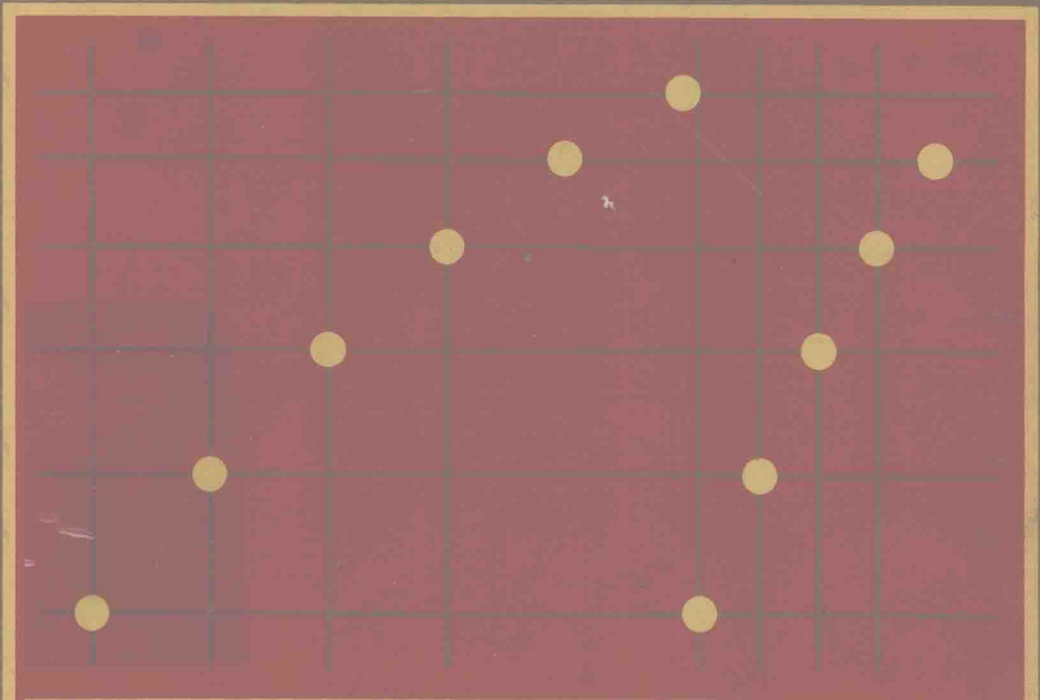
a search for order in the physical universe

Clifford E. Swartz Theodore D. Goldfarb



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preface

This book grew out of a course for nonscience majors that we taught jointly for three years. Although our students were not primarily interested in science or technology, most of them had studied enough mathematics so that they could follow simple algebraic derivations and interpret graphs. They had also been exposed to the standard presentations of one or more high school science courses. It is our conviction that such students are ready for a more challenging experience than would be provided by a wide-wonderful-world survey course.

With such an audience it seemed appropriate to try a different approach to the study of the physical universe. The theme is a study of interactions and a search for conserved quantities, particularly energy. This is the modern approach of scientists working with atomic and nuclear systems; energy becomes a fundamental quantity and force is a derived parameter. Although this method is novel at the introductory level, it is surprisingly powerful in explanation. It is also surprisingly natural and easy for a nonscience major to follow. In addition, our theme is developed with a combination of plausibility arguments and graphs that require no trigonometry and only the simplest of algebra.

After an initial chapter of setting the stage for our investigations, we present phenomena that are most easily understood by defining certain quantities that do not change during interactions. First, kinetic energy and momentum are defined in this manner. In order to extend the range of phenomena governed by such laws, the characteristics of the defined momentum are generalized, and forms of energy other than kinetic are defined. To preserve the energy conservation rule, we then present a model of the microstructure of matter using the study of heat as an approach to atomicity.

Many of the phenomena to be studied can be investigated firsthand by the reader. We have built in such investigations, most of which can be done without any formal laboratory. Since many of our students were preparing to teach in elementary school, we included some demonstrations and experiments that can be successfully done by younger children.

Throughout the text we inserted questions intended to make the reader pause and challenge what the text has just claimed. Our answers to these questions are included at the end of each chapter. Of course, a student can always bypass these questions or turn immediately to our answers. Comprehension seems to be improved, however, if the reader tries first to work out a personal answer for each question, preferably in writing.

Some people fear science because of its aura of cold precision. Actually, scientists usually avoid excessive precision and make frequent use of order-of-magnitude calculations. We frequently appeal to such arguments in the text, and in the appendices have included sections on precision and calculations. In the same spirit, we have tried to avoid fussiness in definitions and classifications. For instance, the words *speed* and *velocity* are used interchangeably, as indeed they are by most research scientists. Similarly, although we make use of vector properties in terms of geometric constructions, we avoid the terminology of vectors.

Wherever possible, the problems and examples given in the text are taken from the real world, and in that sense the material is relevant to everyday life. The theme of the book, however, is not on the technical problems of society or on preparation for employment. Although we agree that such courses can be useful, we believe that attempts to apply science to real problems can be carried out more realistically by students who have been introduced first to the fundamental principles and philosophy that are the foundation of all science and technology. We hope that this text will be of help in meeting this basic need.

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September 1973

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contents

Chapter One

to comprehend the universe

The primitive mysteries remain. We do not know why the universe was formed or how it will end. We do not know whether many of the structural details of the universe and events in its past history were accidental or inevitable. We do not know why there are living creatures, and most important for man, we do not know if there is some purpose or special role for thinking creatures. We do not even know whether it is important that we find out.

Of course, there is a lot that we have found out about the universe in the last few centuries, and especially in the last forty years. It is the business of science to measure the diameters of atoms and the distances to galaxies. It is also the business of science to catalog the objects with sizes in between, and to analyze their interactions. This enterprise has succeeded brilliantly, with experimental discoveries and theoretical revelations tumbling upon us. There is a popular legend that scientific information doubles every seven years or so, and therefore the student of today faces the impossible task of learning all the new facts. We would indeed be drowned by all this information if science did not at the same time provide us with simplifying generalizations. The jumble of recipes and special conditions needed by the alchemist have been systematized by the atomic models of the modern chemists. The complex cycles and epicycles needed by Ptolemy to compute planetary positions have been replaced by the conceptually simpler orbits of Copernicus. It is no more difficult to study science today than it was ten, fifty, or three hundred years ago. How could it be otherwise? Humans remain essentially unchanged, and humans create science.

Question 1.1 Throughout the text we will interrupt the line of argument by proposing questions or challenges. At the end of each chapter we have given our own answers with which you may not always agree. If you turn immediately to our answer you might profit by the rest taken from your reading as you hunt for the appropriate page. But, we believe that you will profit a lot more if you try to answer the questions for yourself before seeing what we said.

Do you really believe that new generalizations of science compensate for the increase in the number of discovered facts? Take any particular generalization with which you happen to be familiar: conservation laws, the nature of electricity or light, or genetic laws, for example. List the separate detailed facts that you can now deduce from that generalization, but which could not have been related three centuries ago.

In this crucial role of explanation and simplification, science becomes an art. It is a particularly human art, requiring skilled command of standard techniques and the daring to depart from them. The fact that the scientific enterprise requires such qualities reveals something about science, and also something about the relationship between humans and their universe. The traditions of western civilization have separated humanity from the rest of the universe. Were not humans, according to the first chapter of Genesis, given "dominion over the fish of the sea, and over the fowl of the air, and over the cattle, and over all the earth"? In the Platonic Greek tradition the world exists in an ideal form outside us. We learn about it, step by step, always approaching closer to some final truth. Perhaps this is not the way things really are. Perhaps what we observe and comprehend is determined more by our human nature than by any world external to us.

In this book we will not be primarily concerned with a detailed description of the physical universe. Any particular fact about this subject or even the great generalizations may or may not be relevant to your life. The problem that does concern us is how people go about comprehending their universe. Is it simply a matter of solving a gigantic puzzle, with the clues lying about and one complete answer waiting for us when we have sufficient facts? Or, do we find the clues to mold the generalizations in our own image? The science of this century has exposed the dependence of the measured fact on the measuring technique, and of the theory on the human or even the political cultural nature of the theorizer. A study of how we comprehend our universe is a study of people as much as it is a study of the universe. It is relevant to humans not only because of the technology that springs from science, but because of the view that it presents of the nature of the universe, of human beings and of their interaction.

The study of science is part of a liberal education. If science consisted merely of the technological fruit of the enterprise, it would be hard to claim that knowledge of science is in any sense "liberating." As long as the phones work and the planes fly on schedule, the educated person does not necessarily have to understand the engineering marvels involved. There is more to science, however, than just gears and tubes. The discoveries of science in the last few centuries have completely altered our understanding of ourselves. Particularly in this century these altered views and the powerful methods of scientific analysis have had a profound influence on philosophy. The study of the microstructure of matter erases the ancient dividing lines between matter and energy and raises in a very sharp way the Platonic questions of reality. Analysis of objects at the edge of the universe, and perhaps at the beginning of time, places humans and their works in a new and different perspective. To understand our human complexities, we must also understand some of the complexities of the universe around us.

Paradoxically, we shall try to understand these complexities by looking at very simple things. Simplicity of description and understanding is usually hard to achieve, as we shall see. The motions of the planets around the sun, for instance, are nearly circular—but not as viewed directly by anyone on earth. Their paths, as viewed in our night sky are very complex. It took detailed knowledge of these observations, plus the imagination of genius, to propose the simple system of elliptical orbits. In Chapter 2 we will look for the simplest event that we can find in order to analyze and thoroughly understand it. Before doing this, however, we should take a look at just a few of the raw facts that are known about the universe. The aim of this stage setting is not to teach the facts but to indicate the nature of the problem.

1.1 the universe as a subject for investigation

Scale. The range of sizes and distances in our universe is difficult to comprehend. As we investigate the micro-world, we find living cells with diameters 100,000 times smaller than the height of a human being. These cells are made of molecules. In turn, these molecules are made of atoms 100,000 times smaller than the cells. The atom itself has a structure, consisting mostly of "empty" space, electrons, and, in the center, a nucleus 100,000 times smaller than the atom. If we turn to the macro-world, a factor of 100,000 times the height of a human being brings us to a distance of a little over 100 miles, a distance with which we are somewhat intuitively familiar. But another factor of 1,000,000 stretches our imaginations with a distance about equal to that of the earth from the sun. The distance of the nearest star to our solar system is yet greater by another factor of 100,000. Our sun is merely one of some ten billion stars in a spiral galaxy with a diameter 25,000 times that of the distance between the sun and the next nearest star. Over a billion of these galaxies are within range of our telescopes. (See Fig. 1-1.) They stretch out to the very edge of visibility, and perhaps to the edge of the universe, at a distance 100,000 times greater than the diameter of our own galaxy.

figure 1-1 This is the great galaxy seen in the constellation of Andromeda. It is so large and bright that, even though it is two million light years away, it can be seen with the naked eye as a diffuse spot in the sky. (A light year is the distance that light travels in a year; it is equal to 9.4×10^{12} km, or 5.87×10^{12} miles.) This galaxy is about 100,000 light years in diameter, and contains about ten billion stars. Our own island universe, the Milky Way, is also a spiral galaxy very similar to this one. (*Courtesy of the Hale Observatories.*)

Since we cannot really comprehend such vast differences in size, let us consider scale models of sections of the universe. Imagine a device that could uniformly expand a single raindrop until it is as large as the planet Earth. An atom in the water drop would then be about human size, but its tiny nucleus (which contains almost all of the atom's mass) would still be only about the size of a bacterium—too small to see without the aid of a high-powered microscope! Now reversing our device, let us imagine the shrinking of our galaxy (a very *small* part of the entire universe) until its outer limit would just fit within the space defined by the earth's orbit around the sun. The earth would then have a diameter about as wide as the head of a pin and its human inhabitants would have atomic dimensions!

Figure 1-2 is an attempt to illustrate the range of sizes and distances encountered in the universe. Note that the *unit* of length used is the *meter*. This unit is part of the *metric* system which has the advantage of being a decimal system (based on ten) just like our number system. Other metric units of length are the *kilometer* (1,000 meters) and the *centimeter* ($\frac{1}{100}$ of a meter). The units of mass (*gram*, *kilo*gram, *centi*gram, etc.) in this system are also decimal. Since it is the official system of measurement in much of the world and is used almost universally by scientists (as well as being used extensively in this book) it is worth spending some time familiarizing yourself with metric units. (See the problems at the end of this chapter.)

The scale in Fig. 1-2 is a *logarithmic* or *powers-of-ten* scale. This permits representing an enormous range of magnitudes on a single diagram or graph. We will make frequent use of powers-of-ten (*exponential*) notation since it is much more convenient to write numbers such as 4,320,000,000 as 4.32×10^9, or 0.00000001576 as 1.576×10^{-8}. If you are not familiar with this form of notation and with the simple algebraic manipulations (addition, subtraction, multiplication, and division) of numbers written this way, turn to Appendix 1 and practice the exercises given there. Note that on the scale of Fig. 1-2, every step represents an increase or decrease of length by a factor of 10. Two steps means a change by a factor of 100, three steps a factor of 1,000, six steps a factor of one million, and nine steps a factor of one billion. Thus the north-south width of the United States is about one million times the height of a man.

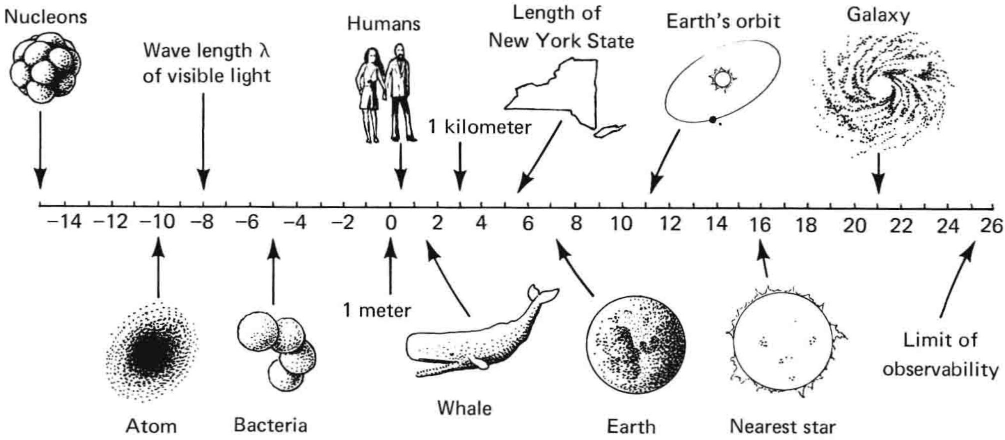


figure 1-2 Map of the Universe. The scale is logarithmic. Each step to the right represents an increase of length by a factor of 10. The unit of length is the meter; hence, 0 (signifying 10^0) represents 1 meter. Similarly, 2 (signifying 10^2) represents 100 meters.

Question 1.2 Verify the positions of: a human, a whale, the length of New York State, and the size of the earth as shown in Fig. 1-2.

Question 1.3 How many times longer would Fig. 1-2 have to be if the scale were linear, rather than logarithmic, and arranged so that 10^{-15} meter represents 1 meter?

Look at the place of humans on the map of the universe. We and all the living objects on earth occupy only a small region between the very small and the very large. The largest of all these creatures is less than twenty times as long as a human. The smallest of these objects that still show some of the characteristics of life is smaller than we are by a factor of ten million. Beyond these limits the universe continues to stretch out. Our immediate perception of the universe is severely limited. With the unaided eye we can see objects that are only $\frac{1}{10}$ millimeter across (10^{-4} on our scale). Below that size we can see only with microscopes which extend our view only to objects one hundred to one thousand times smaller. For large objects we have some intuitive comprehension of size up to a factor of 10^5 larger than ourselves.

To go beyond the normal human grasp of sizes, we must use instruments and interpret their readings in terms of theories that are often complex. The image presented by a microscope is so close to the visual image which we usually see that the only theory needed for comprehension is one that gives us an explanation of magnification. (The concept of magnification cannot be comprehended by most children under the age of ten; the effect is not elementary.) Electron microscopes also produce visual images of a familiar kind, although we may feel uneasy about "seeing" objects with electrons. Of course, the electrons are serving as probes just as the particles of light serve as probes, as shown in Fig. 1-3. In both cases, the probes are transmitted, or scattered, or absorbed. Probes that are even smaller can be used to examine smaller objects, such as atoms and sub-atomic particles. In cases where these small particles are being "seen," the analysis of the scattering and absorption of the probes requires mathematical treatment, and interpretation in terms of theories of particle behavior. However, the pictures that are obtained can be very detailed. Objections are sometimes raised when a scientist claims to have "seen" a subatomic particle by virtue of the visible trail it has left behind in a bubble or spark chamber. The same reaction is not likely to greet the individuals who talk about having seen a movie star when they have actually been observing an image on a movie screen. It is possible to argue about whether a sensory image is caused "directly" or "indirectly" by the subject of investigation but it is certainly preferable to avoid such semantic quibbles. The devices employed in scientific investigations can best be thought of as tools that extend the power of the human senses.

While we might have no intuitive feelings for distances much larger than

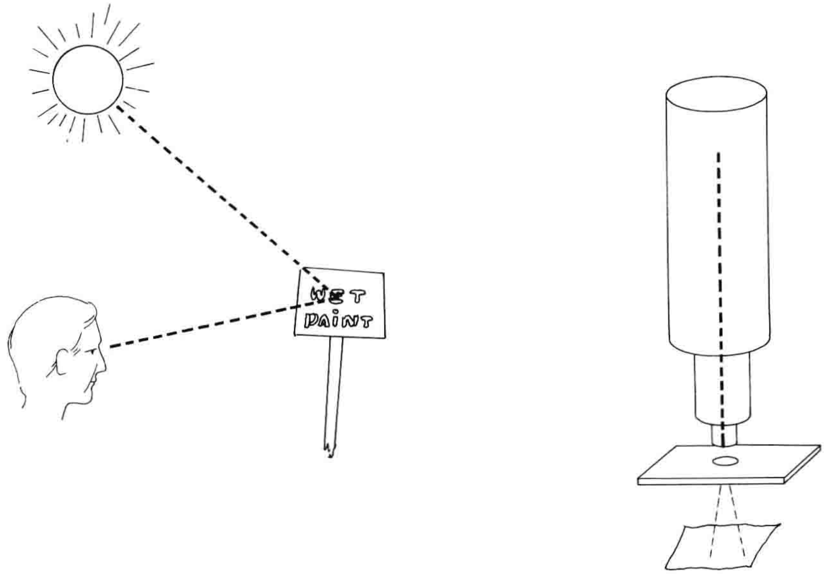
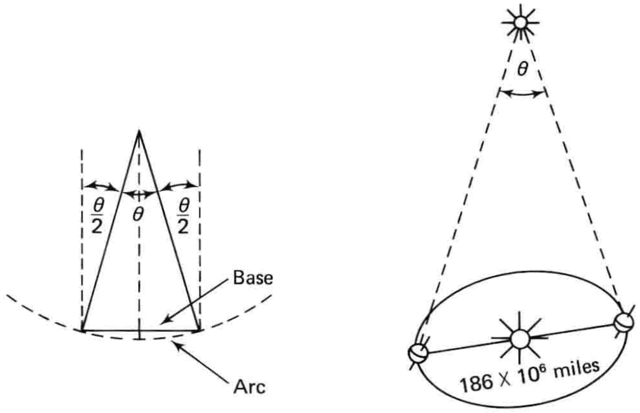


figure 1-3 The "probes" that we use for seeing might be photons (light radiation) that are scattered by an object and are detected by our eyes, or they might be electrons that are scattered by an object and detected with a photographic film. In either case, when our brain processes the scattering pattern, we have "seen" the object.

the size of a state or of our country, our reach beyond these distances can be extended appreciably with ordinary surveying techniques. These techniques consist essentially of sighting on a distant object from two different points. The length of the line between these points and the sighting angles from each of this baseline's end-points can then be related to the unknown distance. Fig. 1-4 illustrates the geometry involved.

Question 1.4 Suppose the surveying base line on the earth is 1,000 miles long. Will an observer at one end of this base line sight a particular point on the moon at a different sighting angle than a person at the other end? Assume the first observer points his telescope directly up; will the second observer's telescope be far from the vertical? The distance to the moon is about 240,000 miles. (Assume that the earth is flat; the correction for the earth's curvature could be made in an actual experiment.) What is the answer to this question if the particular point being sighted were on the sun, 93 million miles away?

In spite of the small angles involved, Greek astronomers at Alexandria, 2,300 years ago, determined the distance to the moon and sun, and their relative



$$\frac{\text{circumference}}{\text{arc}} = \frac{360^\circ}{\theta^\circ} \approx \frac{2\pi r}{\text{base}}$$

$$r \approx \frac{360^\circ}{\theta^\circ}\,\frac{1}{2\pi}\,(\text{base})$$

figure 1-4 From the baseline, the distant object can be sighted and the angles from the perpendicular direction measured. For a small apex angle, θ, the base is approximately equal to the arc of the circumscribed circle, and the distance to the object is approximately equal to the radius. The diagram scale of the solar system-star geometry is greatly exaggerated. The real θ for the nearest star is only 0.0005°.

sizes, with surprising results. Although their value for distance between the earth and the sun was wrong by a factor of 60, their estimate of the distance to the moon was wrong by only 25%. Not only did they use angular differences in sighting to get their estimates, but they also used observations of the appearance of the earth's and moon's shadows during eclipses. Notice that they did all this 2,000 years before the invention of optical telescopes!

Surveying techniques can be used to measure the distance to a few of the very close stars. As we saw in Question 1-4, no base line on the earth is long enough to produce a measurable difference in sighting angles to a star. (Compare the distance to the nearest star on the scale map of the universe with the radius of the earth's orbit—which is the distance from earth to sun.)

Question 1.5 What base line can be used to measure the distance to the nearest star? About how large is the angular difference in sighting angles when this base line is used?

Very elaborate surveying techniques, using a base line that depends on the motion of our sun among the stars, can extend our distance measurements

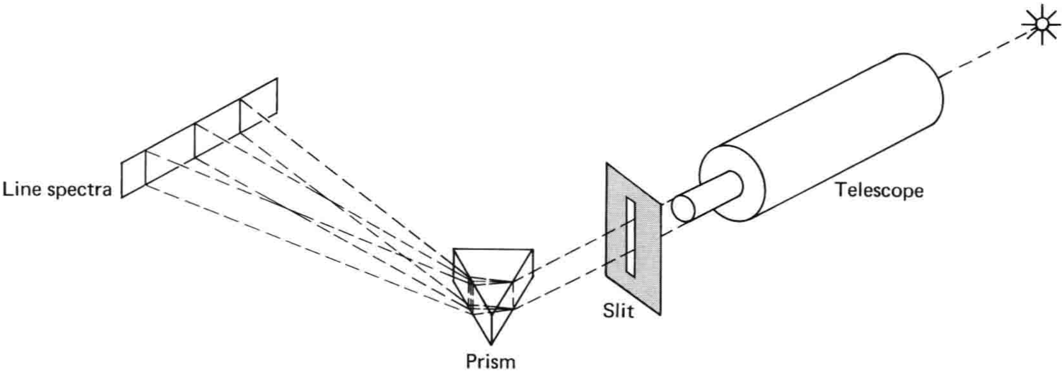


figure 1-5 Light from a star is focused by a telescope onto a spectroscope. A prism (or a diffraction grating) breaks the light into its component colors. Instead of a complete rainbow of colors, a series of certain lines of different colors appears. (Lines are formed because of the geometry of the slit.) The various patterns of the spectral lines indicate which elements produced the light, and also yield information about the motion of the star.

a relatively short distance into our galaxy. Beyond that, as the map in Fig. 1-2 shows, there are still enormous ranges of size. The methods for measuring the distances to other galaxies depend on theories of atomic processes and on the behavior of light when its source is moving with respect to the observer. Raw data for these measurements is obtained with telescopes, but the star light is not simply observed or recorded on film. No amount of magnification can change the appearance of all but a few of the stars that we see. They are so far away that their light always appears to come from a point. What we learn about them is mostly derived from the nature of the light received—its color and intensity, and fluctuations in that intensity. Telescopes focus light on spectroscopes, instruments which spread out the light according to its color, or wavelength. Most of our information about the stars and galaxies, including our knowledge of their distance from us, is deduced from this information. A simple spectrograph is illustrated schematically in Fig. 1-5.

In other sections of the book we examine in more detail some of the small and large regions of our universe. We also study some of the phenomena that allow us to probe these regions and the theories with which we interpret the experimental results. In this preliminary look we only want to emphasize the vastness of the universe that lies within us and beyond us.

Complexity. In addition to presenting a fantastic range of sizes and distances, the objects in the universe display an innumerable variety of other measurable properties. In an effort to simplify and systematize their investigations scientists often categorize or classify the materials they study. A familiar classification scheme is the attempt to label every substance according to its so-called state-of-matter—gaseous, liquid, or solid. A fourth state called *plasma*, containing high temperature, electrically charged particles, has only recently become accessible for study on earth. This fourth state-of-matter is of great importance elsewhere in the universe. Stars, for instance, consist of plasmas.

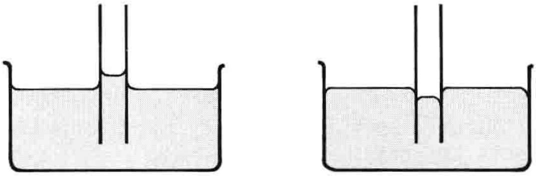
Actually, only fuzzy boundaries exist between these states. Considerable attention has recently been focused on *liquid crystals,* a class of liquids that display many of the properties of a crystalline solid. Common window glass and many plastics have both liquid and solid properties. A gas, under conditions of very high pressure, behaves like a liquid in some ways.

Another scheme for the classification of matter is based upon defined distinctions between *pure substances* (elements and compounds), *solutions*, and *mixtures*. Again, fuzzy boundaries are encountered. Certain *solutions*, (e.g. 95% alcohol, 5% water) have sharply defined boiling or freezing points—one of the criteria used to define *pure substances*. Compounds of certain metals with hydrogen have a variable composition and are therefore *pure substances* by certain criteria and *solutions* by others. Colloidal suspensions of very fine particles in a liquid, or of two (or more) immiscible liquids (homogenized milk, for example) are mixtures that have properties that are very similar to those of solutions.

Efforts aimed at describing certain of the properties of an entire class of substances are useful but invariably an individual object within any single category of any classification scheme will present a unique combination of individual properties (e.g., electrical conductivity, chemical reactivity, elasticity, color).

Question 1.6 How many other schemes for classifying matter can you think of? Do they also have "fuzzy boundaries"?

Interactions. Most of the observations made on objects in the universe involve the *interaction* of one material with others. We note that the level of water rises in a glass tube with a small diameter, whereas the level of mercury is depressed (see Fig. 1-6). This must involve a difference in the type


Capillary tube in water

Capillary tube in mercury

figure 1-6 Water is attracted to glass and wets it. At the boundary the water rises onto the glass, making the surface concave as seen from the side. Mercury does not wet glass. At the boundary between mercury and glass, the mercury surface is depressed and convex.