FUNDAMENTAL UNIVERSITY PHYSICS 2nd Edition

VOLUME ONE
MECHANICS AND THERMODYNAMICS

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PREFACE TO THE SECOND EDITION

Physics is a fundamental science that has a profound influence on all other sciences. Since this is so, not only physics majors and engineering students, but anyone who plans a career in science (including students majoring in biology, chemistry and mathematics), must have a thorough understanding of the fundamental ideas of physics.

The primary purpose of a general physics course (and perhaps the only reason it is allowed a place in the curriculum) is to give the student a unified view of physics. This should be done without bringing in too many details. A unified view of physics is attained by analyzing the basic principles, developing their implications, and discussing their limitations. The student will learn specific applications of the basic principles in the more specialized courses that follow. Consequently, this text presents what we believe are the fundamental ideas that constitute the core of today's physics. We have given careful consideration to the recommendations and suggestions of previous users of the text and the International Advisory Board of Editors in selecting the subject matter and the order and method of its presentation.

In many courses physics is taught as if it were a conglomeration of several sciences, more or less related, but without any real unifying view. The traditional division of physics into (the "science" of) mechanics, heat and kinetic theory, sound, optics, electricity and magnetism, and modern physics no longer has any justification. We have departed from this traditional approach. Instead, we follow a logical and unified presentation, emphasizing the conservation principles, the concepts of fields and waves, and the atomic view of matter. The special theory of relativity is used extensively throughout the text as one of the guiding principles that must be met by any physical theory. Many ideas of quantum physics are introduced rather early.

For convenience, the text appears in three volumes and the subject matter has been divided into five parts (1) Mechanics, (2) Interactions and Fields, (3) Waves, (4) Quantum Physics, (5) Statistical Physics.

In Volume I we present mechanics in order to establish the fundamental principles needed to describe the motions we observe around us. Included in this volume, in order to adapt to the requirements of many schools, we have incorporated an elementary introduction to thermodynamics and statistical mechanics.

All phenomena in nature are the result of interactions, and interactions are analyzed in terms of fields. Part 2, in Volume II, considers not only those kinds of interactions we understand best (the gravitational and electromagnetic interactions, which are the interactions responsible for most of the macroscopic phenomena we observe), but also includes a discussion of the nuclear interaction. For the sake of convenience, the discussion of the gravitational interaction has been placed in Volume I, in Volume II we discuss electromagnetism in considerable detail, concluding with the formulation of Maxwell's equations. Part 3, which deals with wave phenomena as a consequence of the field concept, is also included in Volume II. It is here that we have included much of the material usually covered under the headings of acoustics and optics. The emphasis, however, has been placed on electromagnetic waves as a natural extension of Maxwell's equations. Part 3 and Volume II conclude with a discussion of Matter Waves as an introduction to the mathematical formulation of quantum mechanics. Thus, Volumes I and II cover the usual material in most introductory general physics courses.

Volume III includes the final two Parts of the text. In Part 4 we analyze the structure of matter—that is, atoms, molecules, nuclei and fundamental particles—an analysis preceded by the necessary background in quantum mechanics. This part constitutes an elementary introduction to the quantum theory of matter. Finally, in Part 5 we talk about the properties of matter in bulk. The principles of statistical mechanics are first presented and then applied to some simple, but fundamental, cases. We discuss thermodynamics from the point of view of statistical mechanics. Part 5 concludes with a study of the thermal properties of matter which explains how the principles of statistical mechanics and thermodynamics may be applied. Therefore, Volume III covers the subject matter included in most introductory Modern Physics courses, with the advantage that it constitutes a logical extension of Volumes I and II.

This text differs from standard university-level physics texts not only in its approach, but also in its content. We have included a number of fundamental topics not found in many books and we have deleted other topics that are traditional. The level of mathematics used in the text assumes that the student has had a minimal introduction to calculus and is currently enrolled in the introductory course of that subject. Also, it is highly desirable that the student have had a physics course in high school. Many applications of fundamental principles, as well as a few more advanced topics, appear in the form of worked-out examples; these may be discussed at the instructor's convenience or proposed to individual students on a selective basis. The material in the examples thus allows for flexibility in designing the course in accordance with both the wishes of the instructor and the background of the students. The problems at the end of each chapter are divided into two groups: basic problems and challenging problems. The basic problems are designed to drill the student and assist him in mastering the matter. The majority of these problems should be solved without too much effort. The challenging problems, on the other hand, should serve to stimulate the student, testing his understanding and initiative. A number of the challenging problems have been taken from the free-response section of the Advanced Placement Physics Examination with the permission of the College Entrance Examination Board and the Educational Testing Service. These are identified at the end of the problem; e.g., (AP-B; 1975) identifies a problem from the 1975 B (non-calculus) Exam, while (AP-C; 1975) is a problem from the calculus-based examination of the same year.

Universities have been under great pressure to incorporate into the curricula for all sciences new subjects that are more relevant than the traditional topics. We expect that this text will relieve some of this pressure by raising the students' level of understanding of physical concepts and increasing their ability to manipulate the corresponding mathematical relations. This will permit an upgrading of intermediate courses presently offered in the undergraduate curriculum, from which the traditional courses in mechanics, electromagnetism and modern physics will benefit most. Thus the physics student will finish undergraduate education at a higher level of knowledge than formerly possible—an important benefit for those who terminate their formal training at this point. Also, there will now be room for newer (and perhaps more exciting) courses at the graduate level. It is gratifying to encounter this same trend of upgrading in the more recent basic textbooks in other sciences.

The text is designed for a three-semester or four-quarter general physics course. It may also be used in those curricula in which the general physics course, using Volume I and II, is followed by a one- or two-semester course in modern physics, which would use Volume III. In either case, the sequence would offer a unified presentation to the student.

We hope that this text will be of assistance to those progressive physics instructors who are constantly struggling to improve the courses they teach. We also earnestly hope that it will stimulate the many students who deserve a presentation of physics that is more mature than that of most traditional courses.

We want to express our gratitude to all those whose assistance has made the completion of this work and its revision possible. We recognize our distinguished colleagues, Professors D. Lazarus and H. S. Robertson, who read the original manuscript, and Dr. R. G. Hughes, who solved all the problems. We also wish to express our deep appreciation to the many users throughout the world of the first edition of this text. Their helpful comments, which reached us in any one of the ten languages in which that edition has been published, were responsible for a number of corrections and revisions. In particular, the encouragement and suggestions offered by the International Advisory Board of Editors, whose membership is listed opposite the title page, have greatly assisted us in improving the clarity of presentation. Their help has been invaluable. However, we remain solely responsible for the deficiencies in the text. We are also grateful for the ability and dedication of the staff of the International Division of Addison-Wesley. Last, but certainly not least, we sincerely thank our wives, who have been so patient with us.

Washington, D. C.
March, 1979

M. A.
E. J. F.

NOTE TO THE STUDENT

This is a book about the fundamentals of physics, written for students majoring in science or engineering. The concepts and ideas you learn from it will, in all probability, become part of your professional life and your way of thinking. The better you understand them, the easier the rest of your undergraduate and graduate education will be

The course in physics that you are about to begin is naturally more advanced than your high-school physics course. You must be prepared to tackle numerous difficult puzzles. To grasp the laws and techniques of physics may be, at times, a slow and painful process. Before you enter those regions of physics that appeal to your imagination, you must master other, less appealing, but very fundamental ones, without which you cannot use or understand physics properly.

You should keep two main objectives before you while taking this course. First become thoroughly familiar with the handful of basic laws and principles that constitute the core of physics Second develop the ability to manipulate these ideas and apply them to concrete situations; in other words, to think and act as a physicist You can achieve the first objective mainly by reading and re-reading those sections in large print in the text. To help you attain the second objective, there are many worked-out examples, in small print, throughout the text, and there are the homework problems at the end of each chapter We strongly recommend that you first read the main text and, once you are acquainted with it, proceed with those examples and problems assigned by the instructor. The examples either illustrate an application of the theory to a concrete situation, or extend the theory by considering new aspects of the problem discussed Sometimes they provide some justification for the theory

The problems at the end of each chapter vary in degree of difficulty and have been broken into two categories basic problems and challenging problems The basic problems are mostly of the type that should be solvable after reading the text material; they are made available so that you may apply what you have read to a given particular situation. The challenging problems, on the other hand, should force you to perform a series of steps before the answer can be obtained, in other words, you may be required to return to material previously introduced in order to work a problem Those challenging problems followed by, for example, (AP-B, 1970) or (AP-C, 1970) are taken from the free-response section of the Advanced Placement Physics Examination, the B-exams are non-calculus based and the C-exams are calculus-based, the year stated is the year the question appeared on the given test In general, it is a good idea to try to solve a problem in a symbolic or algebraic form first, and insert numerical values only at the end If you cannot solve an assigned problem in a reasonable time, lay the problem aside and make a second attempt later For those few problems that refuse to yield a solution, you should seek help One source of self-help that will teach you the *method* of problem-solving is the book *How to Solve It* (second edition), by G Polya (Garden City, N Y Doubleday, 1957)

Physics is a quantitative science that requires mathematics for the expression of its ideas All the mathematics used in this book can be found in a standard calculus text, and you should consult such a text whenever you do not understand a mathematical derivation. But by no means should you feel discouraged by a mathematical difficulty; in case of mathematical trouble, consult your instructor or a more advanced student. For the physical scientist and engineer, mathematics is a tool, and is second in importance to understanding the physical ideas. For your convenience, some of the most useful mathematical relations are listed in an appendix at the end of the book.

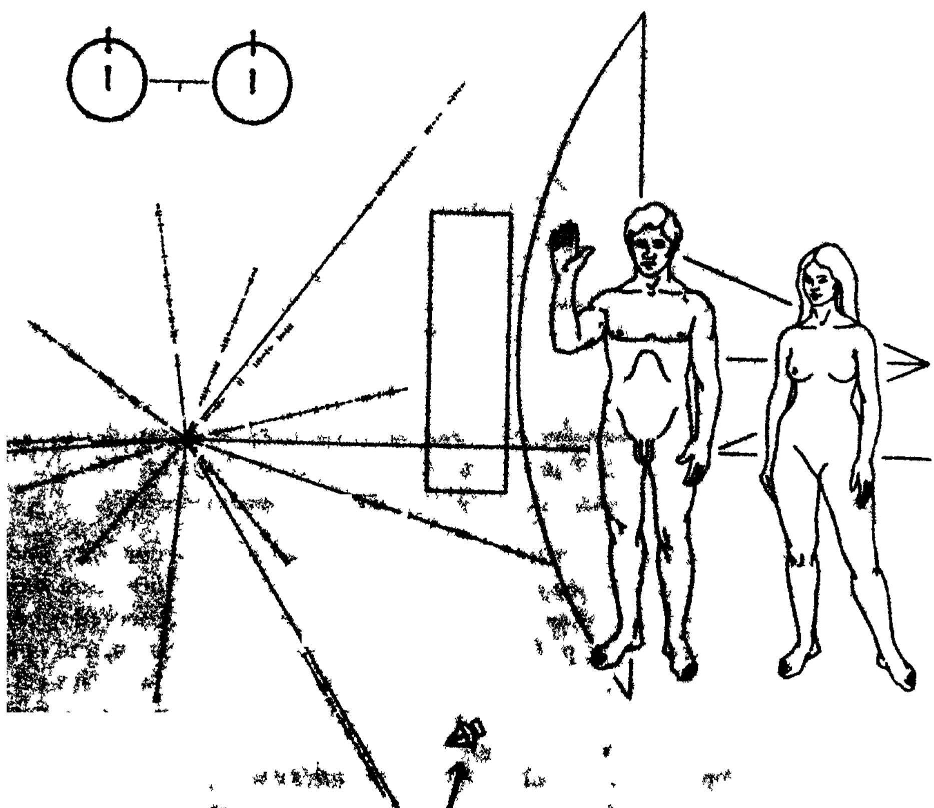
All physical calculations must be carried out using a consistent set of units. In this book the SI system is used. You may find it unfamiliar at first; however, it requires very little effort to become acquainted with it. Also, it is the system that is used in all major government laboratories throughout the world and is becoming standard in all the major scientific publications. It is a good idea to use a mechanical or electronic slide rule from the start; the accuracy of these instruments and their ability to hold intermediate results will save you many hours of computation. Mechanical slide rules, even the simplest, have three-place accuracy and this is almost always sufficient for problems in this text. The electronic slide rule/calculator has considerably greater accuracy and appears to be the indispensable tool for the scientist of the future.

The text does not stress the historical aspects of physics. For those students interested in the evolution of ideas in physics in a historical context, there are a number of informative texts available. In particular, we would recommend the fine book by Holton and Roller, *Foundations of Modern Physical Science*, second edition, (Reading, Mass.: Addison-Wesley, 1973).

CONTENTS

CHAPTER ONE

INTRODUCTION



Studying physics is an exciting and challenging adventure. To be a professional physicist is even more exciting. Among the most absorbing activities of the human intellect are to learn about the world we live in and to attempt to unravel the secrets of nature; these are precisely the aims of physical science. In this chapter we shall analyze and review the objectives and methods of physics before embarking on the systematic and organized study of this science.

1.1 What Is Physics?

The word *physics* comes from a Greek term meaning *nature*; and, therefore, physics should be a science dedicated to the study of all natural phenomena. In fact, until early in the nineteenth century, physics was understood in this broad sense and was called "natural philosophy." However, during the nineteenth century and until very recently, physics was restricted to the study of a more limited group of phenomena, designated by the name of *physical phenomena* and loosely defined as processes in which the *nature* of the participating substances does not change. This somewhat imprecise definition of physics has been gradually discarded, returning to the broader and more fundamental concept of previous times. Accordingly, we may say that *physics is a science whose objective is to study the components of matter and their mutual interactions. In terms of these interactions the scientist explains the properties of matter in bulk, as well as the other natural phenomena we observe.*

In progressing through this course, the student will witness the way this program is developed from basic and general principles and applied to the understanding of a large variety of phenomena, apparently unrelated but obeying the same fundamental laws. Once these great principles are clearly understood, the student will be able to attack new problems with great economy of thought and effort.

1.2 The Classical Branches of Physics

Having inquiring minds, people have always had a great curiosity about how nature works. At the beginning their only sources of information were their senses; and, therefore, they classified the phenomena they observed according to the way they sensed them. *Light* was related to the act of vision, and *optics* was developed as a more or less independent science associated with this act. *Sound* was related to the act of hearing, and *acoustics* developed as a correlative science. *Heat* was related to another kind of physical sensation, and for many years the study of heat (called *thermodynamics*) was yet another autonomous branch of physics. *Motion*, of course, is the most common of all directly observed phenomena; and the science of motion, *mechanics*, developed earlier than any other branch of physics. The motion of the planets caused by their gravitational interactions, as well as the free fall of bodies, was very nicely explained by the laws of mechanics; therefore, *gravitation* was traditionally discussed as a chapter of mechanics. *Electromagnetism*, not being directly related to any sensory experiences—in spite of being responsible for most of them—did not appear as an organized branch of physics until the nineteenth century.

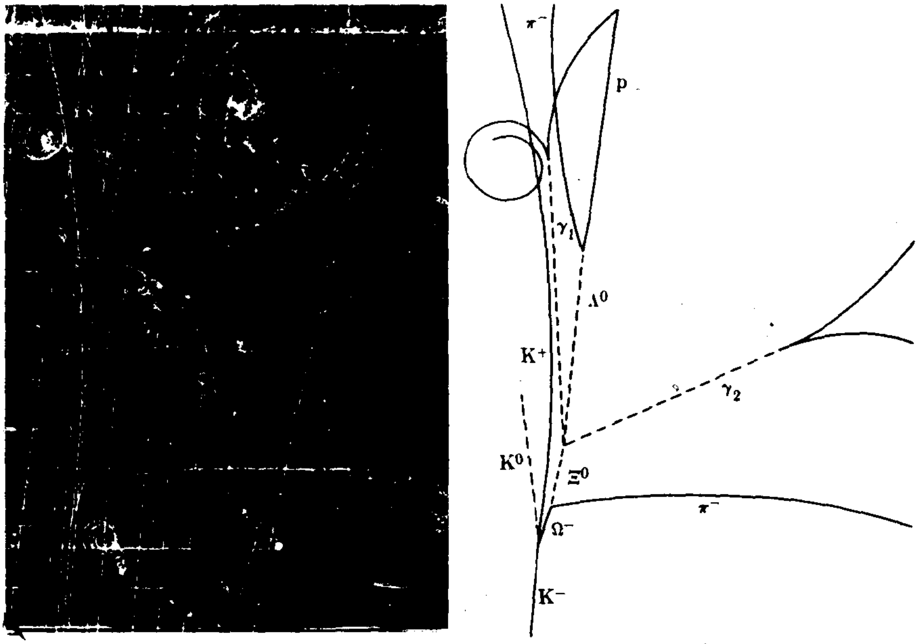
So physics in the nineteenth century appeared to be divided into a few (called *classical*) sciences or branches—mechanics, heat, sound, optics, and electromagnetism—with little or no connection between them although mechanics was, quite properly, the guiding principle for all of them. Physics was so taught to students until very recently. Lately a new branch, called *modern physics*, which covers the developments of twentieth-century physics, has been added to these "classical" branches.

The "classical" branches of physics are and will continue to be very important fields of specialization and professional activity, but to study the fundamentals of physics in such a compartmentalized manner no longer makes sense. The very same set of phenomena included under electromagnetism and modern physics has produced a new, unified, more logical perspective on physical phenomena; and this perspective is one of the great achievements of the twentieth century. This unified presentation of physics calls for a reappraisal of classical physics from a *modern* point of view rather than a division of physics into *classical* and *modern*. There will always be a *modern physics* in the sense that there will be contemporary physics being developed in one's time. This modern physics will require at each instant a revision and a reevaluation of previous ideas and principles. *Classical* and *modern* physics are to be integrated at each stage into a single body of knowledge. Physics will always be a whole that must be considered in a consistent and logical way.

1.3 Our View of the Universe

At present we consider matter to be composed of a handful of fundamental (or elementary) particles and all bodies, both living and inert, to be made up of different groupings or arrangements of such particles. Three of these fundamental particles are especially important because of their presence in many common phenomena: *electrons*, *protons*, and *neutrons*.

There are a few other fundamental particles; but they have a transient life, being continuously created and destroyed (and thus are termed unstable); and



(a) (b)

Figure 1-1. **(a)** Fundamental particle tracks in 80-inch (2 m) liquid-hydrogen bubble chamber, which is placed in a strong magnetic field that forces the charged particles to follow curved paths. These tracks are analyzed, and from the analyses the properties of the different particles are derived. This photograph, taken in 1964, is historic. It provided the first evidence of the existence of the omega minus (Ω^-) particle, which had previously been predicted on a theoretical basis. **(b)** The line diagram shows the more important events registered in the photograph. The Ω^- track is the short line near the bottom of the picture. The particles corresponding to the other tracks are also identified. (Photograph courtesy Brookhaven National Laboratory.)

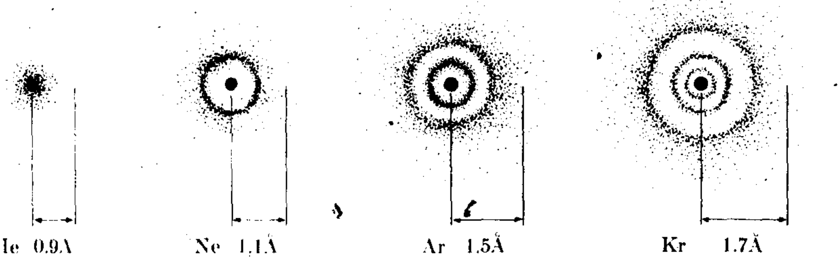


Figure 1-2. Arrangements of electrons around the nucleus in some simple atoms.(helium, He; neon, Ne; argon, Ar; krypton, Kr). Since electrons do not follow well-defined paths, the dark regions are those more likely to be occupied by the electrons (1 Å = 1 angstrom = 10^{-10} m).

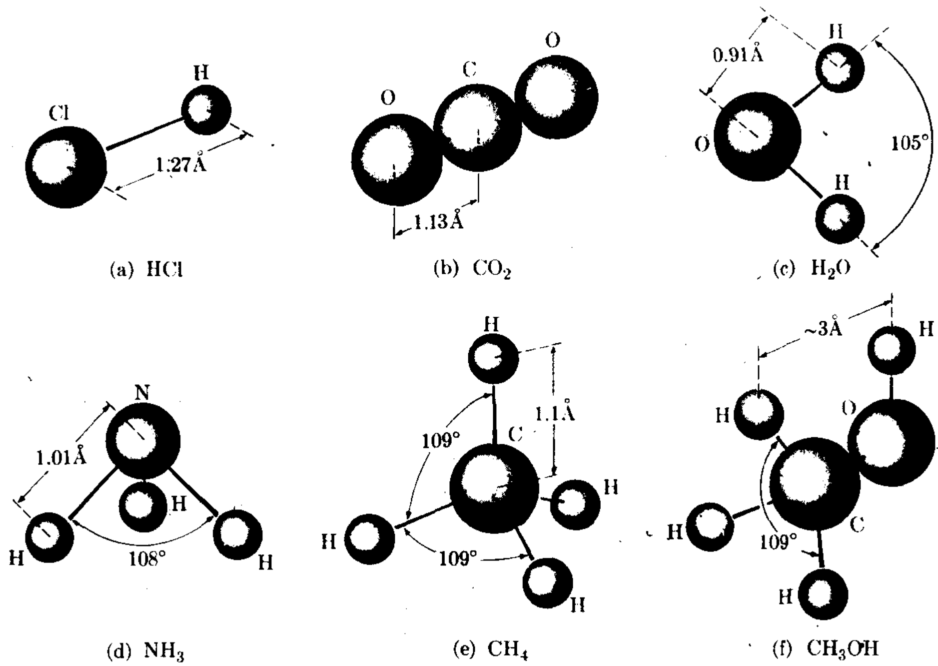
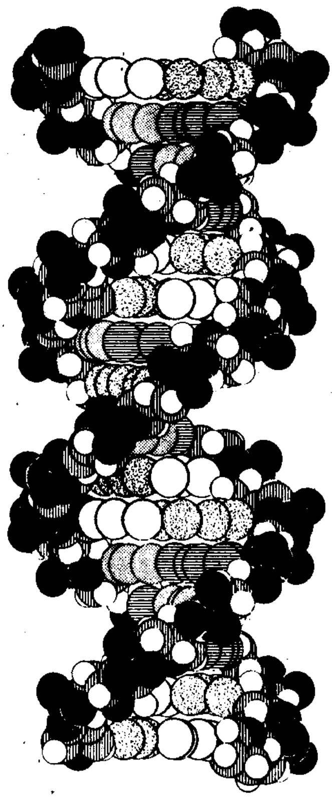


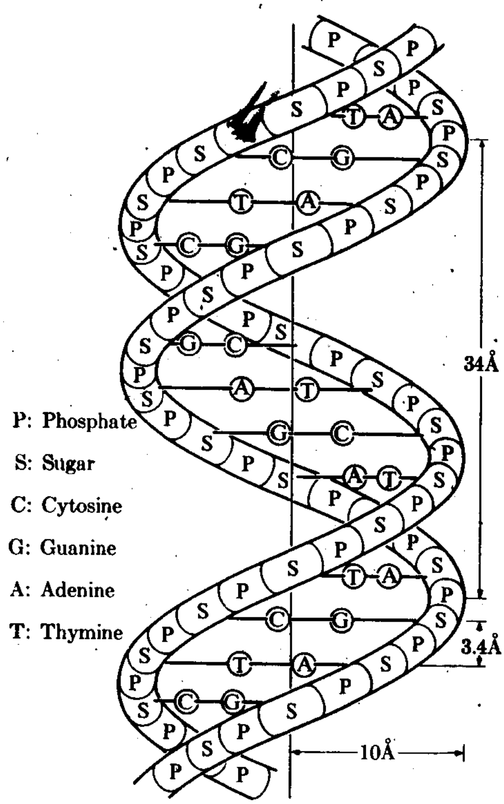
Figure 1-3. Some relatively simple molecules. The inner electrons remain attached to the respective atoms, but the outer ones move either in the space between two atoms or more or less freely over the molecule (1 Å = 1 angstrom = 10^{-10} m).

apparently they do not participate directly in most of the phenomena we observe around us (Fig. 1-1). Their existence is made manifest only by means of rather elaborate observational techniques, and their role in the general scheme is not yet completely understood. Some of these, such as the *pions*, are vital because of the role they play in the interactions between protons and neutrons. Fundamental particle research is of great importance today in obtaining some clue to the structure of the universe.

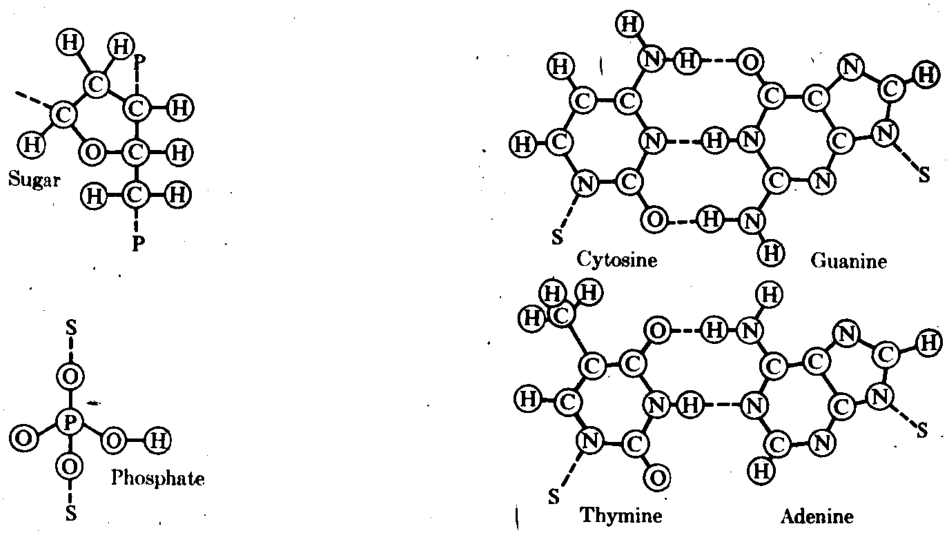
Using an oversimplified language, we may say that the three particles—electron, proton, and neutron—are present in well-defined groups called *atoms*, with the protons and neutrons clustered in a very small central region called the *nucleus* (Fig. 1-2). About 104 distinct "species" of atoms have been recognized (see Table A-1); but there are about 1300 different "varieties" of atoms, called *isotopes*. Atoms, in turn, form other aggregates called *molecules*, of which several thousand different kinds are known to exist. The number of different molecules is extremely large, and more and more new molecules are synthesized every day in chemical laboratories. Some molecules contain just a few atoms; e.g., hydrochloric acid molecules are formed of one atom of hydrogen and one atom of chlorine (Fig. 1-3); other molecules, such as those of proteins, enzymes,



(a)


P: Phosphate
S: Sugar
C: Cytosine
G: Guanine
A: Adenine
T: Thymine
34Å
3.4Å
10Å

(b)


Sugar
Phosphate
Cytosine
Guanine
Thymine
Adenine

(c)

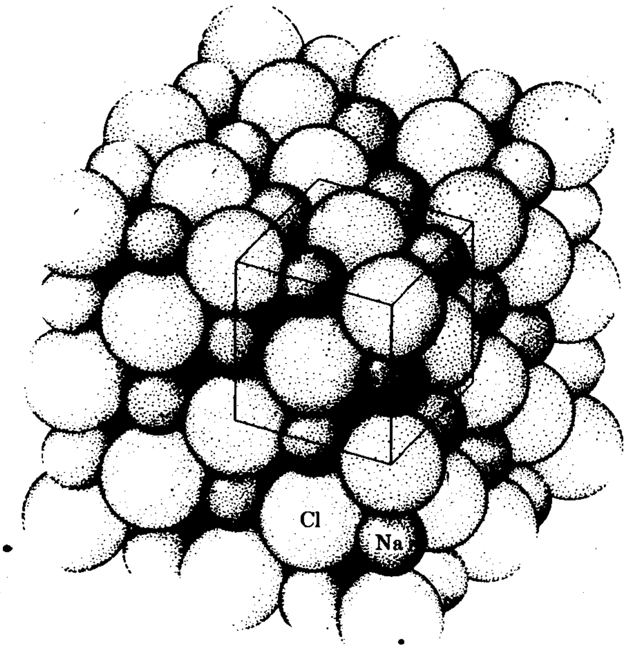


Figure 1-5. Crystal structure of sodium chloride. The atoms are arranged in a regular geometric form that extends over a relatively large volume. This structure is reflected in the external appearance of the macroscopic crystals.

and nucleic acids [DNA and RNA (Fig. 1-4)] or some organic polymers such as polyethylene or polyvinylchloride (PVC), may have several hundred atoms. Finally, molecules group together forming bodies (or matter in bulk), appearing to us as solids, liquids, or gases (Fig. 1-5) although this classification or division is not a rigid one. Another state of matter is the *plasma*, consisting of a gaseous mixture of positive and negative ions (or charges particles). Most of the matter in the universe is in the form of a plasma.

A particularly important kind of body is the living body or *living matter*, called *protoplasm*, in which molecules appear in a highly organized pattern and exhibit properties and functions apparently distinct from those of inert matter. The

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◄ **Figure 1-4.** Crick-Watson model of deoxyribonucleic acid (DNA). One of the two nucleic acids involved in the composition of a chromosome, DNA carries genetic information and is one of the best-studied giant molecules. X-ray diffraction has shown that it consists of two antiparallel helices composed of a sequence of sugar (S) and phosphate (P) groups. The sugar, called deoxyribose, contains five carbon atoms. The two helices are interlocked by pairs of hydrogen-bonded base groups. One pair is formed by two substances called adenine and thymine (A-T); and the other, by cytosine and guanine (C-G). The genetic code of the DNA molecule depends on the sequence or ordering of each base pair. These base pairs are like rungs along a helical stepladder, each rung being about 11 angstroms long. The pitch of each helix is about 34 angstroms, and its overall diameter is about 18 angstroms (1 angstrom = 10^{-10} m).