Preface

Aim of the book. The aim of this book is to help students learn the basic ideas of heat and thermal physics from a simple, modern, and highly unified point of view.

The book is intended for students in any introductory calculus-based physics course. (Indeed, when teaching the introductory physics course at Berkeley, I routinely used the approach in this book to replace the traditional discussion of heat in texts like that of Haliday and Resnick.) The book should also be useful for other students, in chemistry or other fields, who need an introduction to the basic ideas thermodynamics and statistical physics. More generally, this introduction should help all students to be well-prepared to study these subjects at greater depth in their later courses.

Prerequisites. The study of this book presupposes only the following prerequisites: (a) Some basic mathematical knowledge about logarithms and about very simple derivatives and integrals. (The appendices at the end of the book review this basic knowledge about logarithms and calculus.) (b) Some rudimentary knowledge about classical mechanics (i.e., about position and velocity, about kinetic and potential energy, and about the energy law).

Background motivating the book. I have written two previous textbooks dealing with heat, thermodynamics, and statistical mechanics. One of these[1], entitled "Fundamentals of Statistical and Thermal Physics" was intended for beginning graduate students. The other one[2], entitled "Statistical Physics", was volume 5 of the Berkeley Physics Course and, as such, was intended for very well-prepared students in an introductory physics course.

In later years, I came to realize that many of the basic ideas in these books could be presented more simply and clearly so that they could be readily accessible to beginning physics students who might not know any quantum physics. As already mentioned, I then began to teach these ideas as part of an ordinary introductory physics course. The present book is an outgrowth of this past work.

Approach

Fundamental ideas. The entire book is built on the following two basic ideas:

* All matter consists of atomic particles.
* The properties of macroscopic systems, consisting of very many atomic particles, can be understood on the basis of some simple probability considerations.

Emerging results. The elaboration of the preceding two fundamental ideas leads to the following main results:

* A good qualitative understanding of many macroscopically observable phenomena (e.g., the approach to equilibrium, irreversible behavior, heat flow, temperature, etc.).
* General quantitative conclusions about macroscopic systems. These conclusions (the laws of thermodynamics) are completely independent of any detailed knowledge of the atomic particles in these systems, but allow one to make useful inferences about their macroscopic properties.
* Determination of the properties of macroscopic systems in equilibrium since these properties can be derived from specific knowledge about their atomic constituents (e.g., ideal-gas laws, heat capacities of gases, etc.).
* Conclusions about the behavior of atomic particles (e.g., about the distribution of velocities of the molecules in a gas).

Advantages of approach. The preceding atomistic approach has the following advantages:

(1) The approach is highly unified. It explicitly relates the atomic and macroscopic points of view, and shows how they are complementary.

(2) It is more interesting and illuminating than traditional discussions that are largely macroscopic and don't connect macroscopic observables to underlying atomic processes.

(3) The approach is more modern since it builds on present-day knowledge of the atomic structure of matter and reflects more closely points of view prevalent in contemporary physics.

(4) If judiciously introduced, the atomistic approach is appreciably simpler than one restricted to macroscopic considerations. (a) It can build directly on basic ideas of energy familiar from mechanics. (b) It allows students to think of macroscopic phenomena in terms of concretely visualizable mechanisms. For example, internal energy is clearly associated with the motions and interactions of the atomic particles in a system; heat flow can be visualized in terms of energy transfers between neighboring atomic particles; entropy is a measure of atomic randomness and the properties of the entropy merely reflect the tendency of isolated systems to become more random. (c) By contrast, from a purely macroscopic point of view, concepts like internal energy, heat, and entropy are highly abstract and their significance is hard to grasp.

(5) The atomistic approach introduces some powerful and widely useful ideas. (a) It introduces very basic notions of probability, notions which are widely useful in statistics, in the analysis of experimental measurements, in quantum mechanics, and in other domains. (b) It derives the laws of thermodynamics in their full generality, but connects them clearly to underlying atomic mechanisms. Correspondingly, it also transcends the classical formulation of these laws by considering their statistical significance and the fluctuations occurring in equilibrium situations. (c) The atomistic approach thus introduces widely useful basic ideas that can be readily elaborated in more

advanced studies of thermodynamics, statistical mechanics, physical chemistry, and other fields.

(6) The approach adopted in this book is based on simple classical mechanics so as to make the approach accessible to beginning science students unfamiliar with quantum mechanics. The disadvantages of this, as compared to the more correct quantum-mechanical description, are minor and outweighed by the pedagogical advantages. (a) All the considerations are essentially the same in the classical or quantum descriptions. The only difference is that a basic atomic state, instead of being described classically in terms of position and velocity, is then just a quantum state. Correspondingly, most results derived classically are still true in a quantum-mechanical treatment. (The book is careful to point out discrepancies arising from the limitations of the classical approach.) (b) All the arguments in the book can be readily extended to a quantum-mechanical approach. Appendix § points out briefly how this can be done and the main resulting modifications. Of course, the present book makes no attempt to do this in detail, but does prepare students for more quantum-mechanical discussions in their later courses.

Guide to the topics in the book

Outline of topics. The following paragraphs outline briefly the topics discussed in the book. (More details are apparent from the table of contents.)

Chapter 1 examines the relation between macroscopic and atomic descriptions of macroscopic systems. Chapter 2 then discusses how the interaction between such systems can be separated into large-scale and atomic-scale interactions, both of which are macroscopically measurable. The result is the thermodynamic energy law (the first law of thermodynamics) which relates the change of a system's internal energy to macroscopic work and heat.

Chapter 3 shows how elementary probability notions, used in considering the atomic particles in macroscopic systems, can achieve simple statistical descriptions of such systems. Chapter 4 then explores qualitatively some important general implications — the existence of equilibrium situations and of fluctuations in equilibrium, the approach to equilibrium and irreversibility, and the definition of entropy as a useful measure of randomness.

The next three chapters deal more quantitatively with macroscopic systems interacting thermally without doing macroscopic work. Thus Chapter 5 shows how the thermal interaction between such systems leads to heat transfer as the systems approach equilibrium, and how such heat transfer is related to the absolute temperature. Chapter 6 then discusses ideal gases, predicts how the pressure of such a gas is related to its volume and absolute temperature, and applies the conclusions to the measurement of absolute temperature. Chapter 7 then discusses heat capacity and specific heats, and also makes some comments about heat transfer and thermal conductivity.

Chapter 8 extends the preceding considerations to situations where systems interact while also doing macroscopic work. This discussion yields all the basic properties of the entropy and all the laws of thermodynamics in their full generality.

Finally, Chapter 9 discusses some important applications of the preceding ideas — namely heat engines and refrigerators, phase transformations, the Boltzmann factor and velocity distribution of molecules in a gas.

The appendices review basic mathematical knowledge about logarithms and calculus. They also summarize compactly the basic laws of thermal physics and indicate how these are modified when quantum mechanics is taken into account.

Possible selections among the topics. Instructors and students may well be faced with limitations of time in studying the material in this book. (Indeed, only about five weeks or less may be devoted to thermal physics in a typical introductory physics course.) The following comments indicate, therefore, what topics might possibly be omitted if time constraints are sufficiently severe.

Since Chapters 1 through 6 contain the essential core of the book, nothing in these chapters can readily be omitted.

Chapter 7 could be omitted, although its Sections A, B, and C (dealing with heat capacity) are quite basic.

In Chapter 8, Sections A and C are needed for anyone wanting to become familiar with the laws of thermodynamics. However, Section B could readily be omitted.

Chapter 9 deals entirely with applications. This chapter could be omitted, although Section A (dealing with heat engines) is particularly important.

Pedagogical design

Problems for active learning. If students are to acquire usable knowledge, they must be actively involved in their own learning. The pedagogical design of the book is, therefore, similar to that of my previous textbook on basic mechanics[3], i.e., every section of the book is followed by problems which students should work through *immediately after* studying the section. These problems are mostly rather simple, aiming merely to assess whether students have actually understood what they have just studied and can interpret it appropriately. Only the problems at the end of the summary sections are sometimes more complex and comprehensive.

Hints and answers. Problems are accompanied by numbers (like <*h-5*> or <*a-8*>) which refer, respectively, to hints or answers listed at the back of the book. To ensure effective learning, students should refer to a hint only if this is really necessary, and should refer to an answer only *after* they have tried to answer a question as well as possible. (Hints and answers are listed in random order to help ensure that they are not read without deliberate intent.)

Some hints or answers, indicated by crossed-out numbers like ~~<*h-7*>~~ or ~~<*a-9*>~~, are *not* listed at the back of the book (although they may be available to instructors). Students are thereby given the opportunity to assess their ability to work independently under conditions more closely similar to those encountered in real life or on examinations. Furthermore, they should then have greater incentives to engage in discussions with their fellow students or with instructors.

Notational conventions. The chapters in the book are sequentially numbered 1, 2, 3, ..., and each chapter is subdivided into sections labeled A, B, C, ... Equations, statements, and figures are numbered according to the section in which they appear. For example, a reference to (B-7) refers to equation 7 in Section B of the *current* chapter. A reference to an item in *another* chapter includes also the chapter number; for example, (4B-7) refers to equation 7 in Section B of Chapter 4.

Important results are highlighted by being boxed. (The abbreviation *Def.* before such a box indicates an important definition.) Subsidiary material of lesser importance is shown indented.

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(1) Reif, F. (1965). Fundamentals of statistical and thermal physics. New York: McGraw-Hill.
(2) Reif, F. (1967). Statistical Physics (Berkeley Physics Course, volume 5). New York: McGraw-Hill.
(3) Reif, F. (1995) Understanding basic mechanics (Text and Workbook). New York, NY: John Wiley & Sons.