburg, Germany.[2] My school and colleagues at the Center of Applied Mathematics and Physics have been supportive in the construction of a studio for introductory physics courses where I have been able to apply new learning materials and tools for the last few years. In particular, I would like to thank Jürg Krieg who has made sure that funds were available, and Arthur Baumann who has been doing much of the actual setting up of the studio. I would like to express my gratitude to Paolo Lubini for editing Chapter 6, Jürg Hosang for end of chapter problems for that same chapter, Georges Ecoffey for editing the entire book, and David Packer and the staff at Springer who have been patient and always very supportive of this project.

Again, my special gratitude goes to my wife Robin who did the language editing of the entire text.

Winterthur, June 2010 *Hans Fuchs*

1. See the Website for *Physics as a Systems Science—A Virtual Learning Environment* at http://www.zhaw.ch/~fusa/PSS_VLE/index.html.
2. See the Website at http://www.job-stiftung.de.

Preface to the First Edition

The last few decades have seen the development of a general approach to thermodynamic theory. Continuum thermodynamics has demonstrated to us how we can build a theory of the dynamics of heat rather than of statics. In this book I would like to transfer what I have learned about the general theory to an introductory level and to applications in the sciences and engineering.

Two elements combine to make this presentation of thermodynamics distinct. First of all, taking as the foundation the fundamental ideas that have been developed in continuum thermodynamics allows one to combine the classical theory of thermodynamics and the theory of heat transfer into a single edifice. Second, didactic tools have been built that make it not just simple, but rather natural and inevitable to use entropy as the thermal quantity with which to start the exposition. The outcome is a course that is both fundamental and geared toward applications in engineering and the sciences.

In continuum physics an intuitive and unified view of physical processes has evolved: That it is the flow and the balance of certain physical quantities such as mass, momentum, and entropy which govern all interactions. The fundamental laws of balance must be accompanied by proper constitutive relations for the fluxes and other variables. Together, these laws make it possible to describe continuous processes occurring in space and time. The image developed here lends itself to a presentation of introductory material simple enough for the beginner while providing the foundations upon which advanced courses may be built in a straightforward manner. Entropy is understood as the everyday concept of heat, a concept that can be turned into a physical quantity comparable to electrical charge or momentum. With the recognition that heat (entropy) can be created, the law of balance of heat, i.e., the most general form of the second law of thermodynamics, is at the fingertips of the student.

The book contains two lines of development which you can either combine (by reading the chapters in the sequence presented) or read separately. In addition to the four chapters which represent the main line, you will find a Prologue, an Interlude, and an Epilogue which discuss some subjects at a somewhat higher level.

The four chapters that form the main body of the text grew out of my experience in teaching thermodynamics as a part of introductory physics, but represent an extension both in content and level of what I commonly include in those courses. The extension mostly concerns subject matter treated in courses on engineering thermodynamics and heat transfer and applications to solar energy engineering. Still, the chapters maintain the style of a first introduction to the subject. Previous knowledge of thermal physics is not required, but you should be familiar with basic electricity, mechanics, and chemistry, as they are taught in introductory college courses. With the exception of one or two subjects, only a modest amount of calculus is used. Chapter 1 provides an introduction to basic quantities, concepts, and laws. Entropy is introduced as the quantity which is responsible for making bodies warm or for letting ice melt, and the law of balance of entropy is formulated directly on the basis of ideas taken from everyday images of heat. The relation between currents of heat (entropy) and currents of energy is motivated along the lines of Carnot's theory of heat engines, yielding a law which makes the development of thermodynamics rather simple. (The relation is proved later on the basis of some alternative assumptions in the Interlude.) Then, some simple applications which do not rely too heavily upon particular constitutive relations are developed. First among them is a treatment of irreversibility and the loss of power in thermal engines, a subject which teaches us about the importance of the rule of minimal production of heat. Chapters 2, 3, and 4 furnish introductions to constitutive theories. The first of these deals with uniform bodies, which respond to heating by changing mechanical or other variables. A simple version of the constitutive theory of the ideal gas is developed, which leads to a theory of the thermodynamics of ideal fluids. In addition, blackbody radiation and magnetic bodies are treated. A short exposition of the concepts of thermostatics exposes the reader to the difference between dynamics and statics in the field of thermal physics. Chapter 3 deals with theories of heat transfer excluding convection. The general form of the equation of balance of entropy for bodies and control systems is given and applied to various cases. Production rates of heat in conduction and radiation are calculated and applied, among others, to the computation of the maximum power of solar thermal engines. In this chapter, continuous processes are treated for the first time in the context of one-dimensional conduction of heat. The radiation field and the issue of the entropy of radiation are discussed extensively, and a section on solar radiation concludes this Chapter. Chapter 4 extends the theory of heat to processes involving the change and the transport of substances. Subjects such as chemical reactions, phase changes, and convection, and applications to power engineering and to heat exchangers form the body of this Chapter. All of these Chapters include a large number of solved examples in the text.

The second track of the book treats thermodynamics in a more advanced and formal manner. The Prologue provides a brief view of a unified approach to classical physics. Except for the first section, which you definitely should read before starting with Chapters 1 – 4, the Prologue presents several subjects of physics at a relatively quick pace, demonstrating the unified approach to dynamical processes which forms the backbone of the entire book. (The concepts are introduced at a more leisurely pace in the main chapters on thermodynamics.) If you wish, you can then try to read the Interlude which introduces the subject of the thermodynamics of uniform fluids on the basis of the caloric theory of heat. This Chapter repeats the subject of part of Chapter 1 and most of Chapter 2 at a higher mathematical level. In contrast to those chapters, the Interlude also provides a first proof of the relation between currents of entropy and of energy, which shows that the ideal gas temperature can be taken as the thermal potential. Finally, the Epilogue takes the first simple steps into the field of continuum thermodynamics, exposing you to the ideas behind the more advanced subjects which have been the focus of development over the last few decades.

If I seem to succeed in introducing you to an exciting new view of a classical subject, the individuals actually responsible for this achievement are the researchers who have developed this field. Carnot, who gave us an image of how heat works in engines, a view which I have taken as the starting point of my exposition. Gibbs demonstrated how to deal with chemical change and heat. Planck's theory of heat radiation still is one of the clearest expositions of the thermodynamics of radiation. Also, there are the researchers who have built continuum thermodynamics, mainly since the 1960s and who have contributed so much toward clarifying the foundations of the dynamics of heat. They deserve our respect for one of the most fascinating intellectual endeavors.

When it comes to applications we nowadays can turn to computational tools which can make life so much easier. Two such tools which I have used deserve to be mentioned—the system dynamics program Stella (High Performance Systems, Inc., Hanover, New

Hampshire), and the program EES (Engineering Equation Solver; Klein, 1991) which provides for extensive thermophysical functions in addition to a solver for nonlinear equations and initial value problems. Also, in the fields of engineering applications, including solar engineering, I have been inspired by such excellent textbooks as those of Bejan (1988), Moran and Shapiro (1992), Rabl (1985), and Duffie and Beckman (1991).

I am grateful to all my friends, colleagues, and teachers who, through their encouragement and support, have contributed toward the writing of this book. Robert Resnick and Roland Lichtenstein of RPI gave me the courage to take up the project. Walter Cohen, Werner Maurer, and Martin Simon read the book and gave me valuable feedback. Heinz Juzi, Heinz Winzeler, and Klaus Wüthrich helped me with discussions of applications, and many more colleagues gave me kind words of encouragement. Most important, however, has been Werner Maurer's friendship and professional companionship in this endeavor. He and I developed the system dynamics approach to the teaching of physics which you will find in this book.

I would like to acknowledge generous grants made available by the Federal Government of Switzerland and my school, which allowed for the development of labs and courses dealing with renewable energy sources, and I would like to thank my thesis students whose work in solar energy engineering has led to many interesting applications included here.

Finally, let me express my gratitude toward all those at Springer-Verlag, who have made the production of the book possible. Thomas von Foerster, Frank Ganz, and Margaret Marynowski turned the manuscript of an amateur madly hacking away on a Macintosh into a professional product. They were very supportive and encouraging, always with an open mind for my wishes.

This has been a long journey. My wife and my daughter have gone through it with me all the way. I would like to thank them for their love and their patience. When my daughter was very little, she asked me if I would dedicate this book to her. I hope it has been worth waiting for.

Honolulu, 1995 *Hans Fuchs*

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