Introduction and Review

If you drop your shoe and a coin side by side, they hit the ground at the same time. Why doesn’t the shoe get there first, since gravity is pulling harder on it? How does the lens of your eye work, and why do your eye’s muscles need to squash its lens into different shapes in order to focus on objects nearby or far away? These are the kinds of questions that physics tries to answer about the behavior of light and matter, the two things that the universe is made of.

0.1 The Scientific Method

Until very recently in history, no progress was made in answering questions like these. Worse than that, the wrong answers written by thinkers like the ancient Greek physicist Aristotle were accepted without question for thousands of years. Why is it that scientific knowledge has progressed more since the Renaissance than it had in all the preceding millennia since the beginning of recorded history? Undoubtedly the industrial revolution is part of the answer. Building its centerpiece, the steam engine, required improved techniques for precise construction and measurement. (Early on, it was considered a major advance when English machine shops learned to build pistons and cylinders that fit together with a gap narrower than the thickness of a penny.) But even before the industrial revolution, the pace of discovery had picked up, mainly because of the introduction of the modern scientific method. Although it evolved over time, most scientists today would agree on something like the following list of the basic principles of the scientific method:

1. Science is a cycle of theory and experiment. Scientific theories are created to explain the results of experiments that were created under certain conditions. A successful theory will also make new predictions about new experiments under new conditions. Eventually, though, it always seems to happen that a new experiment comes along, showing that under certain
conditions the theory is not a good approximation or is not valid at all. The ball is then back in the theorists' court. If an experiment disagrees with the current theory, the theory has to be changed, not the experiment.

(2) **Theories should both predict and explain.** The requirement of predictive power means that a theory is only meaningful if it predicts something that can be checked against experimental measurements that the theorist did not already have at hand. That is, a theory should be testable. Explanatory value means that many phenomena should be accounted for with few basic principles. If you answer every “why” question with “because that’s the way it is,” then your theory has no explanatory value. Collecting lots of data without being able to find any basic underlying principles is not science.

(3) **Experiments should be reproducible.** An experiment should be treated with suspicion if it only works for one person, or only in one part of the world. Anyone with the necessary skills and equipment should be able to get the same results from the same experiment. This implies that science transcends national and ethnic boundaries; you can be sure that nobody is doing actual science who claims that their work is “Aryan, not Jewish,” “Marxist, not bourgeois,” or “Christian, not atheistic.” An experiment cannot be reproduced if it is secret, so science is necessarily a public enterprise.

As an example of the cycle of theory and experiment, a vital step toward modern chemistry was the experimental observation that the chemical elements could not be transformed into each other, e.g. lead could not be turned into gold. This led to the theory that chemical reactions consisted of rearrangements of the elements in different combinations, without any change in the identities of the elements themselves. The theory worked for hundreds of years, and was confirmed experimentally over a wide range of pressures and temperatures and with many combinations of elements. Only in the twentieth century did we learn that one element could be transformed into one another under the conditions of extremely high pressure and temperature existing in a nuclear bomb or inside a star. That observation didn’t completely invalidate the original theory of the immutability of the elements, but it showed that it was only an approximation, valid at ordinary temperatures and pressures.

**Self-Check**

A psychic conducts seances in which the spirits of the dead speak to the participants. He says he has special psychic powers not possessed by other people, which allow him to “channel” the communications with the spirits. What part of the scientific method is being violated here? [Answer below.]

The scientific method as described here is an idealization, and should not be understood as a set procedure for doing science. Scientists have as many weaknesses and character flaws as any other group, and it is very common for scientists to try to discredit other people’s experiments when the results run contrary to their own favored point of view. Successful science also has more to do with luck, intuition, and creativity than most people realize, and the restrictions of the scientific method do not stifle individuality and self-expression any more than the fugue and sonata forms.
stifled Bach and Haydn. There is a recent tendency among social scientists to go even further and to deny that the scientific method even exists, claiming that science is no more than an arbitrary social system that determines what ideas to accept based on an in-group’s criteria. I think that’s going too far. If science is an arbitrary social ritual, it would seem difficult to explain its effectiveness in building such useful items as airplanes, CD players and sewers. If alchemy and astrology were no less scientific in their methods than chemistry and astronomy, what was it that kept them from producing anything useful?

Discussion Questions
Consider whether or not the scientific method is being applied in the following examples. If the scientific method is not being applied, are the people whose actions are being described performing a useful human activity, albeit an unscientific one?

A. Acupuncture is a traditional medical technique of Asian origin in which small needles are inserted in the patient’s body to relieve pain. Many doctors trained in the west consider acupuncture unworthy of experimental study because if it had therapeutic effects, such effects could not be explained by their theories of the nervous system. Who is being more scientific, the western or eastern practitioners?

B. Goethe, a famous German poet, is less well known for his theory of color. He published a book on the subject, in which he argued that scientific apparatus for measuring and quantifying color, such as prisms, lenses and colored filters, could not give us full insight into the ultimate meaning of color, for instance the cold feeling evoked by blue and green or the heroic sentiments inspired by red. Was his work scientific?

C. A child asks why things fall down, and an adult answers “because of gravity.” The ancient Greek philosopher Aristotle explained that rocks fell because it was their nature to seek out their natural place, in contact with the earth. Are these explanations scientific?

D. Buddhism is partly a psychological explanation of human suffering, and psychology is of course a science. The Buddha could be said to have engaged in a cycle of theory and experiment, since he worked by trial and error, and even late in his life he asked his followers to challenge his ideas. Buddhism could also be considered reproducible, since the Buddha told his followers they could find enlightenment for themselves if they followed a certain course of study and discipline. Is Buddhism a scientific pursuit?

0.2 What Is Physics?

Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective positions of the things which compose it...nothing would be uncertain, and the future as the past would be laid out before its eyes.

Pierre Simon de Laplace

Physics is the use of the scientific method to find out the basic principles governing light and matter, and to discover the implications of those laws. Part of what distinguishes the modern outlook from the ancient mindset is the assumption that there are rules by which the universe functions, and that those laws can be at least partially understood by humans. From the Age of Reason through the nineteenth century, many scientists began to be convinced that the laws of nature not only could be known but, as claimed by Laplace, those laws could in principle be used to predict every-
thing about the universe's future if complete information was available about the present state of all light and matter. In subsequent sections, I’ll describe two general types of limitations on prediction using the laws of physics, which were only recognized in the twentieth century.

Matter can be defined as anything that is affected by gravity, i.e. that has weight or would have weight if it was near the Earth or another star or planet massive enough to produce measurable gravity. Light can be defined as anything that can travel from one place to another through empty space and can influence matter, but has no weight. For example, sunlight can influence your body by heating it or by damaging your DNA and giving you skin cancer. The physicist’s definition of light includes a variety of phenomena that are not visible to the eye, including radio waves, microwaves, x-rays, and gamma rays. These are the “colors” of light that do not happen to fall within the narrow violet-to-red range of the rainbow that we can see.

Self-check

At the turn of the 20th century, a strange new phenomenon was discovered in vacuum tubes: mysterious rays of unknown origin and nature. These rays are the same as the ones that shoot from the back of your TV’s picture tube and hit the front to make the picture. Physicists in 1895 didn’t have the faintest idea what the rays were, so they simply named them “cathode rays,” after the name for the electrical contact from which they sprang. A fierce debate raged, complete with nationalistic overtones, over whether the rays were a form of light or of matter. What would they have had to do in order to settle the issue?

Many physical phenomena are not themselves light or matter, but are properties of light or matter or interactions between light and matter. For instance, motion is a property of all light and some matter, but it is not itself light or matter. The pressure that keeps a bicycle tire blown up is an interaction between the air and the tire. Pressure is not a form of matter in and of itself. It is as much a property of the tire as of the air. Analogously, sisterhood and employment are relationships among people but are not people themselves.

Some things that appear weightless actually do have weight, and so qualify as matter. Air has weight, and is thus a form of matter even though a cubic inch of air weighs less than a grain of sand. A helium balloon has weight, but is kept from falling by the force of the surrounding more dense air, which pushes up on it. Astronauts in orbit around the Earth have weight, and are falling along a curved arc, but they are moving so fast that the curved arc of their fall is broad enough to carry them all the way around the Earth in a circle. They perceive themselves as being weightless because their space capsule is falling along with them, and the floor therefore does not push up on their feet.

Optional Topic

Einstein predicted as a consequence of his theory of relativity that light would after all be affected by gravity, although the effect would be extremely weak under normal conditions. His prediction was borne out by observations of the bending of light rays from stars as they passed close to the sun on their way to the Earth. Einstein also
predicted the existence of black holes, stars so massive and compact that their intense gravity would not even allow light to escape. (These days there is strong evidence that black holes exist.)

Einstein’s interpretation was that light doesn’t really have mass, but that energy is affected by gravity just like mass is. The energy in a light beam is equivalent to a certain amount of mass, given by the famous equation \( E=mc^2 \), where \( c \) is the speed of light. Because the speed of light is such a big number, a large amount of energy is equivalent to only a very small amount of mass, so the gravitational force on a light ray can be ignored for most practical purposes.

There is however a more satisfactory and fundamental distinction between light and matter, which should be understandable to you if you have had a chemistry course. In chemistry, one learns that electrons obey the Pauli exclusion principle, which forbids more than one electron from occupying the same orbital if they have the same spin. The Pauli exclusion principle is obeyed by the subatomic particles of which matter is composed, but disobeyed by the particles, called photons, of which a beam of light is made.

Einstein’s theory of relativity is discussed more fully in book 6 of this series.

The boundary between physics and the other sciences is not always clear. For instance, chemists study atoms and molecules, which are what matter is built from, and there are some scientists who would be equally willing to call themselves physical chemists or chemical physicists. It might seem that the distinction between physics and biology would be clearer, since physics seems to deal with inanimate objects. In fact, almost all physicists would agree that the basic laws of physics that apply to molecules in a test tube work equally well for the combination of molecules that constitutes a bacterium. (Some might believe that something more happens in the minds of humans, or even those of cats and dogs.) What differentiates physics from biology is that many of the scientific theories that describe living things, while ultimately resulting from the fundamental laws of physics, cannot be rigorously derived from physical principles.

**Isolated systems and reductionism**

To avoid having to study everything at once, scientists isolate the things they are trying to study. For instance, a physicist who wants to study the motion of a rotating gyroscope would probably prefer that it be isolated from vibrations and air currents. Even in biology, where field work is indispensable for understanding how living things relate to their entire environment, it is interesting to note the vital historical role played by Darwin’s study of the Galápagos Islands, which were conveniently isolated from the rest of the world. Any part of the universe that is considered apart from the rest can be called a “system.”

Physics has had some of its greatest successes by carrying this process of isolation to extremes, subdividing the universe into smaller and smaller parts. Matter can be divided into atoms, and the behavior of individual atoms can be studied. Atoms can be split apart into their constituent neutrons, protons and electrons. Protons and neutrons appear to be made out of even smaller particles called quarks, and there have even been some claims of experimental evidence that quarks have smaller parts inside them.
This method of splitting things into smaller and smaller parts and studying how those parts influence each other is called reductionism. The hope is that the seemingly complex rules governing the larger units can be better understood in terms of simpler rules governing the smaller units. To appreciate what reductionism has done for science, it is only necessary to examine a 19th-century chemistry textbook. At that time, the existence of atoms was still doubted by some, electrons were not even suspected to exist, and almost nothing was understood of what basic rules governed the way atoms interacted with each other in chemical reactions. Students had to memorize long lists of chemicals and their reactions, and there was no way to understand any of it systematically. Today, the student only needs to remember a small set of rules about how atoms interact, for instance that atoms of one element cannot be converted into another via chemical reactions, or that atoms from the right side of the periodic table tend to form strong bonds with atoms from the left side.

Discussion Questions

A. I’ve suggested replacing the ordinary dictionary definition of light with a more technical, more precise one that involves weightlessness. It’s still possible, though, that the stuff a lightbulb makes, ordinarily called “light,” does have some small amount of weight. Suggest an experiment to attempt to measure whether it does.

B. Heat is weightless (i.e. an object becomes no heavier when heated), and can travel across an empty room from the fireplace to your skin, where it influences you by heating you. Should heat therefore be considered a form of light by our definition? Why or why not?

C. Similarly, should sound be considered a form of light?

0.3 How to Learn Physics

For as knowledges are now delivered, there is a kind of contract of error between the deliverer and the receiver; for he that delivereth knowledge desireth to deliver it in such a form as may be best believed, and not as may be best examined; and he that receiveth knowledge desireth rather present satisfaction than expectant inquiry.

Sir Francis Bacon

Many students approach a science course with the idea that they can succeed by memorizing the formulas, so that when a problem is assigned on the homework or an exam, they will be able to plug numbers in to the formula and get a numerical result on their calculator. Wrong! That’s not what learning science is about! There is a big difference between memorizing formulas and understanding concepts. To start with, different formulas may apply in different situations. One equation might represent a definition, which is always true. Another might be a very specific equation for the speed of an object sliding down an inclined plane, which would not be true if the object was a rock drifting down to the bottom of the ocean. If you don’t work to understand physics on a conceptual level, you won’t know which formulas can be used when.
Most students taking college science courses for the first time also have very little experience with interpreting the meaning of an equation. Consider the equation \( w = \frac{A}{h} \) relating the width of a rectangle to its height and area. A student who has not developed skill at interpretation might view this as yet another equation to memorize and plug in to when needed. A slightly more savvy student might realize that it is simply the familiar formula \( A = wh \) in a different form. When asked whether a rectangle would have a greater or smaller width than another with the same area but a smaller height, the unsophisticated student might be at a loss, not having any numbers to plug in on a calculator. The more experienced student would know how to reason about an equation involving division — if \( h \) is smaller, and \( A \) stays the same, then \( w \) must be bigger. Often, students fail to recognize a sequence of equations as a derivation leading to a final result, so they think all the intermediate steps are equally important formulas that they should memorize.

When learning any subject at all, it is important to become as actively involved as possible, rather than trying to read through all the information quickly without thinking about it. It is a good idea to read and think about the questions posed at the end of each section of these notes as you encounter them, so that you know you have understood what you were reading.

Many students' difficulties in physics boil down mainly to difficulties with math. Suppose you feel confident that you have enough mathematical preparation to succeed in this course, but you are having trouble with a few specific things. In some areas, the brief review given in this chapter may be sufficient, but in other areas it probably will not. Once you identify the areas of math in which you are having problems, get help in those areas. Don't limp along through the whole course with a vague feeling of dread about something like scientific notation. The problem will not go away if you ignore it. The same applies to essential mathematical skills that you are learning in this course for the first time, such as vector addition.

Sometimes students tell me they keep trying to understand a certain topic in the book, and it just doesn't make sense. The worst thing you can possibly do in that situation is to keep on staring at the same page. Every textbook explains certain things badly — even mine! — so the best thing to do in this situation is to look at a different book. Instead of college textbooks aimed at the same mathematical level as the course you're taking, you may in some cases find that high school books or books at a lower math level give clearer explanations. The three books listed on the left are, in my opinion, the best introductory physics books available, although they would not be appropriate as the primary textbook for a college-level course for science majors.

Finally, when reviewing for an exam, don't simply read back over the text and your lecture notes. Instead, try to use an active method of reviewing, for instance by discussing some of the discussion questions with another student, or doing homework problems you hadn't done the first time.

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### Other Books


A high-school textbook at the algebra-based level. This book distinguishes itself by giving a clear, careful, and honest explanation of every topic, while avoiding unnecessary details.


As the name implies, this book's intended audience is liberal arts students who want to understand science in a broader cultural and historical context. Not much math is used, and the page count of this little paperback is about five times less than that of the typical "kitchen sink" textbook, but the intellectual level is actually pretty challenging.

**Conceptual Physics**, Paul Hewitt. Scott Foresman, Glenview, Ill.

This is the excellent book used for Physics 130 here at Fullerton College. Only simple algebra is used.
0.4 Self-Evaluation

The introductory part of a book like this is hard to write, because every student arrives at this starting point with a different preparation. One student may have grown up in another country and so may be completely comfortable with the metric system, but may have had an algebra course in which the instructor passed too quickly over scientific notation. Another student may have already taken calculus, but may have never learned the metric system. The following self-evaluation is a checklist to help you figure out what you need to study to be prepared for the rest of the course.

<table>
<thead>
<tr>
<th>If you disagree with this statement...</th>
<th>you should study this section:</th>
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</thead>
<tbody>
<tr>
<td>I am familiar with the basic metric units of meters, kilograms, and seconds, and the most common metric prefixes: milli- (m), kilo- (k), and centi- (c).</td>
<td>0.5 Basics of the Metric System</td>
</tr>
<tr>
<td>I know about the Newton, a unit of force</td>
<td>0.6 The Newton, the Metric Unit of Force</td>
</tr>
<tr>
<td>I am familiar with these less common metric prefixes: mega- (M), micro- (μ), and nano- (n).</td>
<td>0.7 Less Common Metric Prefixes</td>
</tr>
<tr>
<td>I am comfortable with scientific notation.</td>
<td>0.8 Scientific Notation</td>
</tr>
<tr>
<td>I can confidently do metric conversions.</td>
<td>0.9 Conversions</td>
</tr>
<tr>
<td>I understand the purpose and use of significant figures.</td>
<td>0.10 Significant Figures</td>
</tr>
</tbody>
</table>

It wouldn't hurt you to skim the sections you think you already know about, and to do the self-checks in those sections.

0.5 Basics of the Metric System

The metric system

Units were not standardized until fairly recently in history, so when the physicist Isaac Newton gave the result of an experiment with a pendulum, he had to specify not just that the string was 37 7/8 inches long but that it was “37 7/8 London inches long.” The inch as defined in Yorkshire would have been different. Even after the British Empire standardized its units, it was still very inconvenient to do calculations involving money, volume, distance, time, or weight, because of all the odd conversion factors, like 16 ounces in a pound, and 5280 feet in a mile. Through the nineteenth century, schoolchildren squandered most of their mathematical education in preparing to do calculations such as making change when a customer in a shop offered a one-crown note for a book costing two pounds, thirteen shillings and tuppence. The dollar has always been decimal, and British money went decimal decades ago, but the United States is still saddled with the antiquated system of feet, inches, pounds, ounces and so on.

Every country in the world besides the U.S. has adopted a system of units known in English as the “metric system.” This system is entirely
decimal, thanks to the same eminently logical people who brought about the French Revolution. In deference to France, the system's official name is the Système International, or SI, meaning International System. (The phrase “SI system” is therefore redundant.)

The wonderful thing about the SI is that people who live in countries more modern than ours do not need to memorize how many ounces there are in a pound, how many cups in a pint, how many feet in a mile, etc. The whole system works with a single, consistent set of prefixes (derived from Greek) that modify the basic units. Each prefix stands for a power of ten, and has an abbreviation that can be combined with the symbol for the unit. For instance, the meter is a unit of distance. The prefix kilo- stands for $10^3$, so a kilometer, 1 km, is a thousand meters.

The basic units of the metric system are the meter for distance, the second for time, and the gram for mass.

The following are the most common metric prefixes. You should memorize them.

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Meaning</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>kilo-</td>
<td>k</td>
<td>$10^1$</td>
</tr>
<tr>
<td>centi-</td>
<td>c</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>milli-</td>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

The prefix centi-, meaning $10^{-2}$, is only used in the centimeter; a hundredth of a gram would not be written as 1 cg but as 10 mg. The centi-prefix can be easily remembered because a cent is $10^{-2}$ dollars. The official SI abbreviation for seconds is “s” (not “sec”) and grams are “g” (not “gm”).

The second

The sun stood still and the moon halted until the nation had taken vengeance on its enemies...

Joshua 10:12-14

Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external...

Isaac Newton

When I stated briefly above that the second was a unit of time, it may not have occurred to you that this was not really much of a definition. The two quotes above are meant to demonstrate how much room for confusion exists among people who seem to mean the same thing by a word such as “time.” The first quote has been interpreted by some biblical scholars as indicating an ancient belief that the motion of the sun across the sky was not just something that occurred with the passage of time but that the sun actually caused time to pass by its motion, so that freezing it in the sky...
would have some kind of a supernatural decelerating effect on everyone except the Hebrew soldiers. Many ancient cultures also conceived of time as cyclical, rather than proceeding along a straight line as in 1998, 1999, 2000, 2001,... The second quote, from a relatively modern physicist, may sound a lot more scientific, but most physicists today would consider it useless as a definition of time. Today, the physical sciences are based on operational definitions, which means definitions that spell out the actual steps (operations) required to measure something numerically.

Now in an era when our toasters, pens, and coffee pots tell us the time, it is far from obvious to most people what is the fundamental operational definition of time. Until recently, the hour, minute, and second were defined operationally in terms of the time required for the earth to rotate about its axis. Unfortunately, the Earth's rotation is slowing down slightly, and by 1967 this was becoming an issue in scientific experiments requiring precise time measurements. The second was therefore redefined as the time required for a certain number of vibrations of the light waves emitted by a cesium atoms in a lamp constructed like a familiar neon sign but with the neon replaced by cesium. The new definition not only promises to stay constant indefinitely, but for scientists is a more convenient way of calibrating a clock than having to carry out astronomical measurements.

Self-Check

What is a possible operational definition of how strong a person is?

The meter

The French originally defined the meter as $10^{-7}$ times the distance from the equator to the north pole, as measured through Paris (of course). Even if the definition was operational, the operation of traveling to the north pole and laying a surveying chain behind you was not one that most working scientists wanted to carry out. Fairly soon, a standard was created in the form of a metal bar with two scratches on it. This definition persisted until 1960, when the meter was redefined as the distance traveled by light in a vacuum over a period of $(1/299792458)$ seconds.

A dictionary might define “strong” as “possessing powerful muscles,” but that’s not an operational definition, because it doesn’t say how to measure strength numerically. One possible operational definition would be the number of pounds a person can bench press.
The kilogram

The third base unit of the SI is the kilogram, a unit of mass. Mass is intended to be a measure of the amount of a substance, but that is not an operational definition. Bathroom scales work by measuring our planet’s gravitational attraction for the object being weighed, but using that type of scale to define mass operationally would be undesirable because gravity varies in strength from place to place on the earth.

There’s a surprising amount of disagreement among physics textbooks about how mass should be defined, but here’s how it’s actually handled by the few working physicists who specialize in ultra-high-precision measurements. They maintain a physical object in Paris, which is the standard kilogram, a cylinder made of platinum-iridium alloy. Duplicates are checked against this mother of all kilograms by putting the original and the copy on the two opposite pans of a balance. Although this method of comparison depends on gravity, the problems associated with differences in gravity in different geographical locations are bypassed, because the two objects are being compared in the same place. The duplicates can then be removed from the Parisian kilogram shrine and transported elsewhere in the world.

Combinations of metric units

Just about anything you want to measure can be measured with some combination of meters, kilograms, and seconds. Speed can be measured in m/s, volume in m³, and density in kg/m³. Part of what makes the SI great is this basic simplicity. No more funny units like a cord of wood, a bolt of cloth, or a jigger of whiskey. No more liquid and dry measure. Just a simple, consistent set of units. The SI measures put together from meters, kilograms, and seconds make up the mks system. For example, the mks unit of speed is m/s, not km/hr.

Discussion question

Isaac Newton wrote, “...the natural days are truly unequal, though they are commonly considered as equal, and used for a measure of time... It may be that there is no such thing as an equable motion, whereby time may be accurately measured. All motions may be accelerated or retarded...” Newton was right. Even the modern definition of the second in terms of light emitted by cesium atoms is subject to variation. For instance, magnetic fields could cause the cesium atoms to emit light with a slightly different rate of vibration. What makes us think, though, that a pendulum clock is more accurate than a sundial, or that a cesium atom is a more accurate timekeeper than a pendulum clock? That is, how can one test experimentally how the accuracies of different time standards compare?

0.6 The Newton, the Metric Unit of Force

A force is a push or a pull, or more generally anything that can change an object’s speed or direction of motion. A force is required to start a car moving, to slow down a baseball player sliding into home base, or to make an airplane turn. (Forces may fail to change an object’s motion if they are canceled by other forces, e.g. the force of gravity pulling you down right now is being canceled by the force of the chair pushing up on you.) The metric unit of force is the Newton, defined as the force which, if applied for one second, will cause a 1-kilogram object starting from rest to reach...
speed of 1 m/s. Later chapters will discuss the force concept in more detail. In fact, this entire book is about the relationship between force and motion.

In the previous section, I gave a gravitational definition of mass, but by defining a numerical scale of force, we can also turn around and define a scale of mass without reference to gravity. For instance, if a force of two Newtons is required to accelerate a certain object from rest to 1 m/s in 1 s, then that object must have a mass of 2 kg. From this point of view, mass characterizes an object’s resistance to a change in its motion, which we call inertia or inertial mass. Although there is no fundamental reason why an object’s resistance to a change in its motion must be related to how strongly gravity affects it, careful and precise experiments have shown that the inertial definition and the gravitational definition of mass are highly consistent for a variety of objects. It therefore doesn’t really matter for any practical purpose which definition one adopts.

**Discussion Question**

Spending a long time in weightlessness is unhealthy. One of the most important negative effects experienced by astronauts is a loss of muscle and bone mass. Since an ordinary scale won’t work for an astronaut in orbit, what is a possible way of monitoring this change in mass? (Measuring the astronaut’s waist or biceps with a measuring tape is not good enough, because it doesn’t tell anything about bone mass, or about the replacement of muscle with fat.)

### 0.7 Less Common Metric Prefixes

The following are three metric prefixes which, while less common than the ones discussed previously, are well worth memorizing.

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<tr>
<td>micro-</td>
<td>$\mu$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>nano-</td>
<td>n</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

Note that the abbreviation for micro is the Greek letter mu, $\mu$ — a common mistake is to confuse it with m (milli) or M (mega).

There are other prefixes even less common, used for extremely large and small quantities. For instance, 1 femtometer = $10^{-15}$ m is a convenient unit of distance in nuclear physics, and 1 gigabyte = $10^9$ bytes is used for computers’ hard disks. The international committee that makes decisions about the SI has recently even added some new prefixes that sound like jokes, e.g. 1 yoctogram = $10^{-24}$ g is about half the mass of a proton. In the immediate future, however, you’re unlikely to see prefixes like “yocto-” and “zepto-” used except perhaps in trivia contests at science-fiction conventions or other geeksfests.

This is a mnemonic to help you remember the most important metric prefixes. The word “little” is to remind you that the list starts with the prefixes used for small quantities and builds upward. The exponent changes by 3 with each step, except that of course we do not need a special prefix for $10^0$, which equals one.
Self-Check

Suppose you could slow down time so that according to your perception, a beam of light would move across a room at the speed of a slow walk. If you perceived a nanosecond as if it was a second, how would you perceive a microsecond?

0.8 Scientific Notation

Most of the interesting phenomena our universe has to offer are not on the human scale. It would take about $1,000,000,000,000,000,000,000$ bacteria to equal the mass of a human body. When the physicist Thomas Young discovered that light was a wave, it was back in the bad old days before scientific notation, and he was obliged to write that the time required for one vibration of the wave was $1/500$ of a millionth of a millionth of a second. Scientific notation is a less awkward way to write very large and very small numbers such as these. Here’s a quick review.

Scientific notation means writing a number in terms of a product of something from 1 to 10 and something else that is a power of ten. For instance,

$$32 = 3.2 	imes 10^1$$
$$320 = 3.2 	imes 10^2$$
$$3200 = 3.2 	imes 10^3$$...

Each number is ten times bigger than the previous one.

Since $10^1$ is ten times smaller than $10^2$, it makes sense to use the notation $10^0$ to stand for one, the number that is in turn ten times smaller than $10^1$. Continuing on, we can write $10^{-1}$ to stand for 0.1, the number ten times smaller than $10^0$. Negative exponents are used for small numbers:

$$3.2 = 3.2 	imes 10^0$$
$$0.32 = 3.2 	imes 10^{-1}$$
$$0.032 = 3.2 	imes 10^{-2}$$...

A common source of confusion is the notation used on the displays of many calculators. Examples:

$$3.2 	imes 10^6 \quad \text{(written notation)}$$
$$3.2E+6 \quad \text{(notation on some calculators)}$$
$$3.2^6 \quad \text{(notation on some other calculators)}$$

The last example is particularly unfortunate, because $3.2^6$ really stands for the number $3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 = 1074$, a totally different number from $3.2 \times 10^6 = 3200000$. The calculator notation should never be used in writing. It’s just a way for the manufacturer to save money by making a simpler display.

A microsecond is 1000 times longer than a nanosecond, so it would seem like 1000 seconds, or about 20 minutes.
Self-Check

A student learns that $10^4$ bacteria, standing in line to register for classes at Paramecium Community College, would form a queue of this size:

The student concludes that $10^2$ bacteria would form a line of this length:

Why is the student incorrect?

0.9 Conversions

I suggest you avoid memorizing lots of conversion factors between SI units and U.S. units. Suppose the United Nations sends its black helicopters to invade California (after all who wouldn’t rather live here than in New York City?), and institutes water fluoridation and the SI, making the use of inches and pounds into a crime punishable by death. I think you could get by with only two mental conversion factors:

1 inch = 2.54 cm

An object with a weight on Earth of 2.2 pounds-force has a mass of 1 kg.

The first one is the present definition of the inch, so it’s exact. The second one is not exact, but is good enough for most purposes. (U.S. units of force and mass are confusing, so it’s a good thing they’re not used in science. In U.S. units, the unit of force is the pound-force, and the best unit to use for mass is the slug, which is about 14.6 kg.)

More important than memorizing conversion factors is understanding the right method for doing conversions. Even within the SI, you may need to convert, say, from grams to kilograms. Different people have different ways of thinking about conversions, but the method I’ll describe here is systematic and easy to understand. The idea is that if 1 kg and 1000 g represent the same mass, then we can consider a fraction like

$$\frac{10^3 \text{ g}}{1 \text{ kg}}$$

to be a way of expressing the number one. This may bother you. For instance, if you type 1000/1 into your calculator, you will get 1000, not one. Again, different people have different ways of thinking about it, but the justification is that it helps us to do conversions, and it works! Now if we want to convert 0.7 kg to units of grams, we can multiply 0.7 kg by the number one:

$$0.7 \text{ kg} \times \frac{10^3 \text{ g}}{1 \text{ kg}}$$

If you’re willing to treat symbols such as “kg” as if they were variables as used in algebra (which they’re really not), you can then cancel the kg on top with the kg on the bottom, resulting in

Exponents have to do with multiplication, not addition. The first line should be 100 times longer than the second, not just twice as long.

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To convert grams to kilograms, you would simply flip the fraction upside down.

One advantage of this method is that it can easily be applied to a series of conversions. For instance, to convert one year to units of seconds,

\[
1 \text{ year} \times \frac{365 \text{ days}}{1 \text{ year}} \times \frac{24 \text{ hours}}{1 \text{ day}} \times \frac{60 \text{ min}}{1 \text{ hour}} \times \frac{60 \text{ s}}{1 \text{ min}} = 3.15 \times 10^7 \text{ s}.
\]

**Should that exponent be positive or negative?**

A common mistake is to write the conversion fraction incorrectly. For instance the fraction

\[
\frac{10^3 \text{ kg}}{1 \text{ g}} \quad \text{(incorrect)}
\]

does not equal one, because \(10^3 \text{ kg}\) is the mass of a car, and \(1 \text{ g}\) is the mass of a raisin. One correct way of setting up the conversion factor would be

\[
\frac{10^{-3} \text{ kg}}{1 \text{ g}} \quad \text{(correct)}
\]

You can usually detect such a mistake if you take the time to check your answer and see if it is reasonable.

If common sense doesn't rule out either a positive or a negative exponent, here's another way to make sure you get it right. There are big prefixes and small prefixes:

- Big prefixes: \(\text{k, M}\)
- Small prefixes: \(\text{m, µ, n}\)

(It's not hard to keep straight which are which, since “mega” and “micro” are evocative, and it's easy to remember that a kilometer is bigger than a meter and a millimeter is smaller.) In the example above, we want the top of the fraction to be the same as the bottom. Since \(\text{k}\) is a big prefix, we need to compensate by putting a small number like \(10^{-3}\) in front of it, not a big number like \(10^3\).

**Discussion Question**

Each of the following conversions contains an error. In each case, explain what the error is.

(a) \(1000 \text{ kg} \times \frac{1 \text{ kg}}{1000 \text{ g}} = 1 \text{ g}\)
(b) \(50 \text{ m} \times \frac{1 \text{ cm}}{100 \text{ m}} = 0.5 \text{ cm}\)
(c) "Nano" is \(10^{-9}\), so there are \(10^{-9} \text{ nm}\) in a meter.
(d) "Micro" is \(10^{-6}\), so \(1 \text{ kg}\) is \(10^6 \mu\text{g}\).
0.10 Significant Figures

An engineer is designing a car engine, and has been told that the diameter of the pistons (which are being designed by someone else) is 5 cm. He knows that 0.02 cm of clearance is required for a piston of this size, so he designs the cylinder to have an inside diameter of 5.04 cm. Luckily, his supervisor catches his mistake before the car goes into production. She explains his error to him, and mentally puts him in the “do not promote” category.

What was his mistake? The person who told him the pistons were 5 cm in diameter was wise to the ways of significant figures, as was his boss, who explained to him that he needed to go back and get a more accurate number for the diameter of the pistons. That person said “5 cm” rather than “5.00 cm” specifically to avoid creating the impression that the number was extremely accurate. In reality, the pistons’ diameter was 5.13 cm. They would never have fit in the 5.04-cm cylinders.

The number of digits of accuracy in a number is referred to as the number of significant figures, or “sig figs” for short. As in the example above, sig figs provide a way of showing the accuracy of a number. In most cases, the result of a calculation involving several pieces of data can be no more accurate than the least accurate piece of data. In other words, “garbage in, garbage out.” Since the 5 cm diameter of the pistons was not very accurate, the result of the engineer’s calculation, 5.04 cm, was really not as accurate as he thought. In general, your result should not have more than the number of sig figs in the least accurate piece of data you started with. The calculation above should have been done as follows:

\[
5 \text{ cm (1 sig fig)} + 0.04 \text{ cm (1 sig fig)} = 5 \text{ cm (rounded off to 1 sig fig)}
\]

The fact that the final result only has one significant figure then alerts you to the fact that the result is not very accurate, and would not be appropriate for use in designing the engine.

Note that the leading zeroes in the number 0.04 do not count as significant figures, because they are only placeholders. On the other hand, a number such as 50 cm is ambiguous — the zero could be intended as a significant figure, or it might just be there as a placeholder. The ambiguity involving trailing zeroes can be avoided by using scientific notation, in which \(5 \times 10^1\) cm would imply one sig fig of accuracy, while \(5.0 \times 10^1\) cm would imply two sig figs.

**Self-Check**

(a) The following quote is taken from an editorial by Norimitsu Onishi in the New York Times, August 18, 2002.

Consider Nigeria. Everyone agrees it is Africa’s most populous nation. But what is its population? The United Nations says 114 million; the State Department, 120 million. The World Bank says 126.9 million, while the Central Intelligence Agency puts it at 126,635,626.

What should bother you about this?

The various estimates differ by 5 to 10 million. The CIA’s estimate includes a ridiculous number of gratuitous significant figures. Does the CIA understand that every day, people in are born in, die in, immigrate to, and emigrate from Nigeria?
Dealing correctly with significant figures can save you time! Often, students copy down numbers from their calculators with eight significant figures of precision, then type them back in for a later calculation. That’s a waste of time, unless your original data had that kind of incredible precision.

The rules about significant figures are only rules of thumb, and are not a substitute for careful thinking. For instance, $20.00 + 0.05$ is $20.05$. It need not and should not be rounded off to $20$. In general, the sig fig rules work best for multiplication and division, and we also apply them when doing a complicated calculation that involves many types of operations. For simple addition and subtraction, it makes more sense to maintain a fixed number of digits after the decimal point.

When in doubt, don’t use the sig fig rules at all. Instead, intentionally change one piece of your initial data by the maximum amount by which you think it could have been off, and recalculate the final result. The digits on the end that are completely reshuffled are the ones that are meaningless, and should be omitted.

How many significant figures are there in each of the following measurements?
(a) 9.937 m
(b) 4.0 s
(c) 0.0000037 kg

(a) (b) 4; (c) 2; (d) 2
Summary

Selected Vocabulary

matter ................................ Anything that is affected by gravity.
light ................................... Anything that can travel from one place to another through empty space and can influence matter, but is not affected by gravity.
operational definition .......... A definition that states what operations should be carried out to measure the thing being defined.
Système International ....... A fancy name for the metric system.
mks system ...................... The use of metric units based on the meter, kilogram, and second. Example: meters per second is the mks unit of speed, not cm/s or km/hr.
mass ................................ A numerical measure of how difficult it is to change an object’s motion.
significant figures .......... Digits that contribute to the accuracy of a measurement.

Notation

m ...................................... symbol for mass, or the meter, the metric distance unit
kg ...................................... kilogram, the metric unit of mass
s ........................................ second, the metric unit of time
M- ..................................... the metric prefix mega-, 10^6
k- ...................................... the metric prefix kilo-, 10^3
m- ..................................... the metric prefix milli-, 10^-3
µ- ...................................... the metric prefix micro-, 10^-6
n- ...................................... the metric prefix nano-, 10^-9

Summary

Physics is the use of the scientific method to study the behavior of light and matter. The scientific method requires a cycle of theory and experiment, theories with both predictive and explanatory value, and reproducible experiments.

The metric system is a simple, consistent framework for measurement built out of the meter, the kilogram, and the second plus a set of prefixes denoting powers of ten. The most systematic method for doing conversions is shown in the following example:

\[ 370 \text{ ms} \times \frac{10^{-3} \text{s}}{1 \text{ ms}} = 0.37 \text{ s} \]

Mass is a measure of the amount of a substance. Mass can be defined gravitationally, by comparing an object to a standard mass on a double-pan balance, or in terms of inertia, by comparing the effect of a force on an object to the effect of the same force on a standard mass. The two definitions are found experimentally to be proportional to each other to a high degree of precision, so we usually refer simply to “mass,” without bothering to specify which type.

A force is that which can change the motion of an object. The metric unit of force is the Newton, defined as the force required to accelerate a standard 1-kg mass from rest to a speed of 1 m/s in 1 s.

Scientific notation means, for example, writing \(3.2 \times 10^5\) rather than 320000.

Writing numbers with the correct number of significant figures correctly communicates how accurate they are. As a rule of thumb, the final result of a calculation is no more accurate than, and should have no more significant figures than, the least accurate piece of data.
1. Correct use of a calculator: (a) Calculate \( \frac{74658}{53222 + 97554} \) on a calculator.

[Self-check: The most common mistake results in 97555.40.]

(b) Which would be more like the price of a TV, and which would be more like the price of a house, \( \$ 3.5 \times 10^5 \) or \( \$ 3.5 \)?

2. Compute the following things. If they don’t make sense because of units, say so.

   (a) \( 3 \text{ cm} + 5 \text{ cm} \)  \hspace{1cm}   (b) \( 1.11 \text{ m} + 22 \text{ cm} \)

   (c) \( 120 \text{ miles} + 2.0 \text{ hours} \)  \hspace{1cm}   (d) \( 120 \text{ miles} / 2.0 \text{ hours} \)

3. Your backyard has brick walls on both ends. You measure a distance of 23.4 m from the inside of one wall to the inside of the other. Each wall is 29.4 cm thick. How far is it from the outside of one wall to the outside of the other? Pay attention to significant figures.

4 √. The speed of light is \( 3.0 \times 10^8 \text{ m/s} \). Convert this to furlongs per fortnight. A furlong is 220 yards, and a fortnight is 14 days. An inch is 2.54 cm.

5 √. Express each of the following quantities in micrograms: (a) 10 mg, (b) \( 10^4 \text{ g} \), (c) 10 kg, (d) \( 100 \times 10^3 \text{ g} \), (e) 1000 ng.

6 S. Convert 134 mg to units of kg, writing your answer in scientific notation.

7 √. In the last century, the average age of the onset of puberty for girls has decreased by several years. Urban folklore has it that this is because of hormones fed to beef cattle, but it is more likely to be because modern girls have more body fat on the average and possibly because of estrogen-mimicking chemicals in the environment from the breakdown of pesticides. A hamburger from a hormone-implanted steer has about 0.2 ng of estrogen (about double the amount of natural beef). A serving of peas contains about 300 ng of estrogen. An adult woman produces about 0.5 mg of estrogen per day (note the different unit!). (a) How many hamburgers would a girl have to eat in one day to consume as much estrogen as an adult woman’s daily production? (b) How many servings of peas?

8 S. The usual definition of the mean (average) of two numbers \( a \) and \( b \) is \( (a+b)/2 \). This is called the arithmetic mean. The geometric mean, however, is defined as \( (ab)^{1/2} \). For the sake of definiteness, let’s say both numbers have units of mass. (a) Compute the arithmetic mean of two numbers that have units of grams. Then convert the numbers to units of kilograms and recompute their mean. Is the answer consistent? (b) Do the same for the geometric mean. (c) If \( a \) and \( b \) both have units of grams, what should we call the units of \( ab \)? Does your answer make sense when you take the square root? (d) Suppose someone proposes to you a third kind of mean, called the superduper mean, defined as \( (ab)^{1/3} \). Is this reasonable?

S A solution is given in the back of the book.

√ A computerized answer check is available.

★ A difficult problem.

∫ A problem that requires calculus.
9. In an article on the SARS epidemic, the May 7, 2003 New York Times discusses conflicting estimates of the disease's incubation period (the average time that elapses from infection to the first symptoms). “The study estimated it to be 6.4 days. But other statistical calculations ... showed that the incubation period could be as long as 14.22 days.” What’s wrong here?

10. The photo shows the corner of a bag of pretzels. What’s wrong here?