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.

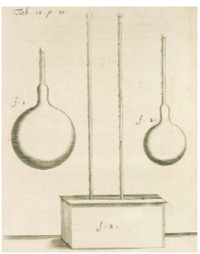
8. Clausius does not distinguish between the quantity and the power of heat. Trying to fool the human mind exacts its price—entropy comes in through the back door and takes its revenge (Fuchs, 1986).

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

much more useful than has been realized up until now. Let us see how these figurative structures of thought made their appearance in the course of the early history of thermal phenomena and thermal physics.

I.3 FROM THE ACCADEMIA DEL CIMENTO TO SADI CARNOT

In 17th century Florence, a group of experimenters who called themselves the Accademia del Cimento studied thermal and other processes (Magalotti, 1666). They reported on their experiments many of which were designed to investigate the power of cold (and heat). They stuck a bulb with a long neck (called the *Vessel*) filled with water or other liquids to be frozen, into a box with ice and salt (Fig. I.1). Then they placed a second such bulb containing alcohol in the ice; this device was their *Thermometer*. They observed the levels of the liquids in the Thermometer and in the Vessel while measuring how long certain steps such as *Rise upon Immersion*, *Abatement*, *Rest*, etc. took and reported the results (Fig. I.1): Degrees of Vessel, Difference, Degrees of Thermometer, Difference, Vibrations (of the clock), and Difference. Basically, they measured the speed at which processes were running.



	The Deg. of the Veſſel.	Differ.	Deg. of Therm.	Differ.	Vibrat.	Diff.
State Natural	142		139			
Riſe upon Immer.	143½	1½	133	6	23	23
Abatement.	120	23½	69	64	255	232
Reſt.	120		49	20	330	75
Remounting.	130	10	33	16	462	132
Spring upon Glaciat.	166	36	33			

Figure I.1: Experimental arrangement set up by members of the Accademia del Cimento to measure the power of cold (left). A table with results of their measurements (right).

To the modern observer, this looks and sounds rather strange. The reason for this is not just that they put the thermometer side by side with the probe in the ice to measure the temperature of the freezing water, but also because of something we don't do any longer (or rather have not done for a long time): we do not use a clock to time such phenomena. Speed is of no importance to us in traditional thermodynamics.

I do not want to say that the Experimenters had anything resembling a theory of thermal processes.[10] What is interesting is their language combined with their actions. As mentioned above, a cognitive scientist might say that they made use of the force dynamic gestalt of heat, and they searched for the power of cold or heat in the dynamics of the processes. They did not carefully distinguish between the separate aspects of this gestalt—learning how to do this was going to take another 150 years.

In the years leading up to Sadi Carnot's and his contemporaries' work, quantities of heat were finally distinguished from the measure of hotness. Joseph Black is credited with making this distinction clear by introducing the concepts of latent and specific heats. The concepts were created on the foundation of the caloric theory of heat.

By the time Carnot created his theory of heat engines, some of the fog was clearing,

10. For a criticism of their work in the light of traditional thermodynamics, see Wiser and Carey (1983).

and formal mathematical models dealing with examples of thermal processes had been produced (see Truesdell, 1980). Among these were a theory of heat conduction and a model of adiabatic processes in gases which was used to explain the observed speed of sound. Again, all of these achievements were based on the assumption that heat was some kind of imponderable fluid.[11]

Understanding of heat engines was still limited, so Carnot proposed to answer questions regarding the *Motive Power of Fire, and Machines Fitted to Develop that Power* (this is a paraphrase of the title of his book). To quote Carnot (1824, p. 3, 6):

> Every one knows that heat can produce motion. That it possesses vast motive-power no one can doubt, in these days when the steam-engine is everywhere so well known.
>
> To heat also are due the vast movements which take place on the earth. It causes the agitations of the atmosphere, the ascension of clouds, the fall of rain and of meteors, the currents of water which channel the surface of the globe, and of which man has thus far employed but a small portion. Even earthquakes and volcanic eruptions are the result of heat.
>
> The phenomenon of the production of motion by heat has not been considered from a sufficiently general point of view. […] A [complete] theory is evidently needed for heat engines. We shall have it only when the laws of physics shall be extended enough, generalized enough, to make known beforehand all the effects of heat acting in a determined manner on any body.

Since Carnot's time, it has become evident that the action of heat can effect more than just motion. Heat drives many other processes, such as electric and chemical ones. We take these phenomena as a sign of the interrelation between different classes of physical processes.

Heat can be used to do things; it can drive engines; it is an agent for effecting things. In other words, heat can do work. Does this mean that heat is some sort of work? The answer should be "no." Water can also be used to drive water wheels and turbines. Does this make water some sort of work? Certainly not. Similarly, electricity, i.e., electric charge, can be used to do work, but it is not work.

The gestalt with its aspects of quantity, intensity, and power must have been present in Carnot's mind. Carnot created a vivid image of the *Power of Heat* by using waterfalls as an analogy for the operation of heat engines. Doing so, he produced the basis of a formal differentiation of the aspects of the gestalt (Carnot, 1824, p. 15):

> According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a fall of water … . The motive power of a fall of water depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what may be termed, on what in fact we will call, the *height of its fall*, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. In the fall of water the motive power is exactly proportional to the difference of level between the higher and lower reservoirs. In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference.

11. Truesdell showed that the assumption regarding the nature of heat is not necessary for the theory of adiabatic motion (Truesdell, 1980). However, the scientists who created it used the caloric theory.

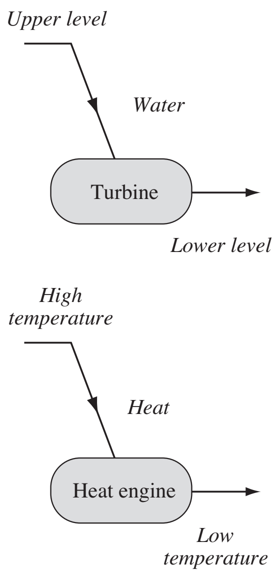


Figure I.2: Hydroelectric and thermal power plants are structurally comparable. Water drives a turbine by falling from a higher to a lower level. Heat drives a heat engine by "falling" from a higher to a lower thermal level.

Quantity, intensity, and power of heat are distinguished, and their relation is made formal—ready to be put in the form of an equation. Just as water falls from a high level to drive a turbine, after which it flows out of the engine at a lower level, heat is imagined to fall from a high temperature to a lower one, thereby driving the heat engine (Fig. I.2), and then flowing out at lower temperature. The principle of operation of heat engines is in accordance with this image. Steam takes up caloric (heat) from a burner, and passes through the engine where it effects motion, just to flow out again and to give up its heat (caloric) to a condenser. As Carnot put it (1824, p. 7):

> The steam is here only a means of transporting the caloric … . The production of motive power is then due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body.

We know today that we can indeed explain the motive power of heat in terms of these images. There is a deep similarity between different types of physical processes. Hydroelectric power plants and heat engines are two examples which serve to drive home this point (Fig. I.2).

Those of you who already know thermodynamics may have noticed that Carnot's heat or caloric can be reinterpreted as the modern-day entropy. We simply have to make sure that we allow for caloric to be produced in irreversible processes. For those of you new to thermal physics, do not let yourselves get confused by an arbitrary, artificial word created by Rudolf Clausius in the 1860s. For us, entropy is the child's heat, the layperson's heat substance, or better, Carnot's caloric—suitably extended by the assumption that it can be produced but not destroyed.

The similarity observed here is a result of the imaginative power of the human mind represented by force dynamic gestalts. There is a branch of physics which makes use of this conceptualization in a broad manner, namely, *continuum physics*. Let me briefly list the basic characteristics of this approach to the description of physical and chemical phenomena.

I.4 A UNIFIED APPROACH TO PHYSICAL PROCESSES

Everything flows. Water and air flow on the surface of the Earth, where they create the multitude of phenomena we know from everyday life. Winds can impart their motion to the water of the oceans, and in a far-away place, this motion can be picked up again through the action of the waves. These processes are maintained by the radiation pouring out from the surface of the sun; light flows from there through space, and some of it is intercepted and absorbed by our planet. Both in nature and in machines, heat is produced and transported from place to place. In electrical machines, we make electricity flow in an imitation of its flow in the atmosphere; in reactors, chemical substances flow while at the same time undergoing change. Today, we even see life as governed by flow processes.

The sum of these observations can lead us to one of the most general description of nature known today. There are a few physical quantities which can flow into and out of systems, which can be absorbed and emitted, and which can be produced and destroyed. Electrical charge is transported in electrical processes, and mass and substance flow in gravitational and chemical phenomena, respectively. In continuum mechanics, motion is seen as the exchange of linear and angular momentum. Thermal physics is the science of the transport and the production of entropy. One of the great advantages of this description of nature is that it relates the different phenomena, which leads to an economical and unified view of physical processes. It turns out that classical continuum physics is a precise method of expressing this point of view for macroscopic systems.

What is this unified approach to physics? First, we have to agree on which physical quantities we are going to use as the fundamental or *primitive* ones; on their basis other quantities are defined, and laws are expressed with their help. Second, there are the fundamental *laws of balance* of the quantities which are exchanged in processes, such as momentum, charge, or amount of substance; we call these quantities *fluidlike*.[12] Third, we need particular laws governing the behavior of, or distinguishing between, different bodies; these laws are called *constitutive relations*. Last but not least, we need a means of relating different types of physical phenomena. The tool which permits us to do this is energy. We use the *energy principle*, i.e., the law which expresses our belief that there is a conserved quantity which appears in all phenomena, and which has a particular relationship with each of the types of processes.[13]

The most basic constitutive relations result from the metaphoric interpretation of the intensive quantities associated with processes—speed with momentum, electric potential with charge, or temperature with entropy. These quantities are levels—remember, they are described as being high or low by virtue of the projection of the schema of verticality onto the polarity which is constructed by our perception. An intensity results from the containment of a fluidlike quantity in a system: Pressure goes up if more liquid or gas is put into a container. This we call a *capacitive relation*. Differences of intensities are conceptualized as *driving forces* of processes. So the electric potential difference serves as a driving force for the flow of charge through a conductor, and a chemical potential difference is visualized as the driving force for the diffusion of a substance through a material. Such relations we call *resistive characteristics*.

The notion of levels and level differences as driving forces is instrumental also for understanding the role of energy in physical processes. We simply relate the power of processes to driving forces and flows, as Carnot did. This is the starting point for my approach to the energy principle used throughout this book (Chapter 2).

12. Falk and Herrmann (1977-1982), who started a unified approach to high school and university physics in their didactic research, coined the term *substancelike*. I prefer *fluidlike* since we transfer the image of fluids into our formal descriptions of processes. The Merriam-Webster Online Dictionary defines *fluidlike* as a "substance (as a liquid or gas) tending to flow or conform to the outline of its container." This is not bad for our purpose. Momentum, charge, or entropy flow and fill space or materials in space. We have to add the notion that some of these quantities can be produced and/or destroyed.

13. This is slightly different from the standard approach in continuum physics (or continuum thermodynamics). Taking the usual approach of continuum mechanics, one formulates laws of balance of momentum, angular momentum, and mass, and complements this with the energy principle. Then constitutive relations are added. Thermal processes are treated as a somewhat different breed. One starts with the already known equations such as for momentum and energy, formulates constitutive laws for the thermal phenomena, and finally adds the law of balance of entropy as a special relation. This does not bring out the deep analogy between thermal and the other kinds of processes I am going to use as my starting point. I take the balance of entropy (the quantity of heat introduced above) as a basic relation alongside those for momentum, charge, or amount of substance. Energy is the special quantity in this approach.

Models are created from combinations of laws of balance and constitutive relations. Since we want to compare the predictions of our models with data from experiments, we need results for the most easily measured quantities such as speed, density, pressure, or temperature. This means that we have to solve for these quantities while eliminating the rest. The "undesirables" are mainly the fundamental fluidlike quantities—charge, momentum, entropy (our modern version of caloric). For example, to study the conduction of heat, one formulates the law of balance of entropy and adds constitutive laws for the storage, flow, and production of entropy. The constitutive laws introduce temperature. Then we eliminate entropy and obtain a *field equation* for temperature which we solve.

This is rather fascinating. We need speed, density, pressure, and temperature to relate our models to the world, and mostly we do not care much about the fluidlike quantities. Who cares about entropy, or momentum? We want to know how warm it is, and how fast a body moves. But we cannot create models, i.e., understand the world, without the help of the quantities which seem to be pure constructs of our imagination.

Continuum physics teaches us these important things about the structure and the role of models of processes. Fortunately, there is a strongly simplified version—a subset—of continuum theory from which we can learn about these things. This version is made up of the *uniform dynamical models* of physical processes—including thermal and chemical ones—which we are going to study for much of the first half of this book.

I.5 DYNAMICAL MODELS OF HEAT

So how do we construct dynamical models of thermal phenomena? Just as we do in (introductory) mechanics, or when we describe the charging or discharging of capacitors. To model a ball falling straight down in air, we formulate the law of balance of momentum for the ball. There are two momentum transports to consider: one due to gravity, the other resulting from friction between the ball an air. Then we express the momentum flows (the forces) by appropriate constitutive laws (force laws), and we formulate the relation between momentum and speed of the body. The constitutive relations introduce the speed of the body. We rearrange the equations so that we end up with an initial value problem for the speed of the ball which we then solve.

Let us transfer this method to thermodynamics. Consider the cooling of hot water in a thin walled can, placed in a room and stirred with the help of a magnetic stirrer. We formulate the law of balance of entropy (heat, caloric) for the body of water. The entropy changes because of cooling, i.e., because of the transport of entropy out of the water and into the room. Moreover, we have to take into consideration the production rate of entropy due to friction between the magnetic bar and water. Now we need constitutive laws for the temperature–entropy relation of water, an expression for the entropy flow from the hot water to the cold environment, and one for the production rate of entropy due to stirring.[14] The material laws introduce the temperature of the body

14. Here we use the energy principle to derive the missing expression. How much entropy is produced in an irreversible process depends upon the quantity of energy dissipated, and upon the temperature at which dissipation is taking place. In thermal design in engineering, it has become customary to express entropy production rates by combining laws of balance of entropy and of energy with appropriate constitutive laws (Bejan, 1988, 1996).

of water. The model has now been cast in the form of a set of differential and algebraic equations. They can be rearranged to yield a single initial value equation for the temperature of the water which we solve.

If it is so simple to produce dynamical models in thermodynamics, why is it not standard practice to do so in physics? The answer has to do with conceptualizations of processes and with basic philosophy of what a model is and what it can do. Here is an example of a problem that has vexed students of thermal physics. Consider a cold block of copper submerged in hot water. In a first step, we would write the laws of balance of entropy for water and copper, and introduce two temperatures, one for water, the other for copper. This means we imagine homogenous bodies having a certain entropy and a certain temperature, capable of absorbing or emitting entropy. Now the entropy flow is between the two bodies whose changes are being considered in the model. Since entropy transfer from a hot to a cold body is irreversible, we have to add an entropy production term to our equations. Moreover, the copper block should be considered an inhomogeneous body between whose parts entropy flows—and again entropy must be produced.

Upon closer inspection, this situation turns out to be anything but trivial from a conceptual viewpoint. I introduced a single temperature of a body as if it were normal for a physical system to have the same temperature throughout. Thermal processes cast a glaring light upon the problem of uniform situations. Normally, when heat (entropy) flows, temperatures change from point to point, which makes it necessary to set up a continuum theory of nature. So, where does this leave us with our desire to learn about thermal processes in the simplest possible settings?

I.5.1 A Continuously Variable World or Eternal Rest?

Objects and systems do not only change with time. Their properties also vary from point to point in space. The point masses of mechanics certainly are not an example of how things are in nature. The electrical capacitor which we describe in terms of a single value for its voltage or its electrical field does not even exist. While bodies move they also may deform, which can make them nonuniform. When air rushes into a vacuum such as in free expansion, we are confronted with a situation which makes it impossible to speak of *the* air pressure.

Thermal phenomena present us with more examples. Experience with the world around us demonstrates most clearly that uniform situations do not exist in general. The temperature never is the same at every point in a body. The Earth's atmosphere is far from a uniform state, and so are our homes and our bodies. When we heat a stone in the Sun or air in a cylinder, heat (entropy) will gradually spread through the system leaving parts closer to the heat source hotter than those further from it. Therefore, the description I just used seems to be utterly unrealistic.

We might think that it should be possible to select parts of bodies small enough for spatial uniformity to prevail to a significant degree. We could attempt to base our description of nature on such systems, from which we would build the world at large. However, this turns out to be impossible: changes of temperature from location to location are required if thermal processes are to take place at all. Heat does not flow without a temperature gradient, not even in the tiniest part of a body. Inevitably, this leads to the production of heat. Thermal processes are dissipative as a matter of fact, leaving us between a rock and a hard place.

You may object to this stark analysis and insist that situations exist in nature in which physical systems can be described as spatially homogeneous. Again, entropy tells the story. If we leave two bodies at different temperatures in contact for a long enough time, their hotnesses will eventually be the same. If we insulate the bodies from the environment we can even maintain this condition over a long period of time without significant change. The air which undergoes free expansion will settle down eventually, making the pressure and temperature uniform throughout. Here, you will say, are cases which we should be able to investigate successfully if we are looking for simple situations.

There only is one problem. The examples provided have nothing to do with *dynamics*. They are cases of eternal rest or, put more prosaically, of *equilibrium*. It seems we must choose between a dynamical world which is too difficult for us to describe, and a simpler, but less interesting, static one.

I.5.2 Uniform Heating in Thermal Superconductors

There must be a way out of this dilemma. After all, we construct theories of mechanical and electrical systems which we describe in simple ways using the notion of spatial uniformity. We calculate the behavior of electrical circuits by assuming them to be composed of discrete elements each of which can be modeled using a few physical variables assumed to have the same values at every point. We model the motion of bodies in the simplest terms, forgetting about spatial inhomogeneity. Ideal pendulums, for example, are points which swing at the end of massless strings through frictionless space. We are quite happy with such simple theories, and we do not let ourselves become unduly worried about the complexities of the real world. After all, the ideal models have an important story to tell despite their shortcomings.

Well, then, let us look for and construct a model of spatially uniform bodies which can undergo thermal processes. How could we conceive of *bodies which remain uniform while they are being heated or cooled*? Obviously we require the spatial variation of temperature in a body to vanish while heat is allowed to flow through it. Carnot imagined bodies which let heat pass easily. The situation he described in such simple words is no stranger to us in other fields of physics. In electricity, we build circuits using wires which "let electricity pass easily," and we do not blink an eye when we set their resistances equal to zero. In fact, we know of a perfectly modern phenomenon which lets us support the assumption of ideal wires, namely *superconductivity*. We simply take the wires as being *superconducting*: they let charge pass easily; the potential difference across their length is zero; and they do not produce any entropy.

What is the thermal equivalent of electrical superconductivity? It is a conductor where entropy does not require a temperature difference to spread from one point to another. Expressed differently, this is a material having zero thermal resistance. If we let the thermal resistance vanish while the flow of entropy is kept constant, the rate of production of entropy will go to zero as well. A body working according to this prescription may very well be said to be a *thermal superconductor*.

Other ways of heating bodies may lead us to the same conclusion, namely that it is not forbidden to construct models of uniform heating. Imagine many tiny electrical heaters distributed uniformly through a body of water emitting the entropy they create at an equal rate into every part of the body. Another form of evenly distributed sources of entropy is encountered in the absorption of radiation in an almost transparent body.

Radiation from the Sun is absorbed by a few cubic meters of air in our atmosphere at just about a uniform rate. In either case, we may model the actual process as one in which the temperature of the body remains uniform all the time.

I.5.3 Models and Truth

Are uniform processes realistic? It is important to realize that it does not matter whether such bodies and circumstances exist in nature precisely as I have described them. They certainly may exist as models in our theories. They are comparable to ideal wires and ideal pendulums. Just like these simple objects (which cannot be found in nature either), thermal superconductors and evenly spread sources of entropy are the building blocks of a theory of dynamics, this time of the dynamics of heat in uniform bodies. In fact, despite all the factors which we are ignoring, this model leads to important results: bodies undergoing uniform thermal processes approximate many real cases rather well. The idea of the change of a body through homogeneous states is an important ingredient of classical thermodynamics. All we have to do now is to investigate the consequences of such a far-reaching assumption.

Physics is not a science that creates words or concepts that have a direct, one-to-one relation with the world out there.[15] We have already seen that certain quantities such as momentum or entropy occupy a special place in the inventory of human concepts. They are absolutely necessary to talk about nature, to understand it, and to formulate models, but we do not really need their values as we need those of speed and temperature to compare our models with reality. We may very well wonder whether or not these quantities exist out there. Certainly, these concepts demonstrate how human imagination works. We imagine fluids and levels, and the force or power of phenomena. Armed with these schemas and their metaphorical projections, we create stories of how nature works. In science, we have learned how to make the stories formal, i.e., create mathematical models that can be simulated and whose results can be compared with data of phenomena observed in the real world.

I.6 AN OVERVIEW OF THE BOOK

I have divided the book into four parts. Part I discusses hydraulic, electric, and some mechanical processes with the goal of learning how to create simple system dynamics models. In Part II, I introduce thermal and chemical phenomena which will be modeled using the idea of uniform dynamical systems. These models will be formalized and extended to spatially continuous situations in Part III. Finally, in Part IV, a number of applications of thermal and chemical physics will be treated that require the more formal tools made available in Part III.

This book starts with fluid, electric, and rotational phenomena which are conceptualized as resulting from the storage and flow of fluids, electrical charge, and angular momentum (spin), respectively. Then we discuss a general theme: the role of energy in physical processes (Chapter 2). Finally, Chapter 3 extends the discussion to examples

15. David Hestenes and I have both discussed the question of the nature of models in the light of modern cognitive science and linguistics (Hestenes, 2006; Fuchs, 2006, 2007).

of translational motion; here, we deal with the transport and storage of momentum. There are several reason for having this part in a book on the dynamics of heat. If we want to model thermal dynamical processes in analogy to how this is done in other fields, we first have to get to know these fields from a systems perspective. Secondly, we need to understand energy in physical processes from a generalized and unified viewpoint. The traditional treatment of the energy principle is not exactly helpful in this respect. I will introduce process diagrams that visualize flows, potentials, power and energy currents, in single systems and in chains of systems. These diagrams can be used as tools in process design (Tyreus, 1999, gives an example in control engineering).

The next six chapters are devoted to an introductory exposition of dynamical thermal and chemical phenomena. With a few exceptions, I will limit the discussion to uniform models. Naturally, if we divide a system into enough uniform parts, we may still get very useful models—certainly good enough for many applications in the sciences, medicine, engineering, and ecology.

Chapter 4 introduces us to hotness, heat (entropy), and energy, and their relation, using simple systems such as water cooling in the environment, two bodies in thermal contact, or (thermoelectric) heat pumps and heat engines. These examples are well suited to the study of basic thermal concepts and for learning how to set up our first dynamical models. The treatment will be extended to substances undergoing phase changes, and to the dynamics of simple fluids such as the ideal gas and thermal radiation (Chapter 5).

Chemical processes—the transport and the reaction of substances—are intimately linked to thermal ones, so it is important to take a closer look at them. In Chapter 6, I will deal with diffusion, solutions, and simple reactions. Concepts—amount of substance and the chemical potential—will be motivated and dynamical models will be set up. Parts of this theme will be important when we take up the transport of heat in Chapters 7 and 8. Finally, in Chapter 9, entropy production minimization will be applied to some interesting examples. This is a particularly useful method of thermal design which leads to models of optimal processes in engineering and in nature.

Chapters 10–12 make up Part III. They detail the construction of a formal theory of the dynamics of heat for uniform and for spatially distributed phenomena. The latter lead to ideas and tools needed for continuum thermodynamics and radiative transfer.

The applications discussed in Part IV deal with conductive and coupled transports (Chapter 13), convective heat transfer (Chapter 14), and phase changes and mixtures and their application to engines and power engineering (Chapter 15). The last chapter describes solar radiation (Chapter 16). The chapters in this part develop more detailed constitutive theories than those encountered in Part II of the book.

Throughout the book, I will use the images and the language of continuum physics as the main tool—to me, continuum physics provides the best example of *images of change* that grow from the basic structures of figurative thought discussed in this Introduction. In this way, I hope to prepare the ground for the approach to thermodynamics which you will find here and in modern treatises of this subject that go beyond what I do here. I believe you will find it advantageous to draw comparisons between different fields of physics and make use of analogical reasoning as often as possible during your journey through thermodynamics.