Chapter 1:
The Nature of Science

Have you ever sorted the books in your library according to their subject matter, only to find a few remaining that "didn't fit"? In a way, this problem is similar to problems that face a scientist. For example, a scientist collects data on crystals or atomic particles or orbiting planets and must face the fact that some of the data does not fit expectations. Such an experience can be unsettling, but it can also lead to new understanding and insight.

One of the primary objectives of this text is to introduce you to a few of the powerful interpretations of natural phenomena used by the physicist to help organize experience. The text discusses some of these phenomena and the patterns of behavior they exhibit. You, in turn, are asked to examine your own experience for additional data to support or contradict these ideas. Occasionally, an unexpected outcome may compel you to reorganize your thinking. A critical approach to all aspects of the text is in order.

Unfortunately, modern culture has become fragmented into specialties. Science was once a branch of philosophy. In modern times, however, science, especially physics, is no longer an intellectual discipline with which every educated person is familiar. There are many reasons for this state of affairs (Fig. 1.1). Probably the most important is that many individuals do not feel a need for a formal study of nature. They develop a commonsense "natural philosophy" as a result of their everyday experiences with hot and cold objects, moving objects, electrical equipment, and so on. For most people, this seems quite adequate.

A second reason is that many of the questions with which modern physicists are concerned seem remote from everyday life. Physicists now study sub-nuclear particles, matter at ultra-low or extremely high temperatures, cosmic-sized objects such as galaxies, the beginning of the universe, and other extraordinary phenomena. The physics that is accessible to the beginning student has a cut-and-dried aspect that lacks the excitement of a quest into the unknown. Therefore, many students tend to think of physics as a finished story that must be memorized and imitated, rather than as a challenge to the creative imagination.

"Why does this magnificent ... science, which saves work and makes life easier, bring us so little happiness? The simple answer runs – because we have not yet learned to make a sensible use of it."

Albert Einstein

A third reason is the frequently indirect nature of the evidence on which physicists base their conclusions. As a result of this indirect evidence, experimental observations are related to theoretical predictions only through long and complicated chains of reasoning, often of a highly mathematical kind.

A fourth reason, of relatively recent origin, is that science has become identified with the invention of destructive weapons (the atomic bomb and biological warfare) and technological advances whose byproducts (smog, detergents) threaten our natural environment. Many individuals reject science, and especially physics, as alien to sensitive, imaginative, and compassionate human beings.

In this text we will try to overcome those difficulties. We will limit the diversity of topics treated, make frequent reference to the phenomena of everyday experience, and examine carefully the ways in which

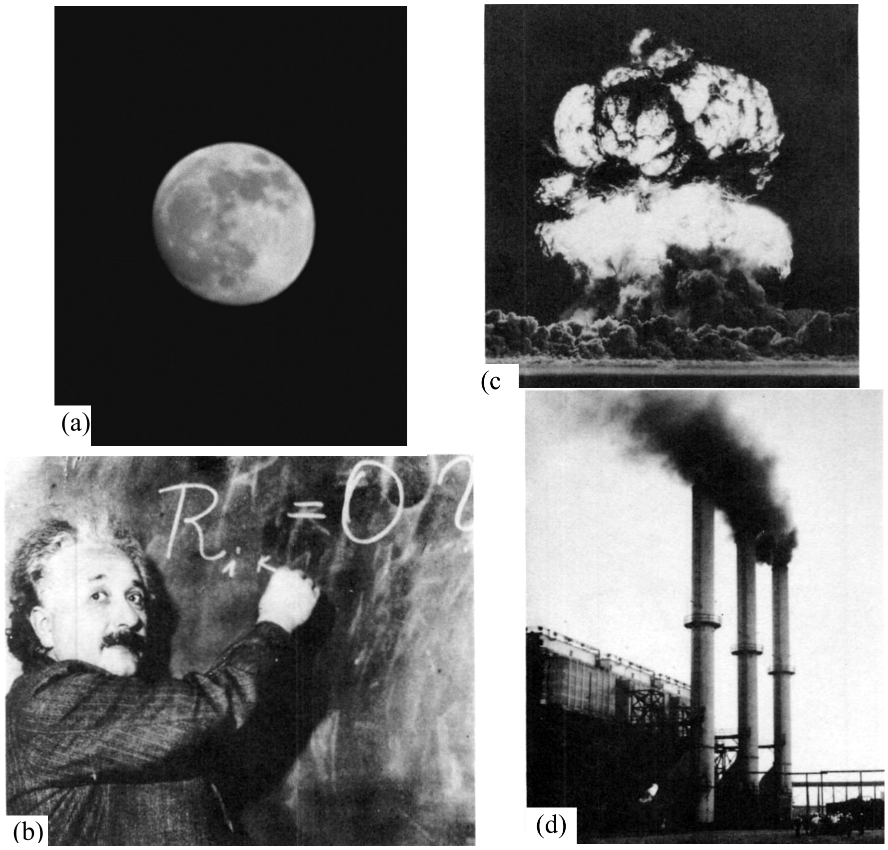


Figure 1.1 What do you think of these reasons?
(a) The familiar surface of the moon. Should you know more about this silvery disk where people may someday live?
(b) Albert Einstein, popular symbol of theoretical, abstruse physics. Should grants for pure research be justifiable in terms of contemporary social needs?
(c) Nuclear explosion, Nevada Proving Grounds, 1957. Physics has become deeply involved in war and peace.
(d) A steel mill's waste gases bring with them one of the hidden costs of our technological civilization. Compare with Fig. 1.2(c).

observations can be interpreted as evidence to support various scientific theories. The goal is to develop your understanding of how physical concepts are interrelated, how they can be used to analyze experience, and that they are employed only as long as there are no better, more powerful alternatives.

The reasons why an educated person should have some understanding of physics have been stated many times (Fig. 1.2). Physics is a part of our culture and has had an enormous impact on technological developments. Many issues of public concern, such as air and water pollution, industrial energy sources, disarmament, nuclear power plants, and space exploration, involve physical principles and require an acquaintance with the nature of scientific evidence. Only a wider public understanding of science will ensure that its potential is developed for our benefit rather than devoted to the destruction of civilization. More personally, your life as an individual can be enriched by greater familiarity with your natural environment and by your ability to recognize the operation of general principles of physics everyday, such as in children swinging and hot coffee getting cold.

1.1 The scientific process

The present formulation of science consists of concepts and relationships that humankind has abstracted from the observation of natural phenomena over the centuries. Throughout this overall evolutionary process occasional major and minor "scientific revolutions" (or, possibly more accurately, "transformations") have reoriented entire fields of endeavor. Examples are the Copernican revolution in astronomy, the Newtonian revolution in the study of moving objects, and the introduction of quantum theory into atomic physics by Bohr. The net result has been the development of the conceptual structure and point of view with which modern scientists approach their work.

"Few things are more benighting than the condescension of one age for another."

Woodrow Wilson

An investigation. Let us briefly and in an oversimplified way look at the way a scientist might proceed with an investigation. For instance, consider a ball that falls to the ground when you release it. After additional similar observations (other objects, such as pieces of wood, a feather, and a glass bowl, all fall to the ground when released), we are ready to formulate a hypothesis: all objects fall to the ground when released. We continue to experiment. Eventually, we release a helium-filled balloon and find that instead of falling, it rises. That is the end of the original hypothesis. Can we modify it successfully? We could say, "All objects fall to the ground when released in a vacuum." This statement is more widely applicable, but it is still limited to regions near the earth or another large heavenly body where there is a "ground." In space, far from the earth, "falling to the ground" is meaningless because there is no ground.

What happens to an object released in space, far from the earth or another body?

This simple description has skipped over two important decisions that we made. First was the judgment as to what constituted "similar"

(a)

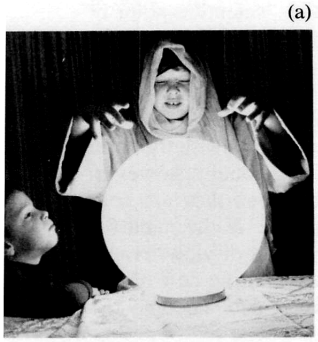
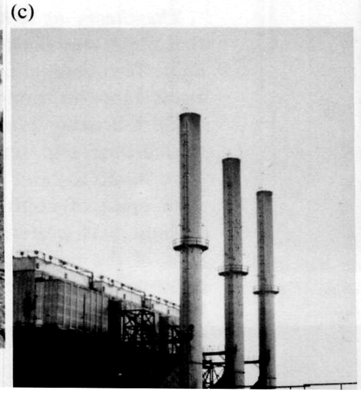


Figure 1·2
Is physics relevant?
(a) Do you base your actions on a crystal ball or on scientific evidence and reasoning?
(b) What clues enable you to identify the vertical direction?
(c) The waste gases from a steel mill are cleaned by the action of "precipitators," which make use of electric fields. Compare with Fig. 1·1 (d).
(d) Medical x-ray photograph after an unlucky fall on a skiing trip.

(b)

(c)



(d)

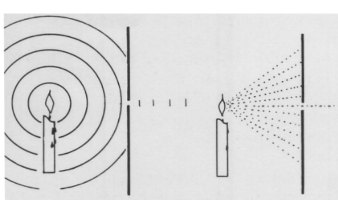
observations. For instance, in the example, we included the balloon along with the ball, weed, feather, and so on. Yet we might have considered the balloon to be very different from the other objects observed. Then the balloon rising rather than falling would not have been considered pertinent to the hypothesis of falling objects. Even for some time after Galileo's telescopic observations of the moon more than 300 years ago, there was controversy as to whether it and other heavenly bodies were material objects to which the hypothesis of falling objects should apply.

The second decision was the judgment about what aspects of the observations were to be compared. We decided to compare the motion of the bodies after they were released. Aristotle, a Greek philosopher who also thought about falling bodies, was more concerned with such objects' ultimate state of rest on the ground, and therefore he reached conclusions very different from those we found above.

"... from my observations, ... often repeated, I have been led to that opinion which I have expressed, namely, that I feel sure that the surface of the Moon is not perfectly smooth, free from inequalities and exactly spherical, as a large school of philosophers consider with regard to the Moon and the other heavenly bodies, but that, on the contrary, it is full of inequalities, uneven, full of hollows and protuberances, just like the surface of the Earth itself, which is varied everywhere by lofty mountains and deep valleys."
Galileo Galilei
Sidereus Nuncius, 1610

"Matter" includes all solid, liquid, and gaseous materials in the universe. In this text, we will not define "matter" more precisely; we will treat "matter" as an undefined term, with a meaning that must be grasped intuitively. Properties of matter, to be described later in this text, include mass, extent in space, permanence over time, ability to store energy, elasticity, and so on.

The scientific point of view. Usually the answers to these two kinds of questions are tacitly agreed upon by the members of the scientific community and constitute what we may call the "scientific point of view." One aspect of this point of view is that a real physical universe composed of matter exists, that we are a part of this universe, and that matter participates in natural phenomena. A second is the assumption that natural phenomena are reproducible: that is, under the same set of conditions the same behavior will occur. A third aspect is that while we ourselves are part of the physical world, we are also able to observe the natural world and to think about our observations. Other aspects of the point of view have to do with the form of an acceptable explanation of a phenomenon. This scientific point of view provides a context for scientific knowledge and for what is (and is not) accepted as scientific knowledge. Occasionally, however, it is very difficult to interpret new observations in a way that is consistent with the accepted scientific way of thinking. Then there is the need for bold and imaginative thinking to develop a new point of view. Hopefully, this new approach will be better able to explain the new observations and the known phenomena. Eventually it may become the accepted scientific point of view. The key idea here is that the scientific point of view (that is, the criteria for what is scientific knowledge) has gradually changed and is certain to continue to change.



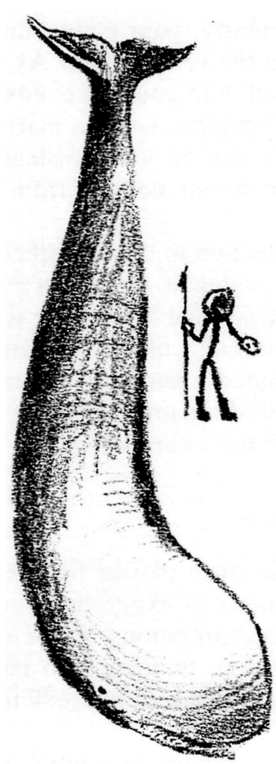
The work of Christian Huygens (1624-1695) and Isaac Newton (1642-1727) on the nature of light will he discussed in Chapters 5, 6, and 7.

The theory of light. A fascinating story in the history of physics that illustrates these remarks deals with the nature and interactions of light. Two competing ideas were advanced in the seventeenth century. Isaac Newton thought that light consisted of a stream of corpuscles, while Christian Huygens believed that light was a wave motion (see illustration to left). Up to that time, experiments and observations on light rays had apparently been made without questioning further the nature of the rays.

In spite of contradictory evidence, Newton's corpuscular theory of light was preferred by the scientific community, largely because of the success of Newton's laws of the motion of material bodies subject to forces. Small bodies (corpuscles) probably provided a more acceptable explanation to Newton's contemporaries and followers than did the waves proposed by Huygens. During the nineteenth century, however, new experimental data on the passage of light near obstacles and through transparent materials contradicted Newton's corpuscular theory conclusively and supported the wave theory. Waves and their motion became the accepted way to explain the observed properties of light.

This point of view flourished until the beginning of the twentieth century, when results of further experiments on the absorption and emission of light by matter conflicted with the wave theory and led to the presently accepted quantum theory of light. Already, however, there are contradictions within this theory, so that it, too, will have to be modified. This is one field of currently active research, and several proposals for new theories are being studied intensively to determine which holds the most promise.

Scientific "truth." Science is, therefore, never complete; there are always some unanswered questions, some unexpected phenomena. These may eventually be resolved within the accepted structure of science, or they may force a revision of the fundamental viewpoint from which the phenomena were interpreted. Progress in science comes from two sources: the discovery of new phenomena and the invention of novel interpretations that illuminate both the new and the well-known phenomena in a new way. Scientific truth is therefore not absolute and permanent: rather, it means agreement with the facts as currently known. Without this qualification, the statement that scientists seek the truth is misleading. It is better to say that scientists seek understanding.



1.2 Domains of magnitude

When and how does a person's experience of space and time originate? Probably the foundations are laid before birth, but the most rapid and important development takes place during an infant's early exploration of the environment. By crawling around, touching objects, looking at objects, throwing objects, hiding behind objects, and so on, an infant forms simple notions of space. By getting hungry and feeling lonely, by enjoying entertainment and playing, by watching things move and by moving himself, he forms notions of time. Even though an adult commands more effective skills with which to estimate, discriminate, and record space-time relations, our need to relate the environment to ourselves is never really outgrown.

Size. As you look about and observe nature, you first recognize objects, such as other people, trees, insects, furniture, and houses that are very roughly your own size. We will call the domain of magnitude of these objects the *macro domain*. It is very broadly defined and spans living creatures from tiny mites to giant whales. All objects to which you relate easily are in this domain.

All other natural phenomena can be divided into two additional domains, depending on whether their scale is much larger or much smaller than the macro domain. The former includes astronomical objects and happenings, such as the planet earth, the solar system, and galaxies. We will call this the *cosmic domain.* Much smaller in scale than the macro domain is the one that includes bacteria, molecules, atoms, and subatomic units of matter; we will call it the *micro domain.*

*The phrase "*geologic times" *is sometimes used to denote very long time intervals because geologic processes (such as changes in the shape of the Earth) are extremely slow.*

Time. It is useful to introduce the concept of domains into time scales as well as into physical size. Thus times from seconds or minutes up to years are *macro times* in the sense that they correspond to the life spans of human beings and other organisms. Beyond centuries and millennia are *cosmic times,* whereas *micro times* are very small fractions of a second. As with physical sizes, the mental images you make for processes of change always represent in seconds or minutes what really may require cosmic times or only micro times to occur.

Applications. In order of size, then, the three domains are the micro, macro, and cosmic. The division is a very broad one, in that the earth and a galaxy, both in the cosmic domain, are themselves vastly different in scale. Likewise, bacteria and atomic nuclei are vastly different. Nevertheless, the division is useful because the mental images you make of physical systems are always in the macro domain, where your sense experience was acquired. You therefore have to remember that your mental image of a cosmic system, such as the solar system, is very much smaller than the real system. Similarly, your mental image of a micro system is very much larger than the real system. As you make mental images of these systems, you will find yourself endowing them with physical properties of macro-sized objects, such as marbles, ball bearings, and rubber balls. This device can be very misleading because, of course, your images are in a different domain from the objects themselves.

When we pointed out in the introductory section to this chapter that physicists frequently must interpret indirect evidence, we had in mind, among other things, the three domains of magnitude. Since our sense organs limit us to observations in the macro domain, all interpretations concerning the other domains require extended chains of reasoning. An illustration relating the domains of magnitude to units of space and time measurement is presented at the end of this chapter in Fig. 1.11.

1.3 Theories and models in science

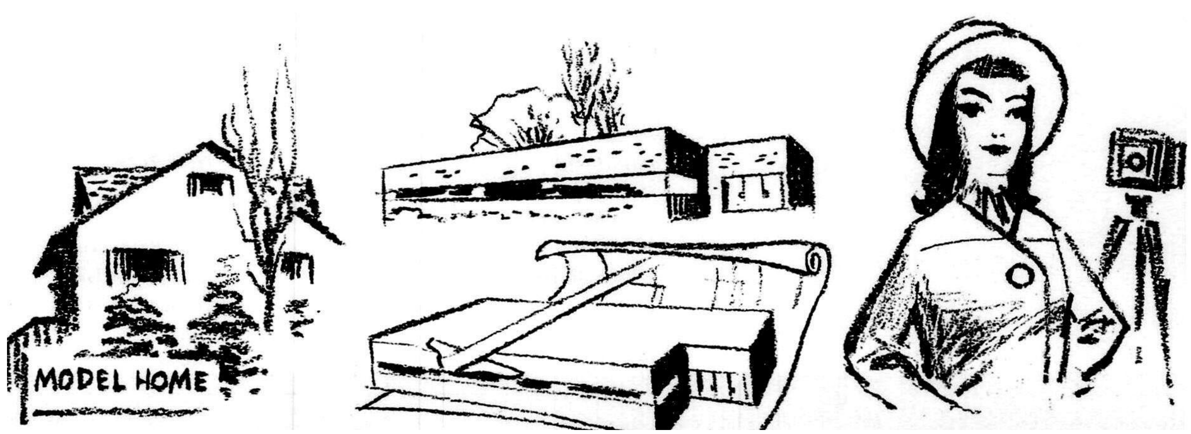
In the preceding section we contrasted the roles played in science by observation and interpretation. Observations of experimental outcomes provide the raw data of science. Interpretations of the data relate them to one another in a logical fashion, fit them into larger patterns, raise new questions for investigation, and lead to predictions that can be tested.

Scientific theories are systematically organized interpretations. Examples are Dalton's atomic theory of chemical reactions, Newton's theory of universal gravitation, Einstein's theory of relativity, and Piaget's theory of intellectual development. Within the framework of a scientific theory, observations can be interpreted in much more far-reaching ways than are possible without a theory. In Newton's theory of gravitation, for instance, data on the orbital motion of the moon lead to a numerical value for the total mass of the earth! In Dalton's theory, the volumes of chemically reacting gases lead to the chemical formulas for the compounds produced. All theories interrelate and extend the significance of the facts that fall within their compass.

Working models. Theories frequently make use of simplified mental images for physical systems. These images are called *working models* for the system. One example is the sphere model for the earth, in which the planet is represented as a uniform spherical body and its topographic and structural complexities are neglected. Another example is the particle model for the sun and planets in the solar system; in this model each of these bodies is represented as a simple massive point in space, and its size as well as its structure is ignored. Still another example is the "rigid body model" for any solid object (a table, a chair) that has a definite shape but may bend or break under a great stress.

Unlike other kinds of models (Fig. 1.3), a working model is an abstraction from reality. Our thoughts can never comprehend the full complexity of all the details of an actual system. Working models are always simplified or idealized representations, as we have already pointed out. Working models, therefore, and the theories of which they are a part, have limitations that must be remembered when their theoretical predictions fail to agree with observations.

Figure 1.3 The word "model" has many connotations in the English language, and most of them are not applicable to the scientific meaning of the word. A scientific "working model" has very little in common with a scale model (model airplane, left), a sample for examination (model home, below left), a visual replica (architectural model, below center), or a person (artist's or fashion model, below right).



The scientist's relationship to the models he constructs is ambivalent. On the one hand, the invention of a model engages his creative talent and his desire to represent the operation of the system he has studied. On the other hand, once the model is made, he seeks to uncover its limitations and weaknesses, because it is from the model's failures that he gains new understanding and the stimulus to construct more effective models. Both creative and critical faculties are involved in the scientist's work with models.

One feature of working models is frequently disturbing to nonscientists: no model perfectly matches reality, and you never know whether a particular model is "right." In fact, the concepts "right" and "wrong" do not really apply to models. Instead, a model may be more or less adequate, depending on how well it represents the functioning of the system it is supposed to represent. Even an inadequate model is better than none at all, and even a very adequate model is often replaced by a still more adequate one. The investigator has to determine whether a particular model is good enough for his purposes or whether it is necessary to seek a better one.

Analogue models. Before a scientist constructs a theory, he often realizes that the system he is studying operates in a way similar to another system with which he is more familiar, or on which he can conduct experiments more easily. This other system is called an analogue model for the first system. You may, for instance, liken the spreading out of sound from a violin to the spreading out of ripples from a piece of wood bobbing on a water surface.

The analogue model for one physical System A is another, more familiar, System B, whose parts and functions can be put into a simple correspondence with the parts and functions of System A. For example, an analogy may be drawn between the human circulatory system and a residential hot water heating system (Table 1.1, below). It is clear that

TABLE 1.1 ANALOGUE MODEL FOR THE HUMAN CIRCULATORY SYSTEM

System A: Human circulatory system	**System B:** Residential hot water heating system
veins, arteries	pipes
blood	water
oxygen	thermal energy
heart	pump
lungs	furnace
capillaries	radiators
hormones	thermostat
(model fails) (or dilation of veins & arteries)	overflow tank
blood pressure	water pressure
white blood cells	(model fails)
carbon dioxide	(model fails)
kidneys	(model fails)
intestine	(model fails)

the human circulatory system fulfills several functions, whereas the heating system fulfills only one. The analogue model is, therefore, not complete, but it is nevertheless instructive.

The virtue of an analogue model is that System B is more familiar than System A. This familiarity can have several advantages:

1. Features of the analogue model can call attention to overlooked features of the original system. (Had you overlooked the role of hormones in the circulatory system, the room thermostat would have reminded you.)
2. Relationships in the analogue model suggest similar relationships in the original system. (Furnace capacity must be adequate to heat the house on a cold day; lung capacity must be adequate to supply oxygen needs during heavy exercise.)
3. Predictions about the original system can be made from known properties of the more familiar analogue model. (Water pressure is high at the inflow to the radiators, low at the outflow; therefore, blood pressure is high in the arteries, low in the veins.)

The limitations of the analogue model can lead to erroneous conclusions, however. On a cold day, for instance, the water temperature is higher in the radiators; therefore, you might predict that the oxygen concentration in the blood will be higher during heavy exercise. Actually, the heartbeat and the rate of blood flow increase to supply more oxygen - the oxygen concentration does not change greatly.

"There are two methods in which we acquire knowledge - argument and experiment."
Roger Bacon (1214-1294)

Thought experiments. In a thought experiment, a model is operated mentally, and the consequences of its operation are deduced from the properties of the model. A thought experiment differs from a laboratory experiment in that the latter serves to provide new information about what really happens in nature, whereas the former seeks new deductions from previous knowledge or from assumptions. By comparing the deductions with observations in real experiments, you can find evidence to support or contradict the properties or assumptions of the model.

A simple example of a mystery system (Fig. 1.4) can be used to illustrate these ideas. Two working models for what might be under the cover in Fig. 1.4 (a) are shown in Figs. 1.4 (b) and (c). If you conduct simple thought experiments with these models, you quickly find out how satisfactory they are. In the first thought experiment, you imagine turning handle A clockwise. In model G, handle B will turn somewhat faster, because the second gear is smaller than the first, but it will turn counterclockwise. This prediction is in disagreement with the properties of the mystery system. In the second thought experiment, you turn handle A in model S. What can you infer from this second experiment? Can you suggest a satisfactory working model?

Thought experiments are important tools of the theoretical scientist because they enable him to make deductions from a working model or a theory. These deductions can then be compared with observation. The usefulness of a theory or model is determined by the agreement between the deduction and observation. Some very general theories,

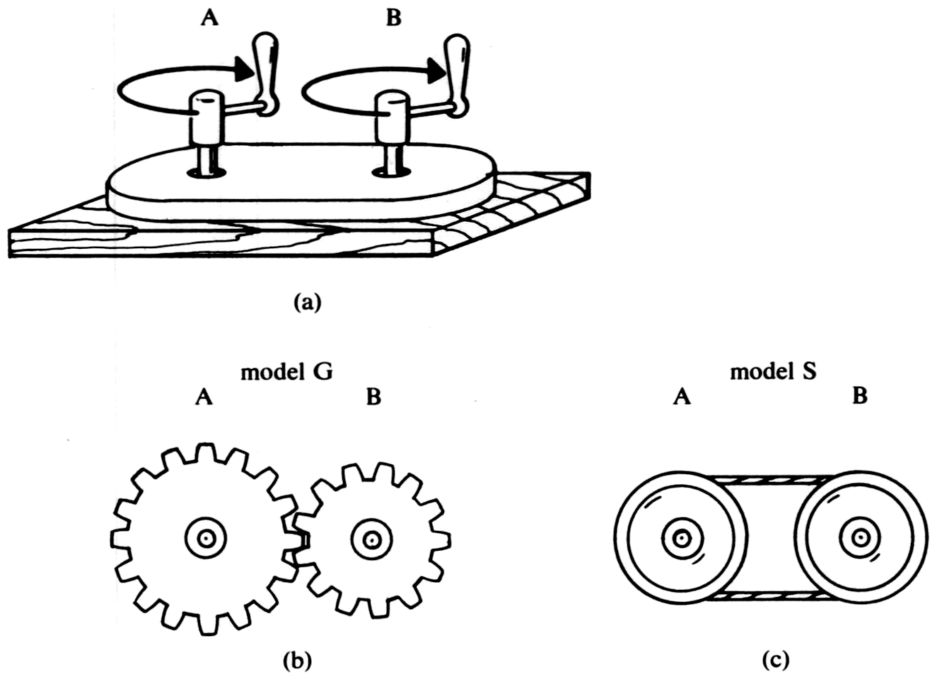


Figure 1·4 A mystery system. (a) When handle A is turned one revolution clockwise, handle B makes 2½ revolutions clockwise. Make models for what is under the cover. (b) Large and small gear model. (c) Two pulley and string model.

Equation 1.1

Mathematical model (algebraic form):
number of turns of handle A = N_A
number of turns of handle B = N_B

$$N_A = N_B$$

Equation 1.2

Mathematical model (algebraic form):
distance $= s$
speed $= v$
time $= t$

$$s = vt$$

such as the theory of relativity, lead to consequences that appear to apply universally. Some models, such as the corpuscular model for light, are useful only in a very limited domain of phenomena.

Mathematical models and variable factors. Scientific theories are especially valuable if they lead to successful quantitative predictions. Working models G and S for the mystery system in Fig. 1.4 both lead to quantitative predictions for the relationship between the number of turns of handles A and B. The relationship deduced from model S (that the handles turn equally) can be represented by the formula in Equation 1·1. We will call such relationships *mathematical models;* the formula in Equation 1.1 is an algebraic way of describing the relationship, which we have also described in words, and which can be described by means of a graph (Fig. 1.5).

A familiar example of a mathematical model, applicable to an automobile trip, is the relation of the distance traveled, time on the road, and speed of the car (Equation 1.2). The distance is equal to the speed times the time. At 50 miles per hour, for example, the car covers 125 miles in 2 ½ hours (Fig. 1.6).

The physical quantities related by a mathematical model are called *variable factors* or *variables*. The numbers of turns of handles A and B are two variable factors in Equation 1.1 and Fig. 1.5. The distance and elapsed time are two variable factors in Equation 1.2 and Fig. 1.6, The speed in this

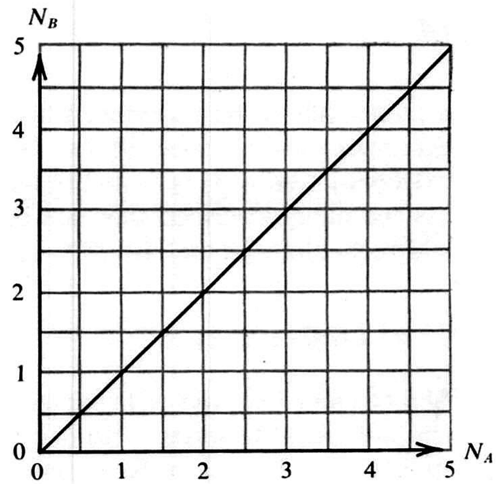


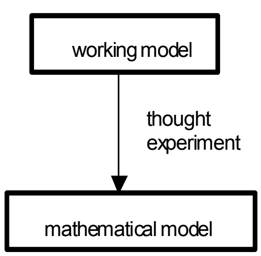
Figure 1.5 Mathematical model (graphical form).

Number of turns of handle A = N_A;

Number of turns of handle B = N_B;

mathematical model is called a constant, because it does not vary. Under different conditions, as in heavy traffic, the speed might be a variable factor.

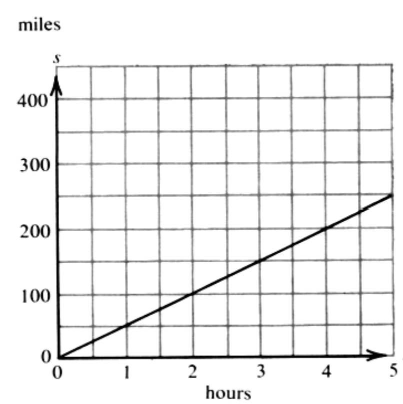
Like the working model for a system, the mathematical model for a relationship is not an exact reproduction of a real happening. No real car, for instance, should be expected to travel at the perfectly steady speed of 50 miles per hour for 2½ hours. The actual speed would fluctuate above and below the 50-mile figure. The actual distances covered at various elapsed times, therefore, might be a little more or a little less than those predicted by the model in Eq. 1.2 and Fig. 1.6. Nevertheless, the model gives a very good idea of the car's progress on its trip, and it is very simple to apply. For these reasons, the model is extremely useful, but you must remember its limitations.



Scientific theories. The making of a physical theory often includes the selection of a working model, the carrying out of thought experiments, and the construction of a mathematical model. All physical theories have limitations imposed by the inadequacies of the working model and the conditions of the thought experiments. Occasionally a theory has to be

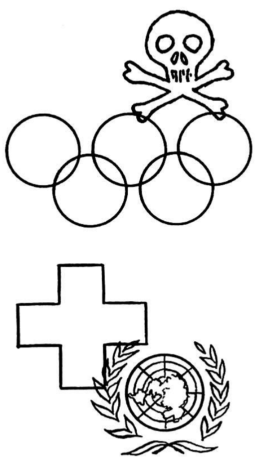
Figure 1.6 Mathematical model of relationship between distance and time (graphical form):

Distance = s (miles), time = t (hours), speed = 50 miles per hour.



abandoned because it ceases to be in satisfactory agreement with observations. Nevertheless, physical theories are extremely useful. It is probably the power of the theory-building process we have described that lies behind the rapid progress of science and technology in the last 150 years.

1.4 Definitions



The primary function of language is to communicate information from one individual to others. Human language consists of signs, gestures, spoken sounds, and marks on paper that function as symbols of some sensed experience. Communication by means of human language is possible so long as the communicants have a common understanding of the meaning of the symbols, that is, so long as all persons relate a given symbol to a particular common experience and to none other.

In learning a language, you must first learn to recognize the symbol, then to relate that symbol to a particular experience. A symbol may refer to a material object, the relation or state of material objects, other symbols, or relations of symbols. The normal device for conveying the meaning of a symbol is the definition, of which we will distinguish two types. These are formal definitions, which use words, and operational definitions, which use operations.

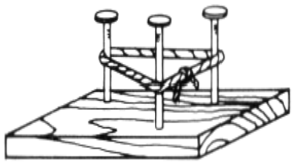
Formal definitions. The familiar dictionary definitions, which identify the meaning of a symbol by the use of words or other symbols, are included in the category of formal definitions. Synonyms, paraphrases, lists of properties, and names of examples are the usual techniques of formal definition.

bottle = jar ?

An example of the use of synonym is "bottle = jar." Synonyms may have exactly the same meaning, but they usually have slightly different meanings. For example, both "bottle" and "jar" are "containers made of glass" (paraphrase) but usually connote different shapes.

An example of definition by paraphrase is "photosynthesis = the conversion of light energy into chemical energy in green plants." Another example is "velocity of an object = the distance traveled divided by the time taken." The paraphrase definition is similar to the definition by synonym, except that the paraphrase contains more words. The paraphrase definition leads to efficiency in communication (or thought, which is self-communication) in that you can substitute the shorter term for the longer phrase. We will occasionally use paraphrases based on a mathematical process to define physical terms, as we did in the velocity example just given.

Operational definitions. The use of real objects and operations (not merely words) to produce, measure, or recognize an instance of a term is the essence of the operational definition. For example, the operational definition of color words, such as red, yellow, mauve, and lime, may be based on a set of color chips that have sample colors on one side and their names on the back. The objects used in this definition are the color chips. The operation is that of comparison of the hue of an unidentified color with those of the color chips. This operational definition is in general use in paint stores.

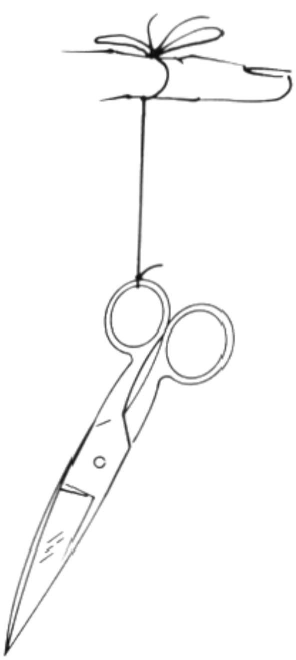


Words can be used to describe an operational definition but the definition itself consists of operations on real objects and not of words. For example, you can construct a triangle by driving three nails into a board and connecting the nails with a stretched string. A figure that matches the figure constructed in this way is also a triangle. These objects and operations define a triangle.

An example of an operational definition that leads to measurement is as follows: the number of seats in an auditorium is the auditorium's capacity. Here the actual seats in the auditorium and the counting operation are combined in an operational definition of the auditorium capacity.

We will soon introduce operational definitions for measuring basic physical quantities, such as length, time, and mass. Each of these definitions makes reference to a standard object that serves as the unit of measurement (in the definition of auditorium capacity, the chair served as the unit of measurement) and a comparison operation that allows the unit to be compared with other objects.

For science, the significance of operational definitions is that their use keeps the description of models and the statement of theories meaningful and testable in the physical world. In contrast to the scientist's operationally defined language, that of the poet rests mainly on terms (for example "beauty," "love," and "grace") that are not defined operationally. However, it is also worth pointing out that the language of a poem generally *does* have a close relationship (or multiple relationships) with the significance, sound, and/or meaning of the words as they are used in the language at large. We also must realize that while scientific concepts must always be somehow logically tied to operational definitions, many scientists use concepts that are only tied to an operational definition through a series of formal definitions. Therefore, scientists often use language that appears just as distant from the real world as the poet's! Finally, poets have anticipated key scientific developments, for example, in ancient times, Lucretius speculated about atoms in his poem, *On the Nature of Things*.



Comparison of formal and operational definitions. In science, formal definitions are frequently used to define one concept in terms of other concepts. For instance, the term "triangle" could have been defined by paraphrase as "a plane figure bounded by three nonparallel straight lines." This definition uses concepts, such as "plane," "nonparallel," "three," and "straight line," for which definitions have to be provided or that may properly remain undefined.

Let us consider another term, "vertical," that can be defined operationally or formally. In the operational definition, a freely hanging plumb line is allowed to come to rest; vertical is the direction indicated by the plumb line. The formal definition is "vertical = the direction toward the center of the earth." The latter definition is a paraphrase that is useful for theoretical purposes, but impossible to apply in practice, as when a house's walls are to be built.

The difference between formal and operational definitions is illustrated especially clearly by their application to "intelligence" and "IQ."

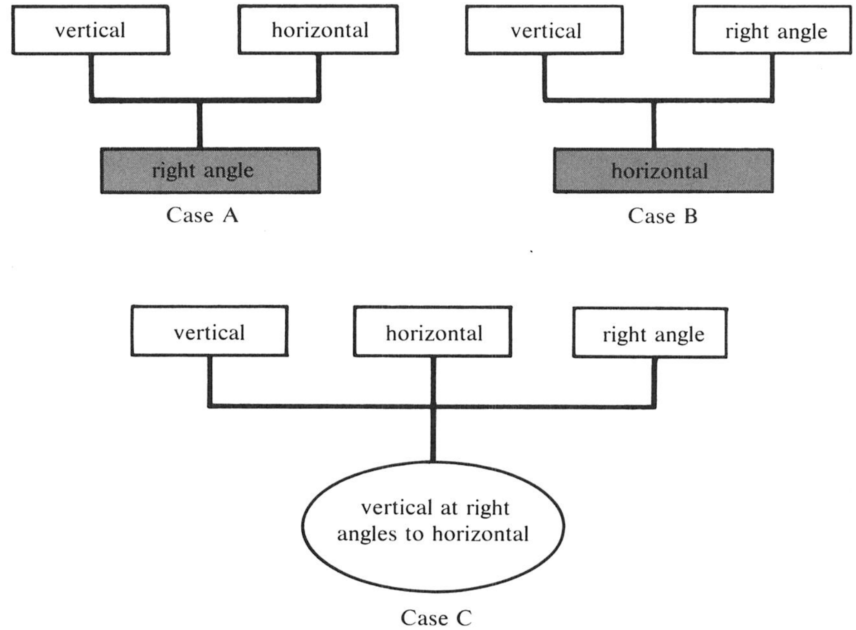


Figure 1.7 Definitions of vertical, horizontal, and right angle. Open box: operationally defined; shaded box: formally defined; oval: experimentally discovered. The definitions are described in Table 1.2

The dictionary defines intelligence as "the ability to apprehend the interrelationships of presented facts in such a way as to guide action toward a desired goal." The value of this formal definition as a positive personal trait seems obvious. It is very difficult, however, to rank individuals according to their intelligence, because this requires applying the definition operationally to specific cases. The intelligence

TABLE 1.2 THREE ALTERNATIVE DEFINITIONS OF VERTICAL, HORIZONTAL AND RIGHT ANGLE

Case A.	Define vertical: direction of a free plumb line at rest. Define horizontal: direction of a free water surface at rest. Define right angle: the angle between the vertical and horizontal.
Case B.	Define vertical: direction of a free plumb line at rest. Define equal angles: angles that match when superposed. Define straight line: matches a stretched string. Define right angle: draw two intersecting straight lines on a given (flat) board so that four equal angles are produced. Each angle is a right angle. Define horizontal: the surface at right angles to the vertical.
Case C.	Define vertical: direction of a free plumb line at rest. Define horizontal: direction of a free water surface at rest. Define right angle: draw two intersecting straight lines on a given (flat) board so that four equal angles are produced. Each angle is a right angle. Experimental relation: vertical and horizontal make a right angle.

quotient (IQ) can be defined operationally by a standard score on a specific test combined with a person's age. However, the *meaning* of the IQ as a personality trait and its functional value (that is, the relationship between an operationally defined IQ and its more generally accepted formal definition) are subjects of controversy that are far from being resolved.

Formal definitions and operational definitions each have their advantages and disadvantages. Operational definitions, as we have already stressed, make direct reference to the physical world and to human perception. This property gives them the advantage of being concrete. At the same time, their dependence on specific objects (such as auditorium seats) limits their scope of application. The definition of "capacity" given for an auditorium, for instance, could not be applied to the gasoline tank of a car. A definition of temperature using an ordinary thermometer would not be applicable in the interior of the sun. Operational definitions tend to be cumbersome in that they demand the availability of certain equipment.

Formal definitions, by contrast, are more concise and efficient. They relate concepts to one another directly. The definitions are much more generally valid. The price that is paid for these advantages is that the language becomes very abstract, because direct connections with reality are buried in the foundations on which the system of formal definitions rests.

In this text we will place more reliance on operational definitions than is customary, because we believe that concrete ties to reality are more valuable to you than efficiency and generality. Our approach, therefore, will be somewhat different from that of other texts. However, the physical world that is being described is the same; the differences are in the logical development and not in the content itself. To illustrate the diversity of possible approaches to the logical development of ideas, Fig. 1.7 and Table 1.2 show how the concepts "vertical," "horizontal," and "right angle" may be defined and related to one another in three different ways.

1.5 Length, time, and mass

That we relate most easily to the macro domain of magnitudes is reflected in the fact that units for measuring length have, since ancient times, been derived from our bodies (Fig. 1.8). The ready availability of the human body made the foot and the inch convenient units, but there was a great deal of local variation, depending on whose foot or thumb was used. With the growth of an international scientific community, it became necessary to adopt standard units of measurement that would be accepted by scientists everywhere. The French Academy of Sciences in 1791 suggested a new unit of length, the meter, which was to be one ten-millionth of the distance from the pole to the equator of the earth. Accordingly, a platinum-iridium bar with two marks separated by the "standard meter" was prepared after seven years of surveying the earth in Spain and France. The original is kept in the Bureau of Weights and Measures near Paris and accurate copies are kept by the National Bureau of Standards near Washington (Fig. 1.9) and by similar agencies

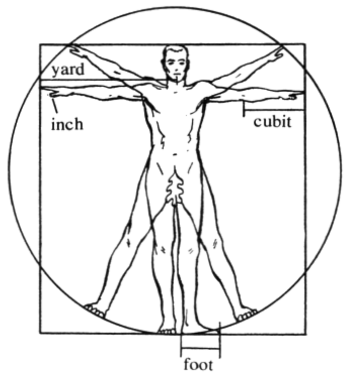


Figure 1-8 Units of measurement related to the human body.

OPERATIONAL DEFINITION

Length or distance is measured by the number of standard units of length that can be placed end to end to match the desired length or distance.

The symbol s (for space) will be used to represent distance.

Abbreviations for units:
1 m = 1 meter
1 cm = 1 centimeter
= 0.01 m = 10^{-2} *m*
1 mm = 1 millimeter
= 0.001 m = 10^{-3} *m*
1 km = 1 kilometer
= 1000 m = 10^{3} *m*

elsewhere. The marks on the rulers you use are derived, through a long chain of copying, from the original standard meter in France.

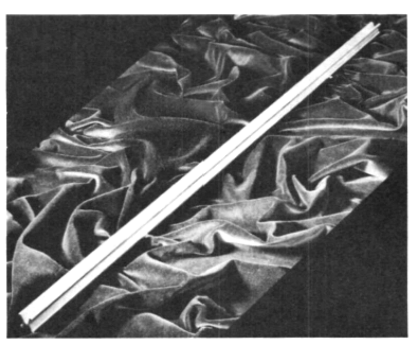
Widely accepted units of measurement are essential to our technological culture. The story of weights and measures and the continuing search for improved standard units will never end.

We turn now to the operational definitions of the basic quantities of length, time, and mass. Since the most primitive measurement operation is that of counting, the definitions involve procedures for comparing the quantity to be measured with accepted standard units and counting the number of standard units that are required.

Length and distance. Length and distance are defined by a matching procedure in which the length of any object can be used as the unit. The generally accepted standard unit of length is the meter, described above. After the meter had been established, it was found that the earlier measurements of the earth had been inaccurate, so the geographical definition was abandoned, but the platinum-iridium bar was kept. However, duplicating the standard length was cumbersome and tended to introduce additional errors. As a result, the current definition of the meter in terms of the wavelength (see Chapter 7) of a specially designed light source was adopted. This definition allows the standard meter to

Figure 1.9 Replicas of the international standards of length and mass. (a) The standard meter bar. (b) The standard kilogram cylinder, whose size is close to that of a small egg.

(a)



(b)

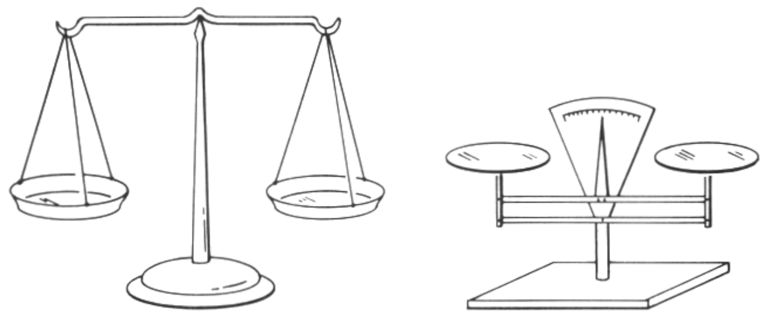


Figure 1.10 Equal-arm balances.

OPERATIONAL DEFINITION
Time interval is measured by the number of standard units of time that elapse during the desired time interval.

The symbol t will be used for time. The symbol Δt will be used for time interval. (Δ is the Greek letter delta, for difference.)
Abbreviations for units:
1 sec = 1 second
1 min = 1 minute = 60 sec
1 hr = 1 hour = 3600 sec
1 day = 86,400 sec
1 yr = 1 year = 3.16 x 10^7 sec

OPERATIONAL DEFINITION
Mass of an object is measured by the number of standard units of mass that are required to balance the desired object on an equal-arm balance.

The symbol M_G will be used for gravitational mass. Abbreviations for units:
1 kg = 1 kilogram
1 g = 1 gram = 0.001 kg = 10^{-3} kg
1 mg = 1 milligram= 10^{-6} kg
1 metric ton= 1000 kg = 10^3 kg
1 megaton = 10^9 kg

be replicated conveniently as needed: you simply measure the wavelength of the standard source to whatever accuracy is required.

Units of length associated with the meter are the centimeter (one hundredth of a meter), millimeter (one thousandth of a meter), and kilometer (1000 meters).

Time. Time intervals are defined by a matching procedure in which the unit of time may be the swing of a pendulum, the emptying of an hourglass, or the completion of some other repeated pattern of motion. The generally accepted standard unit of time is based on the repeating (periodic) motion of the earth around the sun (year) and the rotation of the earth on its axis (day). By means of a pendulum or other such system with a short time of repeating its motion, the second has been defined as 1/86,400 of a mean solar day, which is 1/365.2 ... of a year. As in the case of length, a standard unit of time associated with atomic vibrations has been substituted for the astronomical definition.

Mass. Mass is defined by a matching procedure with an equal-arm balance. The unit of mass could be any object, a stone, or a nail, for example. The accepted unit of mass since 1889 is the kilogram, the mass of a metal cylinder kept under carefully controlled conditions near Paris (Fig. 1.9). The kilogram was intended to be the mass of 1000 cubic centimeters of water at 4° Celsius. Later, more accurate measurements showed that the original determination was slightly in error, so that the reference to water was abandoned. The operational definition of mass makes use of the equal-arm balance (Fig. 1.10), which responds to the downward pull of the earth (commonly known as the weight). Therefore, mass, as we are referring to it here, is called the *gravitational mass*. This idea of mass as intimately connected with the gravitational attraction exerted by the earth will come up again in Section 3.4 where we will explain the related, but distinct, concept of *inertial mass.*

Units of mass derived from the kilogram are the gram (one thousandth of a kilogram), very closely equal to the mass of 1 cubic centimeter of water, and the metric ton (1000 kilograms), very closely equal to the mass of 1 cubic meter of water.

Domain		**Size in meters**		**Time in seconds**
	10^{+24}		10^{+24}	
	10^{+21}	Milky Way (our galaxy)	10^{+21}	
	10^{+18}		10^{+18}	age of Universe
				life on earth
	10^{+15}		10^{+15}	first mammals
		Solar System		first humans
	10^{+12}	orbit of Jupiter	10^{+12}	
Cosmic domain		orbit of Earth		recorded history
	10^{+9}	Sun diameter	10^{+9}	human lifetime
		Earth diameter		year
	10^{+6}	Chicago to NY	10^{+6}	month
				day
	10^{+3}	1 mile	10^{+3}	hour
Macro domain				minute
	10^{0} (1 m.)	Human stride	10^{0} (1 sec.)	heartbeat
	10^{-3}	millimeter	10^{-3}	1 vibration (audible sound wave)
		razor edge		
Micro domain	10^{-6}	single cells	10^{-6}	1 vibration (AM radio wave)
		DNA, proteins		
	10^{-9}	molecules	10^{-9}	1 cycle (1 GHz computer)
		atoms		
	10^{-12}		10^{-12}	1 cycle (1000 GHz computer)
		atomic nuclei		
	10^{-15}		10^{-15}	1 vibration (visible light)
	10^{-18}		10^{-18}	1 vibration (X-ray)
	10^{-21}		10^{-21}	

Figure 1.11 Time and size scale of cosmic, macro, and micro domains.

Other variable factors. It is possible to define units for all other physical variables through definitions based on mass, length, time, and temperature (to be defined in Chapter 10). We will, however, take a different approach, in which we introduce operational definitions for several concepts, such as energy and force, because such an operational procedure makes the physical meaning of the concepts clearer. You will have to accept one disadvantage of this procedure: operational definitions are limited by the technique or operation used and thus will not be the most general ones possible.

Domains of magnitude. We now briefly return to the three domains of magnitude introduced in Section 1.3: the cosmic domain, the macro domain of the everyday world, and the micro domain. Using the definitions of the standard units of measure that we have described, we can approximately characterize the domains by their relationship to these units. Figure 1.11 illustrates this relationship and shows the time and size scale of the various domains.

Summary

*"Go, wondrous creature!
Mount where Science guides;
Go measure earth, weigh air, and state the tides;
Instruct the planets in what orbs to run,
Correct old Time, and regulate the Sun."*

Alexander Pope
Essay on Man, 1732

The phenomena studied by the physical scientist are highly diverse, ranging from the orbital motion of satellites to the propagation of light, from the turbulent motion of gases in the sun to the structure of the atomic nucleus. The space and time dimensions of phenomena are conveniently divided into three domains: the macro domain, roughly comparable to the human body; the cosmic domain of the very large or very enduring phenomena; and the micro domain of the very small or highly transient phenomena.

In the growth of science, the discovery of new facts and the formulation of new theories go hand in hand. New theories encompass the new facts and may reorganize previously established fields. Working models, thought experiments, and mathematical models are the components of a theory. The terms used to describe models and experiments are related to the real world through operational definitions or to concepts through formal definitions. Measurement (quantitative observation) is introduced through the counting of standard units in the operational definitions of length (distance), time intervals, and gravitational mass.

List of new terms

scientific point of view
scientific "truth"
domains of magnitude:
  micro, macro, cosmic
theory
working model
analogue model
mathematical model
thought experiment
variable factor
constant
formal definition
paraphrase
operational definition
standard object
length: meter
time: year, second
mass: kilogram
equal-arm balance

Problems

1. Give two examples from your own life where you had to revise your expectations (or prejudices) in the light of experience.
2. Describe your feelings toward the study of physics.
3. Describe the values of studying physics as part of a liberal education. Comment on these values from your point of view.
4. Give one or two examples from your own life in which your knowledge of physics was inadequate to the requirements (exclude school experiences).
5. Compare the growth of a city to the growth of science. Does the growth of a city have many similarities to the growth of science? Perhaps new homes correspond to new facts. Perhaps new roads correspond to new theories. Point out similarities and differences. Is the city a good analogue model for science in this respect?
6. Compare the growth of science to various other growth processes. Point out similarities and differences. Are these other examples more or less helpful than the one discussed in Problem 5?
7. Use a dictionary to trace the definition of the word matter. Look up the definition of each major word used to define matter, and so on, until you discover where this process leads. Discuss your discovery and compare it with the approach of this text, which is to leave "matter" as an undefined term (see note in margin on p. 6).
8. Express your preferences with regard to the corpuscular and wave theories of light.
9. Compare scientific "truth" with truth in another domain.
10. Tell which of your senses are most effective in detecting events at the lower limit of the macro domain in space and time. Estimate the magnitude of the smallest length and shortest time interval your senses can detect directly.
11. Tell which of your senses are most effective in detecting events at the upper limit of the macro domain in space and time. Estimate the magnitude of the largest length and longest time interval your senses can detect directly.
12. List examples of indirect evidence (not directly perceived by your sense organs) of phenomena in the macro domain.
13. List examples of direct sensory evidence of phenomena in the micro and cosmic domains. What are some tools used to extend the senses to enable them to cope with phenomena in these domains? Describe the use of these tools and explain whether it leads to direct or indirect evidence.
14. Explain the similarities and differences between a scientific "working model" (such as considering the earth as a uniform, smooth

sphere) and each of the following examples of a "model":
(a) A scale model, such as a model airplane.
(b) A small-scale architectural model of a proposed building.
(c) A model home.
(d) An individual who poses for photographs or paintings, a fashion or artists' model.

15. Carefully examine the system illustrated in Fig. 1.4a.
(a) Propose two (or more) working models that are compatible with all the information given in Fig. 1.4.
(b) Describe one (or more) thought experiments in which your two models exhibit different outcomes. (Such experiments can be used in real experimental tests to eliminate models that lead to a wrong prediction.)

16. Describe two or more working models that apply in an academic field of your choice or in everyday life. For each model, describe some of its properties, how it functions, what observations it explains successfully, and where it fails.

EXAMPLE. Protein-carbohydrate-and-fat model for food. All foods consist of these three materials, in various proportions. The energy (Calorie) value of any food can be found from its content of the three materials by a mathematical model. The planning of a balanced diet takes into account the human body's need for the three materials. Gain or loss of weight can be planned on the basis of the Calorie value.

Limitation: it is possible to have a well-balanced diet in terms of proteins, carbohydrates, and fats, yet suffer nutritional deficiencies. The model does not include all the contributions that food makes. Vitamins and minerals are also important, even though they do not contribute to the energy (Calorie) value of food.

Suggested models: computer model for the human brain, gene model for inheritance, "free/efficient market" model for world economy, "economic" model for human beings, demon model for the source of disease.

17. Five blind men investigated an elephant by feeling it with their hands. One felt its tail, one a leg, one a tusk, one an ear, one its side. Describe the analogue models for an elephant they might create individually and by pooling their observations. Describe the implications of this fable for science.

18. Interview three or more children (between ages 7 and 10) to ascertain their ideas as to the source of knowledge and the creation of new knowledge. Ask questions such as, How do we know that 3 + 3 = 6? How do we know that the sun will rise tomorrow? How do we know the earth is round? How do we know how to make a watch (car, rocket, cake....)? Ask questions to probe beyond the first responses. (If possible, undertake this project jointly with several other students so as to obtain a larger collection of responses.) Comment on the responses.

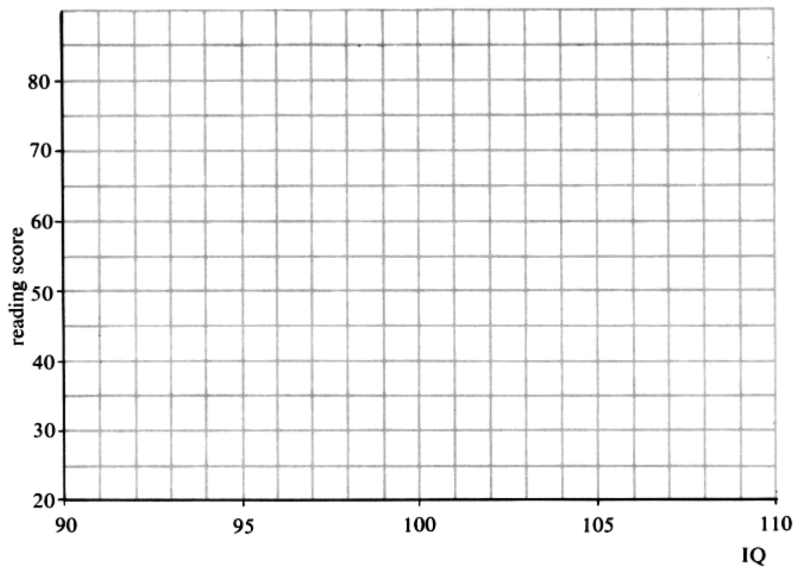


Figure 1.12 Coordinate grid for graph from Problem 19.

TABLE 1-3 READING AND INTELLIGENCE TEST SCORES (PROBLEM 19)

School	*Reading*	*IQ*	*School*	*Reading*	*IQ*
A	33	93	J	51	99
B	59	103	K	31	92
C	57	104	L	51	98
D	46	99	M	69	107
E	48	99	N	73	108
F	54	100	O	48	98
G	52	100	P	75	108
H	52	101	Q	64	105
I	61	103	R	79	111

19. Reading tests and intelligence tests were given sixth graders in a large state. Table 1.3 (above) lists the average scores for schools in eighteen different communities, in order from the largest to the smallest enrollment. Display the data on a graph (Fig 1.12, above), and, if there is a relationship between the two scores, make a mathematical model (in either graphical or algebraic form) for this relationship. Interpret this model. Be careful about making interpretations not actually supported by the given data; explain and criticize whatever assumptions you make, as well as the assumptions that are "hidden" in the data (the test scores).

20. State a formal definition and describe an operational definition for each of the following.

(a) chair	(d) life
(b) gift	(e) person
(c) teacher	(f) scientific literacy

Comment on the advantages and limitations of the definitions you have constructed.

21. To be constitutional, laws must be applicable to real cases with a minimum of ambiguity. Therefore, they often include operational definitions of the terms that are used in them. Find and report three operational definitions that are part of laws. Discuss the extent to which the inclusion of these operational definitions promotes or restricts the achievement of justice.

22. State three or more operational definitions that you use in your everyday life. The definitions should not deal with profound ideas but may be as simple as: ironing temperature (of a flatiron) is measurable by the "sizzling rate" of a water drop that touches the iron.

23. Write a critique of the hypothesis (beginning of Section 1.2) that the foundations of a person's sense of space and time are laid before birth.

24. Identify one or more explanations or discussions in this chapter that you find inadequate. Describe the general reasons for your judgment (conclusions contradict your ideas, steps in the reasoning have been omitted, words or phrases are meaningless, equations are hard to follow, . . .), and make your criticism as specific as you can.

Bibliography

Introductory physics or physical science textbooks and surveys. These references cover the same material as this text but from a different point of view. Many of them present a more mathematical treatment that uses algebra and trigonometry, but none employs calculus.

K. R. Atkins, *Physics*, Wiley, New York, 1966. Emphasizes interaction point of view, more mathematical.

D. Cassidy, G. Holton, J. Rutherford, *Understanding Physics*, Springer Verlag, 2002. This text, an update of Holton's outstanding 1952 book, is particularly recommended for its historical perspective.

L. N. Cooper, *An Introduction to the Meaning and Structure of Physics*, Harper and Row, New York, 1968. Includes much on quantum physics and relativity, many quotations.

E. R. Huggins, *Physics 1*, W. A. Benjamin, New York, 1968. Presents the interaction point of view. Strong on quantum physics and relativity.

R. B. Lindsay and H. Margenau, *Foundations of Physics*, Wiley, New York, 1936.

V. L. Parsegian, A. S. Meltzer, A. S. Luchins, and K. S. Kinerson, *Introduction to Natural Science, Part One: The Physical Sciences*, Academic Press, New York, 1968. Relates biological, historical, philosophical, sociological, and humanistic material to physical science.

U. Haber-Schaim *et al, PSSC Physics*, Kendall/Hunt, Dubuque, Iowa, 1991. Especially good on wave physics.

E. Rogers, *Physics for the Inquiring Mind*, Princeton University Press, Princeton, New Jersey, 1960. Contains informal explanations, quaint diagrams, and many suggestions for simple experiments.

L. W. Taylor, *Physics, the Pioneer Science*, Dover Publications, New York, 1941. Includes a great deal of historical material.

V. F. Weisskopf, *Knowledge and Wonder: The Natural World as Man Knows It*, 2nd Edition, MIT Press, Cambridge, Mass. 1979. An excellent qualitative lecture series on many facets of physical science. Authored by one of the central players in the discovery of quantum mechanics and quantum electrodynamics, a theorist noted both for his brilliance as well as for his infectious, vibrant personality.

Books and essays on the history and philosophy of science, especially physics:

M. J. Aitkin, *Physics and Archeology*, Wiley (Interscience), New York, 1961.

Francis Bacon. *Novum Organum*, Collier, New York, 1902.

W. I. B. Beveridge, *The Art of Scientific Investigation*, W. W. Norton. New York, 1957.

P. W. Bridgman, *The Logic of Modern Physics*, Macmillan, New York, 1946.

J. Bronowski, *Science and Human Values*, Harper and Row, New York, 1965.

J. Bronowski, *The Common Sense of Science*, Harvard University Press, Cambridge, Massachusetts, 1953.

G. B. Brown, *Science, Its Method and Philosophy*, W. W. Norton, New York, 1950.

H. Butterfield, *The Origins of Modern Science*, Macmillan, New York, 1965.

N. Campbell, *What is Science?,* Dover Publications, New York, 1952.

B. K. Cline, *The Questioners*, Crowell, Collier and Macmillan, New York, 1965.

J. B. Conant, *Science and Common Sense*, Yale University Press, New Haven, Connecticut, 1951.

G. de Santillana, *Origins of Scientific Thought*, University of Chicago Press, Chicago, Illinois, 1961.

A. Einstein and L. Infeld, *Evolution of Physics*, Simon and Schuster, New York, 1938.

A. R. Hall, *The Scientific Revolution 1500-1800*, Beacon Press, Boston, Massachusetts, 1954.

W. Heisenberg, *Physics and Philosophy*, Harper and Row, New York, 1958.

E. H. Hutten, *The Ideas of Physics*, Oliver and Boyd, Edinburgh and London, 1967.

S. L. Jaki, *The Relevance of Physics*, University of Chicago Press, Chicago, Illinois, 1966.

T. S. Kuhn, *Structure of Scientific Revolutions*, University of Chicago Press, Chicago, Illinois, 1962.

S. K. Langer, *Philosophy in a New Key*, Harvard University Press, Cambridge, Massachusetts, 1942.

L. Leprince-Ringuet, *Atoms and Men*, University of Chicago Press, Chicago, Illinois, 1961.

H. Margenau, *The Nature of Physical Reality*, McGraw-Hill, New York, 1950.

E. Nagel, *The Structure of Science*, Harcourt, Brace and World, New York, 1961.

H. Poincaré (S. Gould, Editor), *The Value of Science: Essential Writings of Henri Poincaré* (includes three books: Science and Hypothesis, 1903; The Value of Science, 1905; and Science and Method, 1908), Modern Library, 2001.

J. W. N. Sullivan, *The Limitations of Science*, The New American Library, New York, 1952.

Historical source materials and collections of biographies. These references contain short articles appropriate to many of the later chapters, but these articles are not listed again in the chapter bibliographies. If a topic arouses your interest, you should examine one or more of these references for information supplementary to the text.

A. Beiser, Ed., *The World of Physics*, McGraw-Hill, New York, 1960.

B. Brody and N. Capaldi, Ed., *Science: Men, Methods, Goals*, W. A. Benjamin, New York, 1968.

T. W. Chalmers, *Historic Researches*, Scribner's, New York, 1952.

J. B. Conant and L. K. Nash, *Harvard Case Histories in Experimental Science*, Harvard University Press, Cambridge, Massachusetts, 1957.

L. Hamalian and E. L. Volpe, Ed., *Great Essays by Nobel Prize Winners*, Noonday Press, New York, 1960.

W. S. Knickerbocker, *Classics of Modern Science*, Beacon Press, Boston, Massachusetts, 1962.

H. Lipson, *The Great Experiments in Physics*, Oliver and Boyd, Edinburgh and London, 1968.

O. Lodge, *Pioneers of Science*, Dover Publications, New York, 1926.

W. F. Magie, *A Source Book in Physics*, Harvard University Press, Cambridge, Massachusetts, 1963.

G. Schwartz and P. W. Bishop, *Moments of Discovery*, Basic Books, New York, 1958.

M. H. Shamos, *Great Experiments in Physics*, Holt, Rinehart, and Winston, New York, 1959.

Articles from Scientific American. Some or all of these, plus many others, can be obtained on the Internet at http://www.sciamarchive.org/.

A. V. Astin, "Standards of Measurement" (June 1968).

T. G. R. Brower, "The Visual World of Infants" (December 1966).

D. D. Kosambi, "Scientific Numismatics" (February 1966). A study of the fascinating results yielded by the application of modern science to ancient coins.

H. Zuckerman, "The Sociology of the Nobel Prizes" (November 1967).