Graduate Texts in Physics

Hans U. Fuchs

The Dynamics of Heat

A Unified Approach to Thermodynamics and Heat Transfer

Second Edition

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GRADUATE TEXTS IN PHYSICS

Graduate Texts in Physics publishes core learning/teaching material for graduate- and advanced-level undergraduate courses on topics of current and emerging fields within physics, both pure and applied. These textbooks serve students at the MS- or PhD-level and their instructors as comprehensive sources of principles, definitions, derivations, experiments and applications (as relevant) for their mastery and teaching, respectively. International in scope and relevance, the textbooks correspond to course syllabi sufficiently to serve as required reading. Their didactic style, comprehensiveness and coverage of fundamental material also make them suitable as introductions or references for scientists entering, or requiring timely knowledge of, a research field.

To Robin and Kristin

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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by Hans U. Fuchs

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INTRODUCTION

FROM METAPHORS TO MODELS OF HEAT

This book is as much about how people understand thermal and other physical processes as it is about thermodynamics itself. Since the approach chosen here to describe and model thermal phenomena probes the roots of imagination and understanding, a few words about human conceptualizations of natural processes might be in place. This should allow me to set the stage for a theory of the *Dynamics of Heat*.

Even though this chapter is called *Introduction*, the material covered is not introductory. I just want to get some philosophy, cognitive science, continuum physics, history, and modeling theory out of the way before starting on the science of heat. You may prefer to start with Chapter 1—or Chapter 4 if you are familiar with the physics of dynamical systems—and come back to these lines at a later time. After you have tried your hand at a dynamical theory of heat, you will be prepared to tell whether or not you agree with my rationale for the conceptualization of thermal phenomena.

I.1 SOME CONCEPTUAL CHALLENGES

Traditional courses treat thermodynamics in a form unlike anything else known in physics. In particular, we are told that it is a theory of the equilibrium of heat and not of how and how fast things happen in real life. This combines with the conceptualization of heat as energy (or a form of energy) and thermal processes as the result of the motion of little particles. The result is a theory that uses strange d's in its equations, does not produce initial value problems as we know them from the rest of physics, and introduces concepts such as exergy, enthalpy, free energy, and Gibbs free energy, we are hard put to distinguish from energy and entropy and from each other.[1]

How did we arrive at such a representation of thermal phenomena? We know that two to three hundred years ago scientists thought of heat as a kind of subtle fluid that goes

1. Here's a gem from the Internet: "Entropy is never enthalpy, nor free energy. A system's enthalpy is only entropy change (after DH is divided by T) if it is transferred to the surroundings and no work of any sort is done there in the surroundings. A surroundings' enthalpy is only entropy change (after DH being divided by T) when it is transferred to the system and no work is then performed in the system. Gibbs free energy change, DG, is only considered entropy change (after being divided by T) when no useful work of any kind is done by the heat transfer in the system or in the surroundings." (www.2ndlaw.com/gibbs.html; visited on February 15, 2007.)

H.U. Fuchs, *The Dynamics of Heat: A Unified Approach to Thermodynamics and Heat Transfer*, Graduate Texts in Physics, DOI 10.1007/978-1-4419-7604-8_1,

into bodies to warm them or to cause other changes. The concept is called the *caloric theory of heat.* Around 1820, Sadi Carnot (Carnot, 1824) used this conceptualization to create a theory of heat engines (see Section I.3). In his view, caloric passes from a hot to a cold body without being consumed, thereby producing "motive power." This is like water falling from a higher to a lower point driving a water wheel.

His theory met with some problems. On the one hand, it appears that unlimited quantities of heat can be produced in irreversible processes such as rubbing or burning, whereas the caloric theory of heat assumed that caloric was conserved and could not be produced or destroyed (Fox, 1971). On the other hand, and possibly more important from a formal point of view, Carnot's model predicted that the heat capacities of a simple gas should be inversely proportional to its temperature. This contradicted the result based on a view of heat as the energy of the irregular motion of little particles of the gas. In this model, the capacities of a perfect gas should be constant, independent of temperature.[2]

Rudolf Clausius (1850) solved the problems encountered in Carnot's theory by using the idea of the conversion of heat to work. Some of the heat passing from the furnace of a heat engine to the cooler is "converted" to work—only the rest is passed on to the cooler. So heat and work are interconvertible (in some sense), and since work is a form of energy, so must heat be. Clausius proved the existence of an energy function of fluids which made the First Law a result that went beyond the concept of energy as a mere integral of motion. Heat no longer could be visualized as this thermal fluid responsible for making stones warm, or for expanding air, or for melting ice. In Clausius' theory, both problems of Carnot's model were solved. Heat was not produced in irreversible processes but converted from work, and the "heat capacities" of a simple gas turned out to be constant.

This is the theory that brought us the funny d's, the supremacy of equilibrium over dynamics,[3] and concepts everybody confesses cannot be understood but can only be dealt with in mathematical formalisms. Specifically, standard every-day reasoning about a quantity of heat residing in bodies and flowing into and out of these bodies, does not apply in Clausius' *mechanical theory of heat.* The theory does not provide for a quantity of heat except for the case of a quantity of energy transferred as a result of heating or cooling. Any other use of the word *heat* is forbidden.[4]

From a conceptual and emotional viewpoint, we have paid dearly for the new theory of heat. We know of the problems this conceptualization of thermal processes creates for learners, and everyone else for that matter. Every teacher of physics knows this, and years of research into conceptual difficulties learners encounter with the science of heat have confirmed this. What normal person should be able to understand that the heat that was just transferred into a room by heating is not to be found in the room?

2. As Rudolf Clausius put it, "[...] other facts have lately become known which support the view that heat is not a substance but consists in a motion of the least parts of bodies." (Clausius, 1850). See Truesdell (1980) for a discussion of the case of heat capacities.
3. "The single, all-encompassing problem of thermodynamics is the determination of the equilibrium state that eventually results after the removal of internal constraints in a closed, composite system." (Callen, 1985, p.26). Try to say this about mechanics, or electricity, or fluids.
4. It has even been suggested to exorcise the word heat from thermodynamics altogether. See Romer (2001): "Heat is not a noun."

Instead of simple conceptual explanations, we are offered words of wisdom concerning the beauty and mystery of entropy—pop philosophy in place of hard science based on how humans conceptualize natural processes (see Section I.2).

We should not and could not criticize traditional thermodynamics just for being arcane and difficult to comprehend if the theory were the only possible one, and if it delivered a fair description of the real world of dynamical thermal phenomena. It is not, and it does not. We know that in a theory of the equilibrium of heat, there are no evolution equations to be formulated and solved—there is no equation analogous to Newton's equation of motion, or to the balance of charge in electric systems. Engines do not run, they operate infinitely slowly. Irreversible processes are recognized but not quantified. And quite importantly, thermodynamics is said to be wholly different from the science of heat transfer.[5] Generations of engineering students have had to take two separate courses, one on thermodynamics, the other on heat transfer, and in each they learned that one field has nothing to do with the other.

So we have two challenges: How to create a complete and unified theory of the dynamics of heat, and how to make it conceptually accessible from the start. The first is being addressed more and more frequently. Indeed, we basically have this theory in the form of continuum physics. There is a forerunner—irreversible thermodynamics—and there are the modern theories in the form of rational thermodynamics (Truesdell, 1984) and extended thermodynamics (Müller, 1985, Jou et al., 1996; Müller and Ruggeri, 1998). And we have many fascinating examples of the application of finite time thermodynamics and thermal optimization in engineering thermodynamics (Bejan, 1988; Sieniutycz and DeVos, 2000).

The second challenge was dealt with early on by Callendar (1911) and again by Job (1972) who pointed out that Carnot's conceptualization can serve us well in creating an accessible representation of thermal phenomena. Caloric—freed from the requirement of conservation—turns into the latter-day *entropy*. The theme was followed up in physics education research and has led to introductory courses based on a unified approach to physical processes that use entropy from the beginning (Falk and Ruppel, 1976; Schmid, 1982, 1984; Herrmann and Schmid, 1983; Fuchs, 1986, 1987a-c, 1996, 1997a,b, 1998; Burckhadt, 1987; Maurer, 1996; Herrmann, 2000, 1998–2010; Borer et al., 2005; Fuchs et al., 2001–2010).[6] Most importantly, in my view, these developments have demonstrated the validity of strong analogical reasoning that allows us to create new and unified representations of well known phenomena.

In the first edition of this book, I produced a uniform systems version of thermodynamics by combining continuum physics with what we had learned from our didactic research:

> Examining the flow of heat in this way makes it clear that the entropy is the fundamental property that is transported in thermal processes (what in lay terms would be

5. "At this point it is appropriate to note the fundamental difference between heat transfer and thermodynamics. [...] Thermodynamics is concerned with equilibrium states [...] heat transfer is inherently a nonequilibrium process [...] heat transfer therefore seeks to do what thermodynamics is inherently unable to do [...]." (Incropera and DeWitt, 1996, p.12).
6. An analogous development is taking place in chemistry didactics where the chemical potential is given center stage (Job, 2004; Job and Rüffler, 2011; see also Chapter 4 of the first edition of *The Dynamics of Heat*, 1996).

> called "heat"), and that the temperature is the corresponding potential. The resulting theory of the creation, flow, and balance of entropy provides the foundation of a truly dynamical theory of heat that unites thermodynamics and heat transfer into a single subject. (Tom von Foerster, from the back cover of the first edition of *The Dynamics of Heat*, 1996.)

We now know how to formulate ordinary differential equations for initial value problems in thermodynamics in simple yet practical applications accessible to the beginner in high school or at university.

Clearly, the two challenges are related. Without a conceptual structure similar to the one that gives us theories of dynamics in fluids, electricity, or motion, we cannot simply come up with a dynamics of heat. Let me therefore discuss some recent investigations into every-day conceptualizations of physical processes that demonstrate how our imagination produces useful concepts for a formal science.

I.2 COGNITIVE STUDIES OF CONCEPTUALIZATIONS OF PROCESSES

Not so long ago I was told the following story (Sassi, 2006). Little Alex came home from kindergarten. He told his grandmother that the teacher had said they should close the door if they did not want cold to come in. Now his grandmother asked Alex what cold was. He said that cold was a snowman. A snowman was very cold and if he hugged Alex, the boy would also get cold and might get sick. Alex and his grandmother were outside and decided to build a snowman. When his grandmother wanted to build a big one, Alex said that a big snowman would be so cold it could even kill young Alex. He thought it would be better to build a small snowman. Finally, his grandmother wanted to know what he thought heat was. Alex said, heat was a dragon. He could play with little dragons, they were not so hot and dangerous, but a really big dragon would be so hot and strong, its fire could kill the boy.

Now compare this to the description of the concept of heat by the experimenters of the Accademia del Cimento in 1667 who tried to determine the power of heat and cold. According to Wiser and Carey (1983), their concept included the aspects of "substance (particles), quality (hotness), and force." These elements are found in Alex' story as well—size, coldness or hotness, and the power to harm the boy. Now turn your attention to a completely different phenomenon such as justice. If you apply methods developed in linguistics to how we speak about this concept, you will find a closely related structure, an *experiential gestalt* having aspects of quantity ("Let justice flow like water," Martin Luther King), quality or intensity ("He has a horrid history and deserves strong justice"), and power ("The healing power of justice").

These are examples of an understanding of processes which appears in many areas of human experience. My knowledge of the structure of classical physics suggested to me that certain imaginative structures must be recurring in the conceptualization of phenomena. I found background material on schematic structures of human understanding in modern cognitive science and linguistics (Arnheim, 1969; Lakoff and Johnson, 1980, 1999; Johnson, 1987, 2007; Lakoff, 1987; Talmy, 2000a,b; Hampe, 2005). In short, physics, cognitive science, Alex' story, and many examples of how people speak about processes led me to identify what I now call *force dynamic gestalts* (Fuchs, 2007). The human mind seems to generate these perceptual gestalts that have at least the following three aspects: *quantity* (size), *intensity* (quality), and *force* or *power* (the latter stand for forms of causation). The aspects are rooted in image schemas (such as fluid substance, scale and verticality, direct manipulation, and others) that are projected metaphorically[7] onto the particular phenomenon under consideration. For example, verticality is projected onto the concepts of brightness, temperature, or pressure (brightness goes up, temperature is low, etc.) which are created from polar schemas of light and dark, hot and cold, strong and weak.

There are additional schemas related to force dynamic gestalts: balance (or equilibrium), letting, forcing, hindering, preventing, etc. In short, conceptual structures identified in cognitive semantics for a wide range of fields of human interest also apply to the basic conceptualization of natural phenomena such as heat, fluids, electricity, motion, or chemical change.

Clearly, quantity (size), intensity, and power are intertwined in Alex' description of the properties of snowmen and dragons. When I saw that we create the same gestalt in conceptualizing phenomena such as justice or pain, market or information, I became convinced that Alex' story was more than just an offspring of an unchecked imagination of a little boy, an imagination that has to be reigned in later in life if the child is to succeed in school. It testifies to a structure of figurative thought that is foundational to human understanding of nature. In terms of modern cognitive science, what we see here is an experiential gestalt whose aspects are structured through metaphoric projections of just a few image schemas. Since the same gestalt is constructed for different phenomena such as fluids, electricity, heat, and motion, these fields become similar to each other in our mind, which allows us to apply analogical reasoning—understand one field in terms of the structures of another.

Does this mean that anyone can come up with formal descriptions of thermal or other physical processes effortlessly? Not quite. Children and laypersons do not commonly distinguish between the quantity and the intensity of heat, nor is it easy for us to see the difference between intensity and power, or quantity and power.[8] An investigation of the metaphoric base of the gestalt of heat shows that its aspects are not easily kept apart in common sense reasoning.[9] Therefore, one of the most important goals of education must be the differentiation of these aspects in the course of education.

What I have outlined here shows that common-sense conceptions of nature may be

7. Simply put, a metaphor is a device of figurative thought in which knowledge of a source domain is projected onto a target domain. In cognitive science, metaphors are no longer considered just embellishments of language or a rhetorical device. They are given conceptual status, reflecting figurative structures of thought (Lakoff and Johnson, 1980; Koevecses, 2000; Evans and Green, 2006). It is important to distinguish between a linguistic metaphorical expression ("heat escapes the room") and the actual underlying metaphor HEAT IS A FLUID SUBSTANCE. Note that the metaphors I am mentioning here are of a simple, foundational nature (in fact, they are part of conventional language which does not easily let us recognize them as such). These structures are more important to me in the present context than the more obvious metaphors such as THE ATOM IS A SOLAR SYSTEM or A CELL IS A FACTORY. I believe that science is metaphorical at its base, not just at the surface where we try to make a person understand a complex subject by representing it with the help of vivid language and comparisons.

8. Clausius does not distinguish between the quantity and the power of heat. Trying to fool the human mind exacts its price—entropy comes in through the back door and takes its revenge (Fuchs, 1986).

9. For example, we connect quantity and intensity (verticality) in the metaphor MORE IS UP.