

Chapter 1 Introduction and Measurements

In exploring nature, therefore, we must begin by trying to determine its first principles.

Aristotle

The method with which we shall follow in this treatise will be always to make what is said depend on what was said before.

Galileo Galilei

1.1 Historical Background

Physics has its birth in mankind's quest for knowledge and truth. In ancient times, people were hunters following the wild herds for their food supply. Since they had to move with the herds for their survival, they could not be tied down to one site with permanent houses for themselves and their families. Instead these early people lived in whatever caves they could find during their nomadic trips. Eventually these cavemen found that it was possible to

domesticate such animals as sheep and cattle. They no longer needed to follow the wild herds. Once they stayed long enough in one place to take care of their herds, they found that seeds collected from various edible plants in one year could be planted the following year for a new crop. Thus, many of these ancient people became farmers, growing their own food supply. They, of course, found that they could grow a better crop in a warm climate near a readily available source of water. It is not surprising then that the earliest known¹ civilizations sprang up on the banks of the great rivers: the Nile in Egypt and the Tigris and Euphrates in Mesopotamia. Once permanently



Figure 1.1 The caveman steps out of his cave.

located on their farms, these early people were able to build houses for themselves. Trades eventually developed and what would later be called civilization began.

To be successful farmers, these ancient people had to know when to plant the seeds and when to harvest the crop. If they planted the seeds too early, a frost could destroy the crop, causing starvation for their families. If they planted the seeds too late, there might not be sufficient growing time or adequate rain.

In those very dark nights, people could not help but notice the sky. It must have been a beautiful sight without the background street lights that are everywhere today. People began to study that sky and observed a regularity in the movements of the sun, moon, and stars. In ancient Egypt, for example, the Nile river would overflow when Sirius, the Dog Star, rose above the horizon just before dawn. People then developed a calendar based on the position of the stars. By their observation of the sky, they found that when certain known stars were in a particular position in the sky it was time to plant a new crop. With an abundant harvest it was now possible to store enough grain to feed the people for the entire year.

For the first time in the history of humanity, obtaining food for survival was not an all time-consuming job. These ancient people became affluent enough to afford the time to think and question. What is the cause of the regularity in the motion of the heavenly bodies? What makes the sun rise, move across the sky, and then set? What makes the stars and moon move in the night sky? What is the earth made of? What is man? And through this questioning of the world about them, **philosophy** was born - the search for knowledge or wisdom (*philos* in Greek means "love of" and *sophos* means "wisdom"). Philosophy, therefore, originated when these early people began to seek a rational explanation of the world about them, an explanation of the nature of the world without

¹It is not that other civilizations did not exist, only that they had not discovered the technology of writing and hence did not leave records of any of their activities. As an example, there is evidence that at Stonehenge in ancient England, a civilization flourished there before the pyramids of Egypt were ever built. We take writing for granted, but it is one of the greatest technological achievements of all time.

recourse to magic, myths, or revelation. Ancient philosophers studied ethics, morality, and the essence of beings as determined by the mind, but they also studied the natural world itself. This latter activity was called **natural philosophy** - the study of the phenomena of nature. Among early Greek natural philosophers were Thales of Miletus (ca. 624-547 B.C.), Democritus (ca. 460-370 B.C.), Aristarchus (ca. 320-250 B.C.), and Archimedes (ca. 287-212 B.C.), perhaps the greatest scientist and mathematician of ancient times.

For many centuries afterward, the study of nature continued to be called natural philosophy. In fact, one of the greatest scientific works ever written was by Sir Isaac Newton. When it was published in 1687, he entitled it *Philosophiae Naturalis Principia Mathematica* (*The Mathematical Principles of Natural Philosophy*).

Natural philosophy, therefore, studied all of nature. The Greek word for “natural” is physikos. Therefore, the name physics came to mean the study of all of nature. Physics became a separate entity from philosophy because it employed a different method to search for truth. Physics developed and employed an approach called the scientific method in its quest for knowledge.

The **scientific method** is the application of a logical process of reasoning to arrive at a model of nature that is consistent with experimental results. The scientific method consists of five steps:

1. Observation
2. Hypothesis
3. Experiment
4. Theory or law
5. Prediction

This process of scientific reasoning can be followed with the help of the flow diagram shown in figure 1.2.

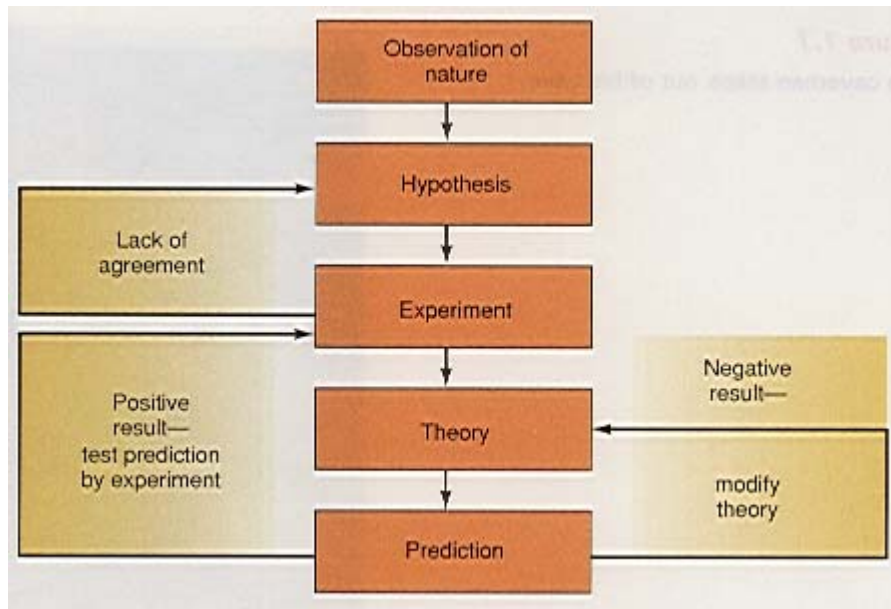


Figure 1.2 The scientific method.

1. *Observation.* The first step in the scientific method is to make an observation of nature, that is, to collect data about the world. The data may be drawn from a simple observation, or they may be the results of numerous experiments.

2. *Hypothesis.* From an analysis of these observations and experimental data, a model of nature is hypothesized. The dictionary defines a hypothesis as an assumption that is made in order to draw out and test its logical or empirical consequences; that is, an assumption is made that in a given situation nature will always work in a certain way. If this hypothesis is correct, we should be able to confirm it by testing. This testing of the hypothesis is called the experiment.

3. *Experiment.* An experiment is a controlled procedure carried out to discover, test, or demonstrate something. An experiment is performed to confirm that the hypothesis is valid. If the results of the experiment do not support the hypothesis, the experimental technique must be checked to make sure that the experiment was really measuring that aspect of nature that it was supposed to measure. If nothing wrong is found with the experimental technique, and the results still contradict the hypothesis, then the original hypothesis must be modified. Another experiment is then made to test the modified hypothesis. The hypothesis can be modified and experiments redesigned as often as necessary until the hypothesis is validated.

4. *Theory*. Finally, success: the experimental results confirm that the hypothesis is correct. The hypothesis now becomes a new theory about some specific aspect of nature, a scientifically acceptable general principle based on observed facts. After a careful analysis of the new theory, a prediction about some presently unknown aspect of nature can be made.

5. *Prediction*. Is the prediction correct? To answer that question, the prediction must be tested by performing a new experiment. If the new experiment does not agree with the prediction, then the theory is not as general as originally thought. Perhaps it is only a special case of some other more general model of nature. The theory must now be modified to conform to the negative results of the experiment. The modified theory is then analyzed to obtain a new prediction, which is then tested by a new experiment. If the new experiment confirms the prediction, then there is reasonable confidence that this theory of nature is correct. This process of prediction and experiment continues many times. As more and more predictions are confirmed by experiment, mounting evidence indicates that a good model of the way nature works has been developed. At this point, the theory can be called a *law of physics*.

This method of scientific reasoning demonstrates that the establishment of any theory is based on experiment. In fact, the success of physics lies in this agreement between theoretical models of the natural world and their experimental confirmation in the laboratory. A particular model of nature may be a great intellectual achievement but, if it does not agree with physical reality, then, from the point of view of physics, that hypothesis is useless. Only hypotheses that can be tested by experiment are relevant in the study of physics.

1.2 The Realm of Physics

Physics can be defined as the study of the entire natural or physical world. To simplify this task, the study of physics is usually divided into the following categories:

- I. Classical Physics
 1. Mechanics
 2. Wave Motion
 3. Heat
 4. Electricity and Magnetism
 5. Light
- II. Modern Physics
 1. Relativity
 2. Quantum Mechanics
 3. Atomic and Nuclear Physics
 4. Condensed Matter Physics
 5. Elementary Particle and High-Energy Physics

Although there are other sciences of nature besides physics, physics is the foundation of these other sciences. For example, astronomy is the application of physics to the study of all matter beyond the earth, including everything from within the solar system out to the remotest galaxies. Chemistry is the study of the properties of matter and the transformation of that matter. Geology is the application of physics to the study of the earth. Meteorology is the application of physics to the study of the atmosphere. Engineering is the application of physics to the solution of practical problems. The science of biology, which traditionally had been considered independent of physics, now uses many of the principles of physics in its study of molecular biology. The health sciences use so many new techniques and equipment based on physical principles that even there it has become necessary to have an understanding of physics.

This distinction between one science and another is usually not clear. In fact, there is often a great deal of overlap among them.

1.3 Physics Is a Science of Measurement

In order to study the entire physical world, we must first observe it. To be precise in the observation of nature, all the physical quantities that are observed should be measured and described by numbers. The importance of numerical measurements was stated by the Scottish physicist, William Thomson (1824-1907), who was made Baron Kelvin in 1892 and has since been referred to as Lord Kelvin:

I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.

We can see the necessity for quantitative measurements from the following example. First, let us consider the following *thought experiment*. (A *thought experiment* is an experiment that we can think through, rather than actually performing the experiment.) Three beakers are placed on the table as shown in figure 1.3. In the first beaker, we place several ice cubes in water. We place boiling water in the third beaker. In the second beaker, we place a mixture of the ice water from beaker 1 and the boiling water from beaker 3. If you put your left hand into beaker 1, you will conclude that the ice water is *cold*. Now place your left hand into beaker 2, which contains the mixture. After coming from the ice water, your hand finds the second beaker to be hot by comparison. So you naturally conclude that the mixture is *hot*.

Now take your right hand and plunge it into the boiling water of beaker 3. (This is the reason that this is only a *thought*

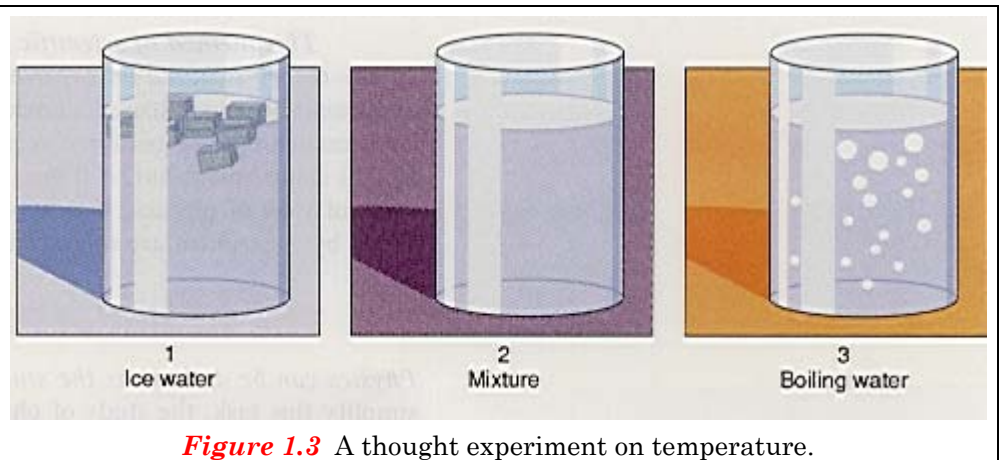


Figure 1.3 A thought experiment on temperature.

experiment. You can certainly appreciate what would happen in the experiment without actually risking bodily harm.) You would then conclude that the water in beaker 3 is certainly *hot*. Now place your right hand into beaker 2. After the boiling water, your hand finds the mixture cold by comparison, so you conclude that the mixture is *cold*. After this relatively “scientific” experiment, you find that you have contradictory conclusions. That is, you have found the middle mixture to be either hot or cold depending on the sequence of the measurements.

We can therefore conclude that in this particular observation of nature, describing something as hot or cold is not very accurate. Unless we can say numerically how hot or cold something is, our observation of nature is incomplete. In practice, of course, we would use a thermometer to measure the temperature of the contents of each beaker and read the hotness or coldness of each beaker as a number on the thermometer. For example, the thermometer might read, 0°C or 50°C or 100°C . We would now have assigned a number to our observation of nature and would thus have made a precise statement about that observation. This example points out the necessity of assigning a number to any observation of nature. The next logical question is, “What should we observe in nature?”

1.4 The Fundamental Quantities

If physics is the study of the entire natural world, where do we begin in our observations and measurements of it? It is desirable to describe the natural world in terms of the fewest possible number of quantities. This idea is not new; some of the ancient Greek philosophers thought that the entire world was composed of only four elements – earth, air, fire, and water. Although today we certainly would not accept these elements as building blocks of the world, *we do accept the basic principle that the world is describable in terms of a few fundamental quantities*.

When we look out at the world, we observe that the world occupies space, that within that space we find matter, and that space and matter exists within something we call time. So we will look for our observations of the world in terms of space, matter, and time. To measure space, we use the fundamental quantity of length. To measure matter, we use the fundamental quantities of mass and electrical charge. To measure time, we use the fundamental quantity of time itself.

*Therefore, to measure the entire physical world, we use the four **fundamental quantities of length, mass, time, and charge**. We call all the other quantities that we observe derived quantities.*

We have assigned ourselves an enormous task by trying to study the entire physical world in terms of only four quantities. The most remarkable part of it all is that it can be done. Everything in the world can be described in terms of these fundamental quantities. For example, consider a biological system, composed of very complex living tissue. But the tissue itself is made up of cells, and the cells are made of chemical molecules. The molecules are made of atoms, while the atoms consist of electrons, protons, and neutrons, which can be described in terms of the four fundamental quantities.

We might also ask of what electrons, protons, and neutrons are made. These particles are usually considered to be fundamental particles, however, the latest hypothesis in elementary particle physics is that protons and neutrons are made of even smaller particles called quarks. And although no one has yet actually found an isolated quark, and indeed some theories suggest that they are confined within the particles and will never be seen, the quark hypothesis has successfully predicted the existence of other particles, which *have* been found. The finding of these predicted particles gives a certain amount of credence to the existence of quarks. Of course if the quark is ever found then the next logical question will be, “Of what is the quark made?”

This progression from one logical question to the next in our effort to study the entire natural world is part of the adventure of physics. But to succeed on this adventure, we need to be precise in our observations, which brings us back to the subject at hand. If we intend to measure the world in terms of the four fundamental quantities of length, mass, time, and charge, we need to agree on some standard of measurement for each of these quantities.

1.5 The Standard of Length

The fundamental quantity of length is used to measure the location and the dimensions of any object in space. An object is located in space with reference to some coordinate system, as shown in figure 1.4. If the object is at the position P , then it can be located by moving a distance l_x in the x direction, then a distance l_y in the y direction, and finally a distance l_z in the z direction. When many points like P are put together in space, they generate lines and surfaces to describe any object in space. That is, two points generate a line; three points generate a triangle which then defines a plane; four points generate a rectangle and when two rectangles are connected together they form a box or a three-dimensional object in space. Continuing in this way, any object in space can be described.

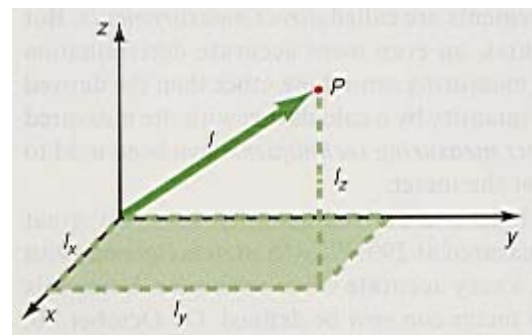


Figure 1.4 The location of an object in space.

But before we can measure the distances l_x , l_y , and l_z , or for that matter, any distance, we need a standard of length that all observers can agree on. For example, suppose we wanted to measure the length of the room. We could use this text book as the standard of length. We would then place the text book on the floor and lay off the entire distance by placing the book end-over-end on the floor as often as necessary until the entire distance is covered. We might then say that the room is 25 books long. But this is not a very good standard of length because there are different sized books, and if you performed the measurement with another book, you would say that the floor has a different length.

We could even use the tile on the floor as a standard of length. To measure the length of the room all we would have to do is count the number of tiles. Indeed, if you worked at laying floor tiles, this would be a very good standard of length. The choice of a standard of length does seem somewhat arbitrary. In fact, just think of some of the units of measurement that you are familiar with:

The *foot* -- historically the foot was used as a standard of length and it was literally the length of the king's foot. Every time you changed the king, you changed the measurement of the foot.

The *yard* -- the yard was the distance from the outstretched hand of the king to the back of his neck. Obviously, this standard of length also changed with each king.

The *inch*--the inch was the distance from the tip of the king's thumb to the thumb knuckle.

With these very arbitrary and constantly changing standards of length, it was obviously very difficult to make a measurement of length that all could agree on.

During the French Revolution, the French National Assembly initiated a proposal to the French Academy of Sciences to reform the systems of weights and measures. Under the guidance of such great physicists as Joseph L. Lagrange and Pierre S. de Laplace, the committee agreed on a measuring system based on the number 10 and its multiples. In this system, the unit of length chosen was one ten-millionth of the distance s from the North Pole to the equator along a meridian passing through Paris, France (figure 1.5). The entire distance from the pole to the equator was not actually measured. Instead a geodetic survey was undertaken for 10 degrees of latitude extending from Dunkirk, in northern France, to Barcelona, in Spain. From these data, the distance from the pole to the equator was found. The meter, the standard of length, was defined as one ten-millionth of this distance. A metal rod with two marks scratched on it equal to this distance was made, and it was stored in Sèvres, just outside Paris. Copies of this rod were distributed to other nations to be used as their standard.

In time, with greater sophistication in measuring techniques, it turned out that the distance from the North Pole to the equator was in error, so the length of the meter could no longer represent one ten-millionth of that distance. But that really did not matter, as long as everyone agreed that this length of rod would be the

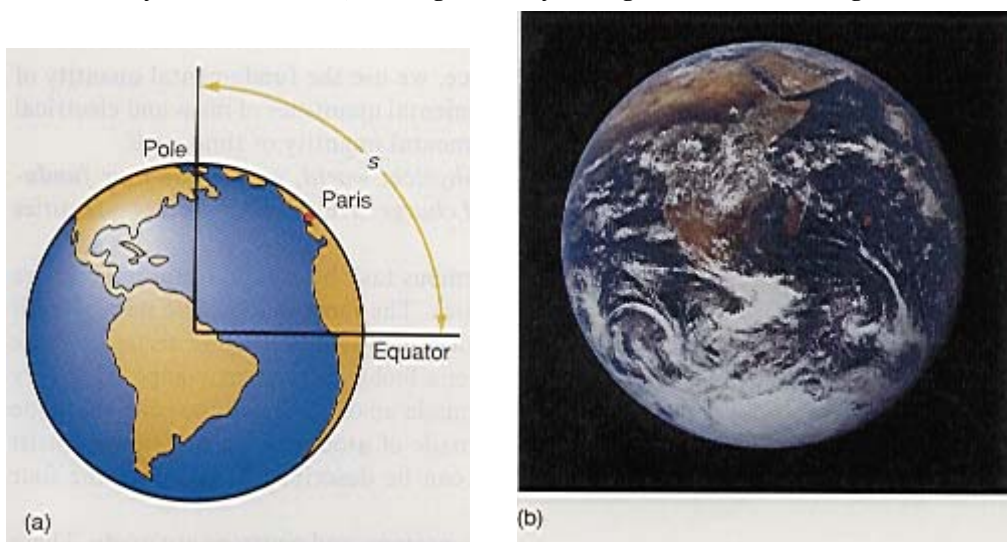


Figure 1.5 (a) The original definition of the meter. (b) View of the earth from space.

standard of length. For years these rods were the accepted standard. However, they also had drawbacks. They were not readily accessible to all the nations of the world, and they could be destroyed by fire or war. A new standard had to be found. The standard remained the meter, but it was now defined in terms of something else. In 1960, the Eleventh General Conference of Weights and Measures defined the meter as a certain number of wavelengths of light from the krypton 86 atom.

Using a standard meter bar or a prescribed number of wavelengths indeed gives us a standard length. Such measurements are called *direct measurements*. But in addition to direct measuring procedures, an even more accurate determination of a quantity sometimes can be made by measuring something other than the desired quantity, and then obtaining the desired quantity by a calculation with the measured quantity. Such procedures, called *indirect measuring techniques*, have been used to obtain an even more precise definition of the meter.

We can measure the speed of light c , a derived quantity, to a very great accuracy. The speed of light has been measured at 299,792,458 meters/second, with an uncertainty of only four parts in 10^9 , a very accurate value to be sure. Using this value of the speed of light, the standard meter can now be defined. On October 20, 1983, the Seventeenth General Conference on Weights and Measures redefined the meter as: “The **meter** is the length of the path traveled by light in a vacuum during a time interval of $1/299,792,458$ of a second.”

We will see in chapter 3 on kinematics that the distance an object moves at a constant speed is equal to the product of its speed and the time that it is in motion. Using this relation the meter is defined as

$$\begin{aligned} \text{distance} &= (\text{speed of light})(\text{time}) \\ &= \left(\frac{299,792,458 \text{ meters}}{\text{second}} \right) \left(\frac{\text{second}}{299,792,458} \right) = 1 \text{ meter} \end{aligned}$$

Hence the meter, the fundamental quantity of length, is now determined in terms of the speed of light and the fundamental quantity of time. The meter, thus defined, is a fixed standard of length accessible to everyone and is nonperishable. For everyone brought up to think of lengths in terms of the familiar inches, feet, or yards, the meter, abbreviated m, is equivalent to

$$1.000 \text{ m} = 39.37 \text{ in.} = 3.281 \text{ ft} = 1.094 \text{ yd}$$

For very precise work, the standard of length must be used in terms of its definition. For most work in a college physics course, however, the standard of length will be the simple meter stick.

The system of measurements based on the meter was originally called the metric system of measurements. Today it is called the **International System (SI) of units**. The letters are written SI rather than IS because the official international name follows French usage, “Le **Système International d’Unités**.” This system of measurements is used by scientists throughout the world and commercially by almost all the countries of the

world except the United States and one island in the Indian ocean. The United States is supposed to be changing over to this system also.

One of the great advantages of using the meter as the standard of length is that the meter is divided into 100 parts called centimeters (abbreviated cm). The centimeter, in turn, is divided into ten smaller divisions called millimeters (mm). The kilometer (abbreviated km) is equal to a thousand meters, and is used to measure very large distances. Thus the units of length measurement become a decimal system, that is,

$$\begin{aligned}1 \text{ m} &= 100 \text{ cm} \\1 \text{ cm} &= 10 \text{ mm} \\1 \text{ km} &= 1000 \text{ m}\end{aligned}$$

A further breakdown of the units of length into powers of ten is facilitated by using the following prefixes:

$$\begin{aligned}\text{tera (T)} &= 10^{12} \\ \text{giga (G)} &= 10^9 \\ \text{mega (M)} &= 10^6 \\ \text{milli (m)} &= 10^{-3} \\ \text{micro (\mu)} &= 10^{-6} \\ \text{nano (n)} &= 10^{-9} \\ \text{pico (p)} &= 10^{-12} \\ \text{femto (f)} &= 10^{-15}\end{aligned}$$

Students unfamiliar with the powers of ten notation, and scientific notation in general, should consult appendix B. Using these prefixes, the lengths of all observables can be measured as multiples or submultiples of the meter.

The decimal nature of the SI system makes it easier to use than the *British engineering system*, the system of units that is used in the United States. For example, compare the simplicity of the decimal metric system to the arbitrary units of the British engineering system:

$$\begin{aligned}12 \text{ inches} &= 1 \text{ foot} \\ 3 \text{ feet} &= 1 \text{ yard} \\ 5280 \text{ feet} &= 1 \text{ mile}\end{aligned}$$

In fact, these units are now officially defined in terms of the meter as

$$\begin{aligned}1 \text{ foot} &= 0.3048 \text{ meters} = 30.48 \text{ centimeters} \\ 1 \text{ yard} &= 0.9144 \text{ meters} = 91.44 \text{ centimeters} \\ 1 \text{ inch} &= 0.0254 \text{ meters} = 2.54 \text{ centimeters} \\ 1 \text{ mile} &= 1.609 \text{ kilometers}\end{aligned}$$

A complete list of equivalent measurements can be found in appendix A.

1.6 The Standard of Mass

The simplest definition of **mass** is that *mass is a measure of the quantity of matter in a body*. This may not be a particularly good definition, but it is one for which we have an intuitive grasp. Mass will be redefined more accurately in terms of its inertial and gravitational characteristics later. For now, let us think of the mass of a body as being the matter that is contained in the sum of all the atoms and molecules that make up that body. For example, the mass of this book is the matter of the billions upon billions of atoms that make up the pages and the print of the book itself.

The standard we use to measure mass can, like the standard of length, also be quite arbitrary. In 1795, the French Academy of Science initially defined the standard as the amount of matter in 1000 cm³ of water at 0°C and called this amount of mass, one kilogram. This definition was changed in 1799 to make the kilogram the amount of matter in 1000 cm³ of water at 4°C, the temperature of the maximum density of water. However, in 1889, *the new and current definition of the **kilogram** became the amount of matter in a specific platinum iridium cylinder 39 mm high and 39 mm in diameter*. The metal alloy of platinum and iridium was chosen because it was considered to be

the most resistant to wear and tarnish. Copies of the cylinder (figure 1.6) are kept in the standards laboratories of most countries of the world.

The disadvantage of using this cylinder as the standard of mass is that it could be easily destroyed and it is not readily accessible to every country on earth. It seems likely that sometime in the future, when the necessary experimental techniques are developed, the kilogram will be redefined in terms of the mass of some specified number of atoms or molecules, thereby giving the standard of mass an atomic definition.

With the standard of mass, the kilogram, defined, any number of identical masses, multiple masses, or submultiple masses can be found by using a simple balance, as shown in figure 1.7. We place a standard kilogram on the left pan of the balance, and then place another piece of matter on the right pan. If the new piece of matter is exactly 1 kg, then the scale will balance and we have made another kilogram mass. If there is too much matter in the tested sample the scales will not balance. We then shave off a little matter from the sample until the scales do balance. On the other hand, if there is not enough matter in the sample, we add a little matter to the sample until the scales do balance. In this way, we can make as many one kilogram masses as we want.

Any multiple of the kilogram mass can now be made with the aid of the original one kilogram masses. That is, if we want to make a 5-kg mass, we place five 1-kg masses on the left pan of the balance and add mass to the right pan until the scale balances. When this is done, we will have made a 5-kg mass. Proceeding in this way, we can obtain any multiple of the kilogram.

To make submultiples of the kilogram mass, we cut a 1-kg mass in half, and place one half of the mass on each of the two pans of the balance. If we have cut the kilogram mass exactly in half, the scales will balance. If they do not, we shave off a little matter from one of the samples and add it to the other sample until the scales do balance. Two 1/2-kg masses thus result.

Since the prefix kilo means a thousand, these half-kilogram masses each contain 500grams (abbreviated g). If we now cut a 500-g mass in half and place each piece on one of the pans of the balance, making of course whatever corrections that are necessary, we have two 250-g masses.

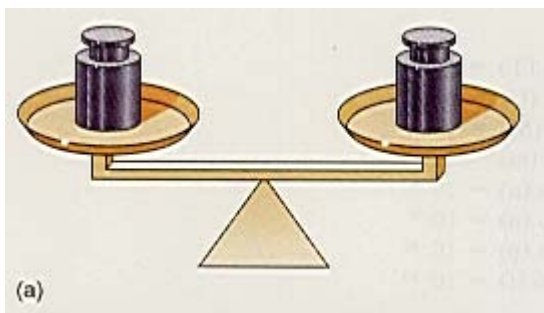


Figure 1.6 The standard kilogram mass.



Figure 1.7 A simple balance.

Continuing this process by taking various combinations of cuttings and placing them on the balance, eventually we can make any submultiple of the kilogram. The assembly of these multiples and submultiples of the kilogram is called a set of masses. (Quite often, this is erroneously referred to as a set of weights.)

We can now measure the unknown mass of any body by placing it on the left pan of the balance and adding any multiple, and/or submultiple, of the kilogram to the right pan until the scales balance. The sum of the combination of the masses placed on the right pan is the mass of the unknown body. So we can determine the mass of any body in terms of the standard kilogram.

The principle underlying the use of the balance is the gravitational force between masses. (The gravitational force will be discussed in detail in chapter 6.) The mass on the left pan is attracted toward the center

of the earth and therefore pushes down on the left pan. The mass on the right pan is also attracted toward the earth and pushes down on the right pan. When the force down on the right pan is equal to the force down on the left pan, the scales are balanced and the mass on the right pan is equal to the mass on the left pan. Mass measured by a balance depends on the force of gravity acting on the mass. Hence, mass measured by a balance can be called *gravitational mass*. The balance will work on the moon or on any planet where there are gravitational forces. The equality of masses on the earth found by a balance will show the same equality on the moon or on any planet. But a balance at rest in outer space extremely far away from gravitational forces will not work at all.

1.7 The Standard of Time

What is time and how do we measure it? Time is such a fundamental concept that it is very difficult to define. We will try by *defining time as a duration between the passing of events*. (Do not ask me to define duration, because I would have to define it as the time during which something happens, and I would end up seemingly caught in circular reasoning. This is the way it is with fundamental quantities, they are so fundamental that we cannot define them in terms of something else. If we could, that something else would become the fundamental quantity.) As with all fundamental quantities, we must choose a standard and measure all durations in terms of that standard. To measure time we need something that will repeat itself at regular intervals. The number of intervals counted gives a quantitative measure of the duration. The simplest method of measuring a time interval is to use the rhythmic beating of your own heart as a time standard. Then, just as you measured a length by the number of times the standard length was used to mark off the unknown length, you can measure a time duration by the number of pulses from your heart that covers the particular unknown duration. Note that Galileo timed the swinging chandeliers in a church one morning by the use of his pulse, finding the time for one complete oscillation of the pendulum to be independent of the magnitude of that oscillation.

In this way, we can measure time durations by the number of heartbeats counted. However, if you start running or jumping up and down your heart will beat faster and the time interval recorded will be different than when you were at rest. Therefore, for any good timing device we need something that repeats itself over and over again, always with the same constant time interval. Obviously, the technique used to measure time intervals should be invariant, and the results obtained should be the same for different individuals. One such invariant, which occurs day after day, is the rotation of the earth.

It is not surprising, then, that the early technique used for measuring time was the rotation of the earth. One complete rotation of the earth was called a day, and the day was divided into 24 hours; each hour was divided into 60 minutes; and finally each minute was divided into 60 seconds. The standard of time became the second. It may seem strange that the day was divided into 24 hours, the hour into 60 minutes, and the minute into 60 seconds. But remember that the very earliest recorded studies of astronomy and mathematics began in ancient Mesopotamia and Babylonia, where the number system was based on the number 60, rather than on the number 10, which we base our number system on. Hence, a count of 60 of their base units was equal to 1 of their next larger units. When they got to a count of 120 base units, they set this equal to 2 of the larger units. Thus, a count of 60 seconds, their base unit, was equal to 1 unit of their next larger unit, the minute. When they got to 60 minutes, this was equal to their next larger unit, the hour.

Their time was also related to their angular measurements of the sky. Hence the year became 360 days, the approximate time for the earth to go once around the sun. They related the time for the earth to move once around the heavens, 360 days, to the angle moved through when moving once around a circle by also dividing the circle into 360 units, units that today are called *angular degrees*. They then divided their degree by their base number 60 to get their next smaller unit of angle, $1/60$ of a degree, which they called a *minute of arc*. They then divided their minute by their base number 60 again to get an angle of 1 second, which is equal to $1/60$ of a minute. The movement of the heavenly bodies across the sky became their calendar. Of course their minutes and seconds of arc are not the same as our minutes and seconds of time, but because of their base number 60 our measurements of arc and time are still based on the number 60.

What is even more interesting is that the same committee that originally introduced the meter and the kilogram proposed a clock that divided the day into 10 equal units, each called a *deciday*. They also divided a quadrant of a circle (90°) into a hundred parts each called the *grade*. They thus tried to place time and angle measurements into a decimal system also, but these units were never accepted by the people.

So the second, which is $1/86,400$ part of a day, was kept as the measure of time. However, it was eventually found that the earth does not spin at a constant rate. It is very close to being a constant value, but it does vary ever so slightly. In 1967, the Thirteenth General Conference of Weights and Measures decided that the primary standard of time should be based on an atomic clock, figure 1.8. *The **second** is now defined as "the*

duration of 9,192,631,770 periods (or cycles) of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom.” The atomic clock is located at the National Bureau of Standards in Boulder, Colorado. The atomic clock is accurate to 1 second in a thousand years and can measure a time interval of one millionth of a second.

The atomic clock provides the reference time, from which certain specified radio stations (such as WWV in Fort Collins, Colorado) broadcast the correct time. This time is then transmitted to local radio and TV stations and telephone services, from which we usually obtain the time to set our watches.

For the accuracy required in a freshman college physics course, the unit of time, the second, is the time it takes for the second hand on a nondigital watch to move one interval.



Figure 1.8 The atomic clock.

1.8 The Standard of Electrical Charge

One of the fundamental characteristics of matter is that it has not only mass but also electrical charge. We now know that all matter is composed of atoms. These atoms in turn are composed of electrons, protons, and neutrons. Forces have been found that exist between these electrons and protons, forces caused by the electrical charge that these particles carry. The smallest charge ever found is the charge on the electron. By convention we call it a negative charge. The proton contains the same amount of charge, but it is a positive charge. Most matter contains equal numbers of electrons and protons, and hence is electrically neutral.

Although electrical charge is a fundamental property of matter, it is a quantity that is relatively difficult to measure directly, whereas the effects of electric current--the flow of charge per unit time--is much easier to measure. *Therefore, the fundamental unit of electricity is defined as the ampere, where “the ampere is that constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per meter of length.”* This definition will be explained in more detail when electricity is studied in section 22.7. The ampere, the unit of current, is also defined as the passage of 1 **coulomb** of charge per second in a circuit. This represents a passage of 6.25×10^{18} electrons per second. Therefore, the charge on one electron is 1.60×10^{-19} coulombs.

1.9 Systems of Units

When the standards of the fundamental quantities are all assembled, they are called a *system of units*. The standards for the fundamental quantities, discussed in the previous sections, are part of a system of units called the International System of units, abbreviated SI units. They were adopted by the Eleventh General Conference of Weights and Measures in 1960. This system of units refines and replaces the older metric system of units, and is very similar to it. Table 1.1 shows the two systems of units that will be considered.

Let us add another quantity to table 1.1, namely the quantity of weight or force. In SI units this is not a fundamental quantity, but rather a derived quantity. (A complete definition of the concepts of force and weight will be given in chapter 4.) For the present, let us add it to the table and say the weight and mass of an object are related but not identical quantities. As already indicated, mass is a measure of the quantity of matter in a body. The weight of a body here on earth is a measure of the gravitational force of attraction of the earth on that mass, pulling the mass of that body down toward the center of the earth. In the international system, the unit of weight or force is called the *newton*, named of course after Sir Isaac Newton.

Table 1.1 Systems of Units		
Physical Quantity	International System (SI)	British Engineering System
Length	meter (m)	foot (ft)
Mass	kilogram (kg)	slug
Time	second (s)	second (s)
Electric current	ampere (A)	
Electric charge	coulomb (C)	
Weight or force	newton (N)	pound (lb)

As already indicated, mass is a measure of the quantity of matter in a body. The weight of a body here on earth is a measure of the gravitational force of attraction of the earth on that mass, pulling the mass of that body down toward the center of the earth. In the international system, the unit of weight or force is called the *newton*, named of course after Sir Isaac Newton.

An important distinction between mass and weight can easily be shown here. If you were to go to the moon, figure 1.9, you would find that the gravitational force on the moon is only 1/6 of the gravitational force found here on earth. Hence, on the moon you would only weigh 1/6 what you do on earth. That is, if you weigh 180 lb on earth, you would only weigh 30 lb on the surface of the moon. Yet your mass has not changed at all. The thing that you call you, all the complexity of atoms, molecules, cells, tissue, blood, bones, and the like, is still the same. Your weight would have changed, but not your mass. The difference between mass and weight will be explained in much more detail in a later chapter. The unit of weight or force, the newton, is only placed in the table now in order to compare it to the next system of units.



Figure 1.9 Your weight on the moon is very different from your weight on earth.

The system of units that you are probably accustomed to using is called the British engineering system of units (see table 1.1). In that system, the unit of length is the foot. (Recall that the unit of a foot is now defined in terms of the standard of length, the meter.) The unit of time is again the second. In the British engineering system (BES), mass is not defined as a fundamental quantity; instead the weight of a body is described as fundamental, and its mass is derived from its weight. The fundamental unit of weight in the BES is defined as the pound with which we are all familiar. The unit of mass is derived from the unit of weight, and is called a *slug*. Whenever you hear or see the word pound it means a weight or a force, never a mass. *The British engineering system is an obsolete system of units. (Even the British no longer use the British engineering system.)* As we just pointed out, mass is a more fundamental quantity than weight. It is the same everywhere in the universe, while the weight would vary almost everywhere in the universe. Yet the British engineering system considers weight to be a fundamental quantity, which it certainly is not. This is another reason why the British engineering system should be replaced in the United States by the international system. The international system is also a better system because it is a much easier system to use and it is used by all the other countries in the world.

In SI units, the unit of weight is the newton. However, if you go to the local supermarket and buy an average-sized can of vegetables, you will see printed on it “Net wt. 595 g.” The business sector has erroneously equated mass and weight by calling them the same name, grams or kilograms. What the businessman really means is that the can of vegetables has a mass of 595 grams. The weight of an object in SI units should be expressed in newtons. We will show how to deal with this new confusion later. In this book, however, whenever you see the word kilogram or gram it will refer to the mass of an object.

To simplify the use of units in equations, abbreviations will be used. All unit abbreviations in SI units are one or two letters long and the abbreviations do not require a period following them. The name of a unit based on a proper name is written in lower-case letters, while its abbreviation is capitalized. All other abbreviations are written in lower-case letters. The abbreviations are shown in table 1.1.

Almost all of the measurements used in this book will be in SI units. However, occasionally you will want to convert a unit from the British engineering system to the international system, and vice versa. In order to do this, it is necessary to make use of a conversion factor.

1.10 Conversion Factors

A **conversion factor** is a factor by which a quantity expressed in one set of units must be multiplied in order to express that quantity in different units. The numbers for a conversion factor are usually expressed as an equation, relating the quantity in one system of units to the same quantity in different units. Appendix A, at the back of this book, contains a large number of conversion factors. An example of an equation leading to a conversion factor is

$$1 \text{ m} = 3.281 \text{ ft}$$

If both sides of the above equality are divided by 3.281 ft we get

$$\frac{1 \text{ m}}{3.281 \text{ ft}} = \frac{3.281 \text{ ft}}{3.281 \text{ ft}} = 1$$

Thus,

$$\frac{1 \text{ m}}{3.281 \text{ ft}} = 1$$

is a conversion factor that is equal to unity. If a height is multiplied by a conversion factor, we do not physically change the height, because all we are doing is multiplying it by the number one. The effect, however, expresses the same height as a different number with a different unit. A conversion factor is also used to change a quantity expressed in one system of units to a value in different units of the same system.

Example 1.1

Converting feet to meters. The height of a building is 100.0 ft. Find the height in meters.

Solution

To express the height h in meters, multiply the height in feet by the conversion factor that converts feet to meters, that is,

$$h = 100.0 \text{ ft} \left(\frac{1 \text{ m}}{3.281 \text{ ft}} \right) = 30.48 \text{ m}$$

Notice that the units act like algebraic quantities. That is, the unit foot, which is in both the numerator and the denominator of the equation, divides out, leaving us with the single unit, meters.

[To go to this interactive example, click on this sentence.](#)

The technique to remember in using a conversion factor is that the unit in the numerator that is to be eliminated, must be in the denominator of the conversion factor. Then, because units act like algebraic quantities, identical units can be divided out of the equation immediately.

Conversion factors should also be set up in a chain operation. This will make it easy to see which units cancel. For example, suppose we want to express the time T of one day in terms of seconds. This number can be found as follows:

$$\begin{aligned} T &= 1 \text{ day} \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) \left(\frac{60 \text{ min}}{1 \text{ hr}} \right) \left(\frac{60 \text{ s}}{1 \text{ min}} \right) \\ &= 86,400 \text{ s} \end{aligned}$$

By placing the conversion factors in this sequential fashion, the units that are not wanted divide out directly and the only unit left is the one we wanted, seconds. This technique is handy because if we make a mistake and use the wrong conversion factor, the error is immediately apparent. These examples are, of course, trivial, but the important thing to learn is the technique. Later when these ideas are applied to problems that are not trivial, if the technique is followed as shown, there should be no difficulty in obtaining the correct solutions.

1.11 Derived Quantities

Most of the quantities that are observed in the study of physics are derived in terms of the fundamental quantities. For example, the speed of a body is the ratio of the distance that an object moves to the time it takes to move that distance. This is expressed as

$$\begin{aligned} \text{speed} &= \frac{\text{distance travelled}}{\text{time}} \\ v &= \frac{\text{length}}{\text{time}} \end{aligned}$$

That is, the speed v is the ratio of the fundamental quantity of length to the fundamental quantity of time. Thus, speed is derived from length and time. For example, the unit for speed in SI units is a meter per second (m/s).

Another example of a derived quantity is the volume V of a body. For a box, the volume is equal to the length times the width times the height. Thus,

$$V = (\text{length})(\text{width})(\text{height})$$

But because the length, width, and height of the box are measured by a distance, the volume is equal to the cube of the fundamental unit of length L . That is,

$$V = L^3$$

Hence, the SI unit for volume is m^3 .

As a final example of a derived quantity, the density of a body is defined as its mass per unit volume, that is,

$$\begin{aligned}\rho &= \frac{m}{V} \\ &= \frac{\text{mass}}{(\text{length})^3}\end{aligned}$$

Hence, the density is defined as the ratio of the fundamental quantity of mass to the cube of the fundamental quantity of length. The SI unit for density is thus kg/m^3 . *All the remaining quantities of physics are derived in this way, in terms of the four fundamental quantities of length, mass, charge, and time.*

Note that the international system of units also recognizes temperature, luminous intensity, and “quantity of matter” (the mole) as fundamental. However, they are not fundamental in the same sense as mass, length, time, and charge. Later in the book we will see that temperature can be described as a measure of the mean kinetic energy of molecules, which is described in terms of length, mass, and time. Similarly, intensity can be derived in terms of energy, area, and time, which again are all describable in terms of length, mass, and time. Finally, the mole is expressed in terms of mass.

These derived quantities can also be expressed in many different units. Appendix A contains conversion factors from almost all British engineering system of units to International system of units and vice versa. Using these conversion factors the student can express any fundamental or derived quantity in any unit desired.

Example 1.2

Converting cubic feet to cubic meters. The volume of a container is 75.0 ft^3 . Find the volume of the container in cubic meters.

Solution

There are two ways to express the volume V in cubic meters. First let us multiply by the conversion factor that converts feet to meters. When we do this, however, we see that we have ft^3 in the numerator and the conversion factor has only ft in the denominator. In order to cancel out the unit ft^3 we have to cube the conversion factor, that is,

$$V = 75.0 \text{ ft}^3 \left(\frac{1 \text{ m}}{3.281 \text{ ft}} \right)^3 = 2.12 \text{ m}^3$$

Notice that by cubing the conversion factor the unit ft^3 , which is now in both the numerator and the denominator of the equation, divides out, leaving us with the single unit, m^3 .

A second way to make the conversion is to find a conversion factor that converts the unit ft^3 directly into m^3 . As an example in Appendix A we see that $1 \text{ ft}^3 = 2.83 \times 10^{-2} \text{ m}^3$. We now use this conversion factor as

$$V = 75.0 \text{ ft}^3 \left(\frac{2.83 \times 10^{-2} \text{ m}^3}{1 \text{ ft}^3} \right) = 2.12 \text{ m}^3$$

Notice that we get the same result either way. If you have access to the direct conversion factor, as in Appendix A, then use that factor. If not, you can use the simplified version as we did in the first part of this example.

To go to this interactive example click on this sentence.

Example 1.3

Converting horsepower to watts. A certain engine is rated as having a power output of 200 horsepower. Find the power rating of this engine in SI units.

Solution

Although we have not yet discussed the concept of power, we can still convert a unit in one system of units to another system of units by using the conversion factors for those quantities. Horsepower, abbreviated hp, is a unit of power in the British engineering system of units. The unit of power in the international system of units is a watt, abbreviated W. We find in appendix A the conversion from horsepower to watts as $1 \text{ hp} = 746 \text{ W}$. Hence, the power expressed in SI units becomes

$$P = 200 \text{ hp} \left(\frac{746 \text{ W}}{1 \text{ hp}} \right)$$
$$P = 1.49 \times 10^5 \text{ W}$$

To go to this interactive example click on this sentence.

In this way, if we are given any physical quantity expressed in the British Engineering System of Units we can convert this quantity into SI units and then solve the problem completely in SI units. Conversely, when a problem is solved in SI units and the answer is desired in the British Engineering System, a conversion factor will allow you to convert the answer into that system of units. Most of the problems at the end of this chapter will ask you to convert between these two systems, so that in the later chapters we can work strictly in the International System of Units. As a help in converting from one set of units to another see the Interactive Tutorial #49 at the end of this chapter. When you open this tutorial on your computer the Conversion Calculator will allow you to convert from a quantity in one system of units to that same quantity in another system of units and/or to convert to different units within the same system of units.

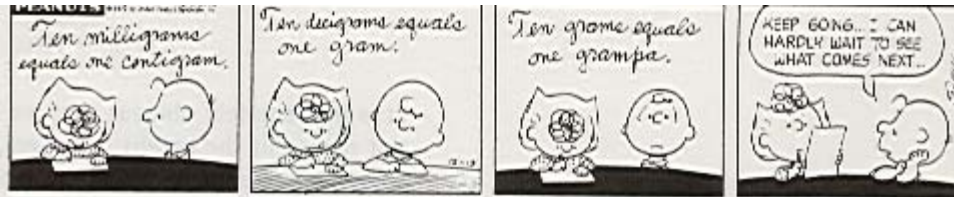


Figure 1.10 Learning physics at an early age.
PEANUTS reprinted by permission of UFS, Inc.

The Language of Physics

Philosophy

The search for knowledge or wisdom (p.).

Natural philosophy

The study of the natural or physical world (p.).

Physics

The Greek word for “natural” is *physikos*. Therefore, the word physics came to mean the study of the entire natural or physical world (p.).

Scientific method

The application of a logical process of reasoning to arrive at a model of

nature that is consistent with experimental results. The scientific method consists of five steps: (1) observation, (2) hypothesis, (3) experiment, (4) theory or law, and (5) prediction (p.).

Fundamental quantities

The most basic quantities that can

be used to describe the physical world. When we look out at the world, we observe that the world occupies space, and within that space we find matter, and that space and matter exists within something we call time. So the observation of the world can be made in terms of space, matter, and time. The fundamental quantity of length is used to describe space, the fundamental quantities of mass and electrical charge are used to describe matter, and the fundamental quantity of time is used to describe time. All other quantities, called derived quantities, can be described in terms of some combination of the fundamental quantities (p.).

International System (SI) of units

The internationally adopted system of units used by all the scientists

and all the countries of the world (p.).

Meter

The standard of length. It is defined as the length of the path traveled by light in a vacuum during an interval of $1/299,792,458$ of a second (p.).

Mass

The measure of the quantity of matter in a body (p.).

Kilogram

The unit of mass. It is defined as the amount of matter in a specific platinum iridium cylinder 39 mm high and 39 mm in diameter (p.).

Second

The unit of time. It is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the

ground state of the cesium-133 atom of the atomic clock (p.).

Coulomb

The unit of electrical charge. It is defined in terms of the unit of current, the ampere. The ampere is a flow of 1 coulomb of charge per second. The ampere is defined as that constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newtons per meter of length (p.).

Conversion factor

A factor by which a quantity expressed in one set of units must be multiplied in order to express that quantity in different units (p.).

Questions for Chapter 1

1. Why should physics have separated from philosophy at all?

2. What were Aristotle's ideas on physics, and what was their effect on science in general, and on physics in particular?

3. Is the scientific method an oversimplification?

4. How does a law of physics compare with a civil law?

5. Is there a difference between saying that an experiment validates a law of nature and that an experiment verifies a law of

nature? Where does the concept of truth fit in the study of physics?

6. How does physics relate to your field of study?

7. In the discussion of hot and cold in section 1.3, what would happen if you placed your right hand in the hot water and your left hand in the cold water, and then placed both of them in the mixture simultaneously?

8. Can you think of any more examples that show the need for quantitative measurements?

9. Compare the description of the world in terms of earth, air, fire, and water with the description in terms of length, mass, electrical charge, and time.

10. Discuss the pros and cons of dividing the day into decadays. Do you think this idea should be reintroduced into society? Using yes and no answers, have your classmates vote on a change to a decaday. Is the result surprising?

11. Discuss the difference between mass and weight.

Problems for Chapter 1

In all the examples and problems in this book we assume that whole numbers, such as 2 or 3, have as many significant figures as are necessary in the solution of the problem.

1. The Washington National Monument is 555 ft high. Express this height in meters.

2. The Statue of Liberty is 305 ft high. Express this height in meters.

3. A basketball player is 7 ft tall. What is this height in meters?

4. A floor has an area of 144 ft². What is this area expressed in m²?

5. How many seconds are there in a day? a month? a year?

6. Calculate your height in meters.

7. A speed of 60.0 miles per hour (mph) is equal to how many ft/s?

8. What is 90 km/hr expressed in mph?

9. How many feet are there in 1 km?

10. Express the age of the earth (approximately 4.6×10^9 years) in seconds.

11. The speed of sound in air is 331 m/s at 0 °C. Express this speed in ft/s and mph.

12. The speedometer of a new car is calibrated in km/hr. If the speed limit is 55 mph, how fast can the car go in km/hr and still stay below the speed limit?

13. The density of 1 g/cm³ is equal to how many kg/liter?

14. A tank contains a volume of 50 ft³. Express this volume in cubic meters.

15. Assuming that an average person lives for 75 yrs, how many (a) seconds and (b) minutes are there in this lifetime? If the heart beats at an average of 70 pulses/min, how many beats does the average heart have?

16. A cube is 50 cm on each side. Find its surface area in m² and ft² and its volume in m³ and ft³.

17. The speed of light in a vacuum is approximately 186,000 miles/s. Express this speed in mph and m/s.

18. The distance from home plate to first base on a baseball field is 90 ft. What is this distance in meters?

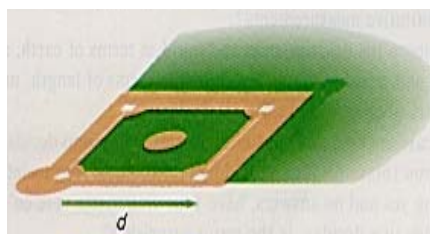


Diagram for problem 18.

19. In the game of football, a first down is 10 yd long. What is this distance in meters? If the field is 100 yd long, what is the length of the field in meters?

20. The diameter of a sphere is measured as 6.28 cm. What is its volume in cm³, m³, in.³, and ft³?

21. The Empire State Building is 1245 ft tall. Express this height in meters, miles, inches, and millimeters.

22. A drill is 1/4 in. in diameter. Express this in centimeters, and then millimeters.

23. The average diameter of the earth is 7927 miles. Express this in km.



Diagram for problem 23.

24. A 31-story building is 132 m tall. What is the average height of each story in feet?

25. Light of a certain color has a wavelength of 589 nm. Express this wavelength in (a) pm, (b) mm, (c) cm, (d) m. How many of these 589 nm waves are there in an inch?

26. Calculate the average distance to the moon in meters if the distance is 239,000 miles.

27. How many square meters are there in 1 acre, if 1 acre is equal to 43,560 ft²?

28. The mass of a hydrogen atom is 1.67×10^{-24} g. Calculate the number of atoms in 1 g of hydrogen.

29. How many cubic centimeters are there in a cubic inch?

30. A liter contains 1000 cm³. How many liters are there in a cubic meter?

31. Cells found in the human body have a volume generally in the range of 10^4 to 10^6 cubic microns. A micron is an older name of the unit that is now called a micrometer and is equal to 10^{-6} m. Express this volume in cubic meters and cubic inches.

32. The diameter of a deoxyribonucleic acid (DNA) molecule is about 20 angstroms. Express this diameter in picometers, nanometers, micrometers, millimeters, centimeters, meters, and inches.

Note that the old unit angstrom is equal to 10^{-10} m.

33. A glucose molecule has a diameter of about 8.6 angstroms. Express this diameter in millimeters and inches.

34. Muscle fibers range in diameter from 10 microns to 100 microns. Express this range of diameters in centimeters and inches.

35. The axon of the neuron, the nerve cell of the human body, has a diameter of approximately 0.2 microns. Express this diameter in terms of (a) pm, (b) nm, (c) μ m, (d) mm, and (e) cm.

36. The Sears Tower in Chicago, the world's tallest building, is 1454 ft high. Express this height in meters.

37. A baseball has a mass of 145 g. Express this mass in slugs.

38. One shipping ton is equal to 40 ft³. Express this volume in cubic meters.

39. A barrel of oil contains 42 U.S. gallons, each of 231 in.³. What is its volume in cubic meters?

40. The main span of the Verrazano Narrows Bridge in New York is 1298.4 m long. Express this distance in feet and miles.

41. The depth of the Mariana Trench in the Pacific Ocean is 10,911 m. Express this depth in feet.

42. Mount McKinley is 6194 m high. Express this height in feet.

43. The average radius of the earth is 6371 km. Find the area of the surface of the earth in m² and in ft². Find the volume of the earth in m³ and ft³. If the mass of the earth is 5.97×10^{24} kg, find the average density of the earth in kg/m³.

44. Cobalt-60 has a half-life of 5.27 yr. Express this time in (a) months, (b) days, (c) hours, (d) seconds, and (e) milliseconds.

45. On a certain European road in a quite residential area, the speed limit is posted as 40 km/hr. Express this speed limit in miles per hour.

46. In a recent storm, it rained 6.00 in. of rain in a period of 2.00 hr. If the size of your property is 100 ft by 100 ft, find the total volume of water that fell on your property. Express your answer in (a) cubic feet, (b) cubic meters, (c) liters, and (d) gallons.

47. A cheap wrist watch loses time at the rate of 8.5 seconds a day. How much time will the watch

be off at the end of a month? A year?

48. A ream of paper contains 500 sheets of 8 1/2 in. by 11 in. paper. If the package is 1 and 7/8 in. high, find (a) the thickness of each sheet of paper in inches and millimeters, (b) the dimensions of the page in millimeters, and (c) the area of a page in square meters and square millimeters.

Interactive Tutorials

49. *Conversion Calculator*. The Conversion Calculator will allow you to convert from a quantity in one system of units to that same quantity in another system of units and/or to convert to different units within the same system of units.

To go to this interactive tutorial click on this sentence.

To go to another chapter, return to the table of contents by clicking on this sentence.

