ESSENTIAL UNIVERSITY PHYSICS

VOLUME 1 THIRD EDITION

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Doing Physics

What You Know

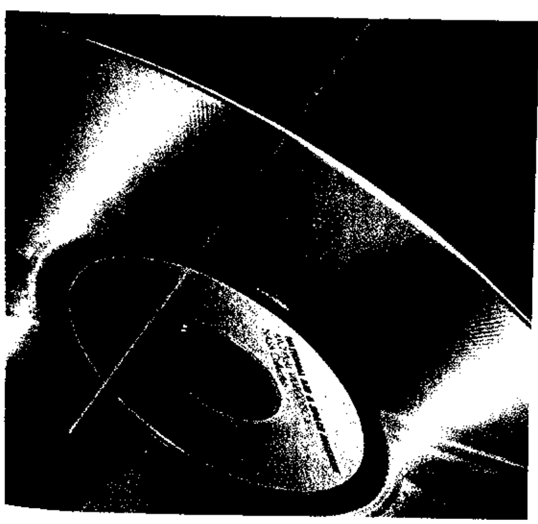
- You're coming to this course with a solid background in algebra, geometry, and trigonometry.
- You may have had calculus, or you'll be starting it concurrently.
- You don't need to have taken physics to get a full understanding from this book.

What You're Learning

- This chapter gives you an overview of physics and its subfields, which together describe the entire physical universe.
- You'll learn the basis of the SI system of measurement units.
- You'll learn to express and manipulate numbers used in quantitative science.
- You'll learn to deal with precision and uncertainty.
- You'll develop a skill for making quick estimates.
- You'll learn how to extract information from experimental data.
- You'll see a strategy for solving physics problems.

How You'll Use It

- Skills and knowledge that you develop in this chapter will serve you throughout your study of physics.
- You'll be able to express quantitative answers to physics problems in scientific notation, with the correct units and the appropriate uncertainty expressed through significant figures.
- Being able to make quick estimates will help you gauge the sizes of physical effects and will help you recognize whether your quantitative answers make sense.
- The problem-solving strategy you'll learn here will serve you in the many physics problems that you'll work in order to really learn physics.



Which realms of physics are involved in the workings of your DVD player?

You slip a DVD into your player and settle in to watch a movie. The DVD spins, and a precisely focused laser beam "reads" its content. Electronic circuitry processes the information, sending it to your video display and to loudspeakers that turn electrical signals into sound waves. Every step of the way, principles of physics govern the delivery of the movie from DVD to you.

1.1 Realms of Physics

That DVD player is a metaphor for all of **physics**—the science that describes the fundamental workings of physical reality. Physics explains natural phenomena ranging from the behavior of atoms and molecules to thunderstorms and rainbows and on to the evolution of stars, galaxies, and the universe itself. Technological applications of physics are the basis for everything from microelectronics to medical imaging to cars, airplanes, and space flight.

At its most fundamental, physics provides a nearly unified description of all physical phenomena. However, it's convenient to divide physics into distinct realms (Fig. 1.1). Your DVD player encompasses essentially all those realms. **Mechanics**, the branch of physics that deals with motion, describes the spinning disc. Mechanics also explains the motion of a car, the orbits of the planets, and the stability of a skyscraper. Part 1 of this book deals with the basic ideas of mechanics.

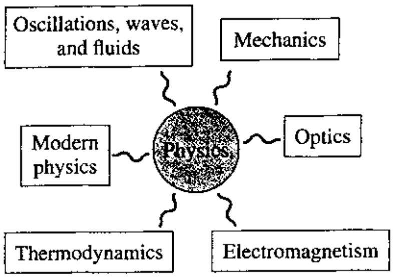


FIGURE 1.1 Realms of physics.

Those sound waves coming from your loudspeakers represent **wave motion**. Other examples include the ocean waves that pound Earth's coastlines, the wave of standing spectators that sweeps through a football stadium, and the undulations of Earth's crust that spread the energy of an earthquake. Part 2 of this book covers wave motion and other phenomena involving the motion of fluids like air and water.

When you burn your own DVD, the high temperature produced by an intensely focused laser beam alters the material properties of a writable DVD, thus storing video or computer information. That's an example of **thermodynamics**—the study of heat and its effects on matter. Thermodynamics also describes the delicate balance of energy-transfer processes that keeps our planet at a habitable temperature and puts serious constraints on our ability to meet the burgeoning energy demands of modern society. Part 3 comprises four chapters on thermodynamics.

An electric motor spins your DVD, converting electrical energy to the energy of motion. Electric motors are ubiquitous in modern society, running everything from subway trains and hybrid cars, to elevators and washing machines, to insulin pumps and artificial hearts. Conversely, electric generators convert the energy of motion to electricity, providing virtually all of our electrical energy. Motors and generators are two applications of **electromagnetism** in modern technology. Others include computers, audiovisual electronics, microwave ovens, digital watches, and even the humble lightbulb; without these electromagnetic technologies our lives would be very different. Equally electromagnetic are all the wireless technologies that enable modern communications, from satellite TV to cell phones to wireless computer networks, mice, and keyboards. And even light itself is an electromagnetic phenomenon. Part 4 presents the principles of electromagnetism and their many applications.

The precise focusing of laser light in your DVD player allows hours of video to fit on a small plastic disc. The details and limitations of that focusing are governed by the principles of **optics**, the study of light and its behavior. Applications of optics range from simple magnifiers to contact lenses to sophisticated instruments such as microscopes, telescopes, and spectrometers. Optical fibers carry your e-mail, web pages, and music downloads over the global Internet. Natural optical systems include your eye and the raindrops that deflect sunlight to form rainbows. Part 5 of the book explores optical principles and their applications.

That laser light in your DVD player is an example of an electromagnetic wave, but an atomic-level look at the light's interaction with matter reveals particle-like "bundles" of electromagnetic energy. This is the realm of **quantum physics**, which deals with the often counterintuitive behavior of matter and energy at the atomic level. Quantum phenomena also explain how that DVD laser works and, more profoundly, the structure of atoms and the periodic arrangement of the elements that is the basis of all chemistry. Quantum physics is one of the two great developments of **modern physics**. The other is Einstein's **theory of relativity**. Relativity and quantum physics arose during the 20th century, and together they've radically altered our commonsense notions of time, space, and causality. Part 6 of the book surveys the ideas of modern physics, ending with what we do—and don't—know about the history, future, and composition of the entire universe.

CONCEPTUAL EXAMPLE 1.1 Car Physics

Name some systems in your car that exemplify the different realms of physics.

EVALUATE *Mechanics* is easy; the car is fundamentally a mechanical system whose purpose is motion. Details include starting, stopping, cornering, as well as a host of other motions within mechanical subsystems. Your car's springs and shock absorbers constitute an *oscillatory* system engineered to give a comfortable ride. The car's engine is a prime example of a *thermodynamic* system, converting the energy of burning gasoline into the car's motion. *Electromagnetic* systems range from the starter motor and spark plugs to sophisticated electronic devices that monitor and optimize engine performance. *Optical* principles govern rear- and side-view mirrors and headlights. Increasingly, optical fibers transmit information to critical safety systems. *Modern physics* is less obvious in your car, but ultimately, everything from the chemical reactions of burning gasoline to the atomic-scale operation of automotive electronics is governed by its principles.

1.2 Measurements and Units

"A long way" means different things to a sedentary person, a marathon runner, a pilot, and an astronaut. We need to quantify our measurements. Science uses the **metric system**, with fundamental quantities length, mass, and time measured in meters, kilograms, and seconds, respectively. The modern version of the metric system is **SI**, for Système International d'Unités (International System of Units), which incorporates scientifically precise definitions of the fundamental quantities.

The three fundamental quantities were originally defined in reference to nature: the meter in terms of Earth's size, the kilogram as an amount of water, and the second by the length of the day. For length and mass, these were later replaced by specific artifacts—a bar whose length was defined as 1 meter and a cylinder whose mass defined the kilogram. But natural standards like the day's length can change, as can the properties of artifacts. So early SI definitions gave way to **operational definitions**, which are measurement standards based on laboratory procedures. Such standards have the advantage that scientists anywhere can reproduce them. By the late 20th century, two of the three fundamental units—the meter and the second—had operational definitions, but the kilogram did not.

A special type of operational definition involves giving an exact value to a particular constant of nature—a quantity formerly subject to experimental determination and with a stated uncertainty in its value. As described below, the meter was the first such unit to be defined in this way. By the early 21st century, it was clear that defining units in terms of fundamental, invariant physical constants was the best way to ensure long-term stability of the SI unit system. Currently, SI is undergoing a sweeping revision, which will result in redefining the kilogram and three of the four remaining so-called base units with definitions that lock in exact values of fundamental constants. These so-called **explicit-constant** definitions will have similar wording, making explicit that the unit in question follows from the defined value of the particular physical constant.

APPLICATION Units Matter: A Bad Day on Mars

In September 1999, the Mars Climate Orbiter was destroyed when the spacecraft passed through Mars's atmosphere and experienced stresses and heating it was not designed to tolerate. Why did this $125-million craft enter the Martian atmosphere when it was supposed to remain in the vacuum of space? NASA identified the root cause as a failure to convert the English units one team used to specify rocket thrust to the SI units another team expected. Units matter!

Length

The **meter** was first defined as one ten-millionth of the distance from Earth's equator to the North Pole. In 1889 a standard meter was fabricated to replace the Earth-based unit, and in 1960 that gave way to a standard based on the wavelength of light. By the 1970s, the speed of light had become one of the most precisely determined quantities. As a result, the meter was redefined in 1983 as the distance light travels in vacuum in 1/299,792,458 of a second. The effect of this definition is to make the speed of light a defined quantity: 299,792,458 m/s. Thus, the meter became the first SI unit to be based on a defined value for a fundamental constant. The new SI definitions won't change the meter but will reword its definition to make it of the explicit-constant type:

> The meter, symbol m, is the unit of length; its magnitude is set by fixing the numerical value of the speed of light in vacuum to be equal to exactly 299,792,458 when it is expressed in the SI unit m/s.

Time

The **second** used to be defined by Earth's rotation, but that's not constant, so it was later redefined as a specific fraction of the year 1900. An operational definition followed in 1967, associating the second with the radiation emitted by a particular atomic process. The new definition will keep the essence of that operational definition but reworded in the explicit-constant style:

> The second, symbol s, is the unit of time; its magnitude is set by fixing the numerical value of the ground-state hyperfine splitting frequency of the cesium-133 atom, at rest and at a temperature of 0 K, to be exactly 9,192,631,770 when it is expressed in the SI unit s^{-1}, which is equal to Hz.

The device that implements this definition—which will seem less obscure once you've studied some atomic physics—is called an *atomic clock*. Here the phrase "equal to Hz" introduces the unit hertz (Hz) for frequency—the number of cycles of a repeating process that occur each second.

Mass

Since 1889, the kilogram has been defined as the mass of a single artifact—the international prototype kilogram, a platinum–iridium cylinder kept in a vault at the International Bureau of Weights and Measures in Sèvres, France. Not only is this artifact-based standard awkward to access, but comparison measurements have revealed tiny yet growing mass discrepancies between the international prototype kilogram and secondary mass standards based on it.

In the current SI revision, the kilogram will become the last of the SI base units to be defined operationally, with a new explicit-constant definition resulting from fixing the value of *Planck's constant*, h, a fundamental constant of nature related to the "graininess" of physical quantities at the atomic and subatomic levels. The units of Planck's constant involve seconds, meters, and kilograms, and giving h an exact value actually sets the value of $1\ \text{s}^{-1} \cdot \text{m}^2 \cdot \text{kg}$. But with the meter and second already defined, fixing the unit $\text{s}^{-1} \cdot \text{m}^2 \cdot \text{kg}$ then determines the kilogram. A device that implements this definition is the *watt balance*, which balances an unknown mass against forces resulting from electrical effects whose magnitude, in turn, can be related to Planck's constant. The new formal definition of the kilogram will be similar to the explicit-constant definitions of the meter and second, but the exact value of Planck's constant is yet to be established.

The angle θ in radians is defined as the ratio of the subtended arc length s to the radius r: $\theta = \frac{s}{r}$.

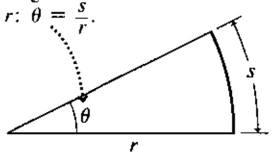


FIGURE 1.2 The radian is the SI unit of angle.

Other SI Units

The SI includes seven independent base units: In addition to the meter, second, and kilogram, there are the ampere (A) for electric current, the kelvin (K) for temperature, the mole (mol) for the amount of a substance, and the candela (cd) for luminosity. We'll introduce these units later, as needed. In the ongoing SI revision these will be given new, explicit-constant definitions; for all but the candela, this involves fixing the values of fundamental physical constants. In addition to the seven physical base units, two supplementary units define geometrical measures of angle: the radian (rad) for ordinary angles (Fig. 1.2) and the steradian (sr) for solid angles. Units for all other physical quantities are derived from the base units.

Table 1.1 SI Prefixes

Prefix	Symbol	Power
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
—	—	10^{0}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

SI Prefixes

You could specify the length of a bacterium (e.g., 0.00001 m) or the distance to the next city (e.g., 58,000 m) in meters, but the results are unwieldy—too small in the first case and too large in the latter. So we use prefixes to indicate multiples of the SI base units. For example, the prefix k (for "kilo") means 1000; 1 km is 1000 m, and the distance to the next city is 58 km. Similarly, the prefix μ (the lowercase Greek "mu") means "micro," or 10^{-6}. So our bacterium is 10 µm long. The SI prefixes are listed in Table 1.1, which is repeated inside the front cover. We'll use the prefixes routinely in examples and problems, and we'll often express answers using SI prefixes, without doing an explicit unit conversion.

When two units are used together, a hyphen appears between them—for example, newton-meter. Each unit has a symbol, such as m for meter or N for newton (the SI unit of force). Symbols are ordinarily lowercase, but those named after people are uppercase. Thus "newton" is written with a small "n" but its symbol is a capital N. The exception is the unit of volume, the liter; since the lowercase "l" is easily confused with the number 1, the symbol for liter is a capital L. When two units are multiplied, their symbols are separated by a centered dot: $\text{N} \cdot \text{m}$ for newton-meter. Division of units is expressed by using the slash (/) or writing with the denominator unit raised to the -1 power. Thus the SI unit of speed is the meter per second, written m/s or $\text{m} \cdot \text{s}^{-1}$.

EXAMPLE 1.1 Changing Units: Speed Limits

Express a 65 mi/h speed limit in meters per second.

EVALUATE According to Appendix C, 1 mi = 1609 m, so we can multiply miles by the ratio 1609 m/mi to get meters. Similarly, we use the conversion factor 3600 s/h to convert hours to seconds. Combining these two conversions gives

$$65\ \text{mi/h} = \left(\frac{65\ \cancel{\text{mi}}}{\cancel{\text{h}}}\right)\left(\frac{1609\ \text{m}}{\cancel{\text{mi}}}\right)\left(\frac{1\ \cancel{\text{h}}}{3600\ \text{s}}\right) = 29\ \text{m/s}$$

■

Other Unit Systems

The inches, feet, yards, miles, and pounds of the so-called English system still dominate measurement in the United States. Other non-SI units such as the hour are often mixed with English or SI units, as with speed limits in miles per hour or kilometers per hour. In some areas of physics there are good reasons for using non-SI units. We'll discuss these as the need arises and will occasionally use non-SI units in examples and problems. We'll also often find it convenient to use degrees rather than radians for angles. The vast majority of examples and problems in this book, however, use strictly SI units.

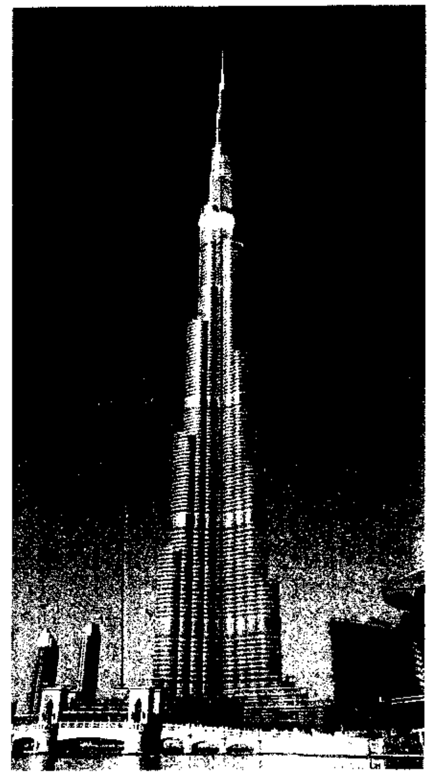


FIGURE 1.3 Dubai's Burj Khalifa is the world's tallest structure.

Changing Units

Sometimes we need to change from one unit system to another—for example, from English to SI. Appendix C contains tables for converting among unit systems; you should familiarize yourself with this and the other appendices and refer to them often.

For example, Appendix C shows that 1 ft = 0.3048 m. Since 1 ft and 0.3048 m represent the same physical distance, multiplying any distance by their ratio will change the units but not the actual physical distance. Thus the height of Dubai's Burj Khalifa (Fig. 1.3)—the world's tallest structure—is 2717 ft or

$$(2717\ \text{ft})\left(\frac{0.3048\ \text{m}}{1\ \text{ft}}\right) = 828.1\ \text{m}$$

Often you'll need to change several units in the same expression. Keeping track of the units through a chain of multiplications helps prevent you from carelessly inverting any of the conversion factors. A numerical answer cannot be correct unless it has the right units!

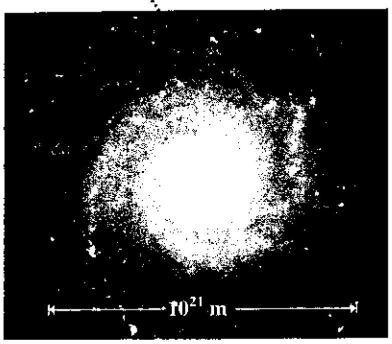
GOT IT? 1.1 A Canadian speed limit of 50 km/h is closest to which U.S. limit expressed in miles per hour? (a) 60 mph; (b) 45 mph; (c) 30 mph

1.3 Working with Numbers

Scientific Notation

The range of measured quantities in the universe is enormous; lengths alone go from about 1/1,000,000,000,000,000 m for the radius of a proton to 1,000,000,000,000,000,000,000 m for the size of a galaxy; our telescopes see 100,000 times farther still. Therefore, we frequently express numbers in **scientific notation**, where a reasonable-size number is multiplied by a power of 10. For example, 4185 is 4.185×10^3 and 0.00012 is 1.2×10^{-4}. Table 1.2 suggests the vast range of measurements for the fundamental quantities of length, time, and mass. Take a minute (about 10^2 heartbeats, or 3×10^{-8} of a typical human lifespan) to peruse this table along with Fig. 1.4.

This galaxy is 10^{21} m across and has a mass of $\sim 10^{42}$ kg.



Your movie is stored on a DVD in "pits" only 4×10^{-7} m in size.

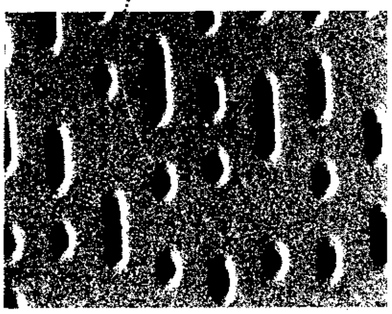


FIGURE 1.4 Large and small.

Table 1.2 Distances, Times, and Masses (rounded to one significant figure)

Radius of observable universe	1×10^{26} m
Earth's radius	6×10^{6} m
Tallest mountain	9×10^{3} m
Height of person	2 m
Diameter of red blood cell	1×10^{-5} m
Size of proton	1×10^{-15} m
Age of universe	4×10^{17} s
Earth's orbital period (1 year)	3×10^{7} s
Human heartbeat	1 s
Wave period, microwave oven	5×10^{-10} s
Time for light to cross a proton	3×10^{-24} s
Mass of Milky Way galaxy	1×10^{42} kg
Mass of mountain	1×10^{18} kg
Mass of human	70 kg
Mass of red blood cell	1×10^{-13} kg
Mass of uranium atom	4×10^{-25} kg
Mass of electron	1×10^{-30} kg

Scientific calculators handle numbers in scientific notation. But straightforward rules allow you to manipulate scientific notation if you don't have such a calculator handy.

TACTICS 1.1 Using Scientific Notation

Addition/Subtraction

To add (or subtract) numbers in scientific notation, first give them the same exponent and then add (or subtract):

$$3.75 \times 10^{6} + 5.2 \times 10^{5} = 3.75 \times 10^{6} + 0.52 \times 10^{6} = 4.27 \times 10^{6}$$

Multiplication/Division

To multiply (or divide) numbers in scientific notation, multiply (or divide) the digits and add (or subtract) the exponents:

$$(3.0 \times 10^{8}\ \text{m/s})(2.1 \times 10^{-10}\ \text{s}) = (3.0)(2.1) \times 10^{8+(-10)}\ \text{m} = 6.3 \times 10^{-2}\ \text{m}$$

Powers/Roots

To raise numbers in scientific notation to any power, raise the digits to the given power and multiply the exponent by the power:

$$\sqrt{(3.61 \times 10^{4})^{3}} = \sqrt{3.61^{3} \times 10^{(4)(3)}} = (47.04 \times 10^{12})^{1/2}$$
$$= \sqrt{47.04} \times 10^{(12)(1/2)} = 6.86 \times 10^{6}$$

EXAMPLE 1.2 Scientific Notation: Tsunami Warnings

Earthquake-generated tsunamis are so devastating because the entire ocean, from surface to bottom, participates in the wave motion. The speed of such waves is given by $v = \sqrt{gh}$, where $g = 9.8\ \text{m/s}^2$ is the gravitational acceleration and h is the depth in meters. Determine a tsunami's speed in 3.0-km-deep water.

EVALUATE That 3.0-km depth is 3.0×10^{3} m, so we have

$$v = \sqrt{gh} = [(9.8\ \text{m/s}^2)(3.0 \times 10^{3}\ \text{m})]^{1/2} = (29.4 \times 10^{3}\ \text{m}^2/\text{s}^2)^{1/2}$$
$$= (2.94 \times 10^{4}\ \text{m}^2/\text{s}^2)^{1/2} = \sqrt{2.94} \times 10^{2}\ \text{m/s} = 1.7 \times 10^{2}\ \text{m/s}$$

where we wrote $29.4 \times 10^{3}\ \text{m}^2/\text{s}^2$ as $2.94 \times 10^{4}\ \text{m}^2/\text{s}^2$ in the second line in order to calculate the square root more easily. Converting the speed to km/h gives

$$1.7 \times 10^{2}\ \text{m/s} = \left(\frac{1.7 \times 10^{2}\ \cancel{\text{m}}}{\cancel{\text{s}}}\right)\left(\frac{1\ \text{km}}{1.0 \times 10^{3}\ \cancel{\text{m}}}\right)\left(\frac{3.6 \times 10^{3}\ \cancel{\text{s}}}{\text{h}}\right)$$
$$= 6.1 \times 10^{2}\ \text{km/h}$$

This speed—about 600 km/h—shows why even distant coastlines have little time to prepare for the arrival of a tsunami. ■

Significant Figures

How precise is that 1.7×10^2 m/s we calculated in Example 1.2? The two **significant figures** in this number imply that the value is closer to 1.7 than to 1.6 or 1.8. The fewer significant figures, the less precisely we can claim to know a given quantity.

In Example 1.2 we were, in fact, given two significant figures for both quantities. The mere act of calculating can't add precision, so we rounded our answer to two significant figures as well. Calculators and computers often give numbers with many figures, but most of those are usually meaningless.

What's Earth's circumference? It's $2\pi R_E$, and π is approximately 3.14159. . . . But if you only know Earth's radius as 6.37×10^6 m, knowing π to more significant figures doesn't mean you can claim to know the circumference any more precisely. This example suggests a rule for handling calculations involving numbers with different precisions:

> In multiplication and division, the answer should have the same number of significant figures as the least precise of the quantities entering the calculation.

You're engineering an access ramp to a bridge whose main span is 1.248 km long. The ramp will be 65.4 m long. What will be the overall length? A simple calculation gives 1.248 km + 0.0654 km = 1.3134 km. How should you round this? You know the bridge length to ± 0.001 km, so an addition this small is significant. Therefore, your answer should have three digits to the right of the decimal point, giving 1.313 km. Thus:

> In addition and subtraction, the answer should have the same number of digits to the right of the decimal point as the term in the sum or difference that has the smallest number of digits to the right of the decimal point.

In subtraction, this rule can quickly lead to loss of precision, as Example 1.3 illustrates.

EXAMPLE 1.3 Significant Figures: Nuclear Fuel

A uranium fuel rod is 3.241 m long before it's inserted in a nuclear reactor. After insertion, heat from the nuclear reaction has increased its length to 3.249 m. What's the increase in its length?

EVALUATE Subtraction gives 3.249 m − 3.241 m = 0.008 m or 8 mm. Should this be 8 mm or 8.000 mm? Just 8 mm. Subtraction affected only the last digit of the four-significant-figure lengths, leaving only one significant figure in the answer. ■

✓TIP Intermediate Results

Although it's important that your final answer reflect the precision of the numbers that went into it, any intermediate results should have at least one extra significant figure. Otherwise, rounding of intermediate results could alter your answer.

GOT IT? 1.2 Rank the numbers according to (1) their size and (2) the number of significant figures. Some may be of equal rank. 0.0008, 3.14×10^7, 2.998×10^{-9}, 55×10^6, 0.041×10^9

What about whole numbers ending in zero, like 60, 300, or 410? How many significant figures do they have? Strictly speaking, 60 and 300 have only one significant figure, while 410 has two. If you want to express the number 60 to two significant figures, you should write 6.0×10^1; similarly, 300 to three significant figures would be 3.00×10^2, and 410 to three significant figures would be 4.10×10^2.

Working with Data

In physics, in other sciences, and even in nonscience fields, you'll find yourself working with data—numbers that come from real-world measurements. One important use of data in the sciences is to confirm hypotheses about relations between physical quantities. Scientific hypotheses can generally be described quantitatively using equations, which often give or can be manipulated to give a linear relationship between quantities. Plotting such data and fitting a line through the data points—using procedures such as regression analysis, least-squares fitting, or even "eyeballing" a best-fit line—can confirm the hypothesis and give useful information about the phenomena under study. You'll probably have opportunities to do such data fitting in your physics lab and in other science courses. Because it's so important in experimental science, we've included at least one data problem with each chapter. Example 1.4 shows a typical example of fitting data to a straight line.

EXAMPLE 1.4 Data Analysis: A Falling Ball

As you'll see in Chapter 2, the distance fallen by an object dropped from rest should increase in proportion to the square of the time since it was dropped; the proportionality should be half the acceleration due to gravity. The table shows actual data from measurements on a falling ball. Determine a quantity such that, when you plot fall distance y against it, you should get a straight line. Make the plot, fit a straight line, and from its slope determine an approximate value for the gravitational acceleration.

Time (s)	0.500	1.00	1.50	2.00	2.50	3.00
Distance (m)	1.12	5.30	12.2	18.5	34.1	43.6
Time Squared (s^2)	0.250	1.00	2.25	4.00	6.25	9.00

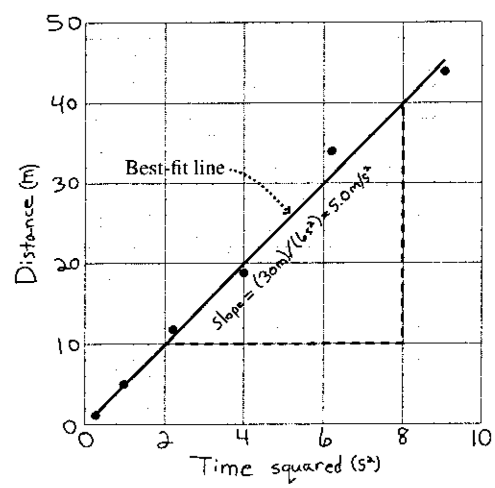


FIGURE 1.5 Our graph for Example 1.4. We "eyeballed" the best-fit line using a ruler; note that it doesn't go through particular points but tries to capture the average trend of all the data points.

EVALUATE We're told that the fall distance y should be proportional to the square of the time; thus we choose to plot y versus t^2. So we've added a row to the table, listing the values of t^2. Figure 1.5 is our plot. Although we did this one by hand, on graph paper, you could use a spreadsheet or other program to make your plot. A spreadsheet program would offer the option to draw a best-fit line and give its slope, but a hand-drawn line, "eyeballed" to catch the general trend of the data points, works surprisingly well. We've indicated such a line, and the figure shows that its slope is very nearly 5.0 m/s^2.

ASSESS The fact that our data points lie very nearly on a straight line confirms the hypothesis that fall distance should be proportional to time squared. Real data almost never lie exactly on a theoretically predicted line or curve. A more sophisticated analysis would show error bars, indicating the measurement uncertainty in each data point. Because our line's measured slope is supposed to be half the gravitational acceleration, our analysis suggests a gravitational acceleration of about 10 m/s^2. This is close to the commonly used value of 9.8 m/s^2. ■

MP

PhET: Estimation

Estimation

Some problems in physics and engineering call for precise numerical answers. We need to know exactly how long to fire a rocket to put a space probe on course toward a distant planet, or exactly what size to cut the tiny quartz crystal whose vibrations set the pulse of a digital watch. But for many other purposes, we need only a rough idea of the size of a physical effect. And rough estimates help check whether the results of more difficult calculations make sense.

EXAMPLE 1.5 Estimation: Counting Brain Cells

Estimate the mass of your brain and the number of cells it contains.

EVALUATE My head is about 6 in. or 15 cm wide, but there's a lot of skull bone in there, so maybe my brain is about 10 cm or 0.1 m across. I don't know its exact shape, but for estimating, I'll take it to be a cube. Then its volume is $(10\,\text{cm})^3 = 1000\,\text{cm}^3$, or $10^{-3}\,\text{m}^3$. I'm mostly water, and water's density is 1 gram per cubic centimeter ($1\,\text{g/cm}^3$), so my 1000-cm^3 brain has a mass of about 1 kg.

How big is a brain cell? I don't know, but Table 1.2 lists the diameter of a red blood cell as about 10^{-5} m. If brain cells are roughly the same size, then each cell has a volume of approximately $(10^{-5}\,\text{m})^3 = 10^{-15}\,\text{m}^3$. Then the number of cells in my 10^{-3}-m^3 brain is roughly

$$N = \frac{10^{-3}\,\text{m}^3/\text{brain}}{10^{-15}\,\text{m}^3/\text{cell}} = 10^{12}\,\text{cells/brain}$$

Crude though they are, these estimates aren't bad. The average adult brain's mass is about 1.3 kg, and it contains at least 10^{11} cells (Fig. 1.6).

FIGURE 1.6 The average human brain contains more than 10^{11} cells.

■

1.4 Strategies for Learning Physics

You can learn *about* physics, and you can learn to *do* physics. This book is for science and engineering students, so it emphasizes both. Learning about physics will help you appreciate the role of this fundamental science in explaining both natural and technological phenomena. Learning to do physics will make you adept at solving quantitative problems—finding answers to questions about how the natural world works and about how we forge the technologies at the heart of modern society.

Physics: Challenge and Simplicity

Physics problems can be challenging, calling for clever insight and mathematical agility. That challenge is what gives physics a reputation as a difficult subject. But underlying all of physics is only a handful of basic principles. Because physics is so fundamental, it's also inherently simple. There are only a few basic ideas to learn; if you really understand those, you can apply them in a wide variety of situations. These ideas and their applications are all connected, and we'll emphasize those connections and the underlying simplicity of physics by reminding you how the many examples, applications, and problems are manifestations of the same few basic principles. If you approach physics as a hodgepodge of unrelated laws and equations, you'll miss the point and make things difficult. But if you look for the basic principles, for connections among seemingly unrelated phenomena and problems, then you'll discover the underlying simplicity that reflects the scope and power of physics—the fundamental science.

Problem Solving: The IDEA Strategy

Solving a quantitative physics problem always starts with basic principles or concepts and ends with a precise answer expressed as either a numerical quantity or an algebraic expression. Whatever the principle, whatever the realm of physics, and whatever the specific situation, the path from principle to answer follows four simple steps—steps that make up a comprehensive strategy for approaching all problems in physics. Their acronym, IDEA, will help you remember these steps, and they'll be reinforced as we apply them over and over again in worked examples throughout the book. We'll generally write all four steps separately, although the examples in this chapter cut right to the EVALUATE phase. And in some chapters we'll introduce versions of this strategy tailored to specific material.

The IDEA strategy isn't a "cookbook" formula for working physics problems. Rather, it's a tool for organizing your thoughts, clarifying your conceptual understanding, developing and executing plans for solving problems, and assessing your answers. Here's the big IDEA:

PROBLEM-SOLVING STRATEGY 1.1 Physics Problems

INTERPRET The first step is to *interpret* the problem to be sure you know what it's asking. Then *identify* the applicable concepts and principles—Newton's laws of motion, conservation of energy, the first law of thermodynamics, Gauss's law, and so forth. Also *identify* the players in the situation—the object whose motion you're asked to describe, the forces acting, the thermodynamic system you're to analyze, the charges that produce an electric field, the components in an electric circuit, the light rays that will help you locate an image, and so on.

DEVELOP The second step is to *develop* a plan for solving the problem. It's always helpful and often essential to *draw* a diagram showing the situation. Your drawing should indicate objects, forces, and other physical entities. Labeling masses, positions, forces, velocities, heat flows, electric or magnetic fields, and other quantities will be a big help. Next, *determine* the relevant mathematical formulas—namely, those that contain the quantities you're given in the problem as well as the unknown(s) you're solving for. Don't just grab equations—rather, think about how each reflects the underlying concepts and principles that you've identified as applying to this problem. The plan you develop might include calculating intermediate quantities, finding values in a table or in one of this text's several appendices, or even solving a preliminary problem whose answer you need in order to get your final result.

EVALUATE Physics problems have numerical or symbolic answers, and you need to *evaluate* your answer. In this step you *execute* your plan, going in sequence through the steps you've outlined. Here's where your math skills come in. Use algebra, trig, or calculus, as needed, to solve your equations. It's a good idea to keep all numerical quantities, whether known or not, in symbolic form as you work through the solution of your problem. At the end you can plug in numbers and work the arithmetic to *evaluate* the numerical answer, if the problem calls for one.

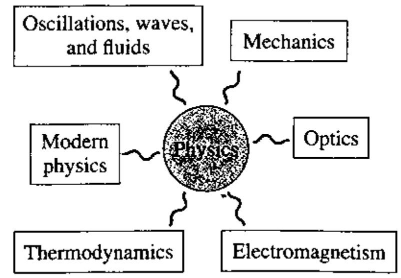
ASSESS Don't be satisfied with your answer until you *assess* whether it makes sense! Are the units correct? Do the numbers sound reasonable? Does the algebraic form of your answer work in obvious special cases, like perhaps "turning off" gravity or making an object's mass zero or infinite? Checking special cases not only helps you decide whether your answer makes sense but also can give you insights into the underlying physics. In worked examples, we'll often use this step to enhance your knowledge of physics by relating the example to other applications of physics.

Don't memorize the IDEA problem-solving strategy. Instead, grow to understand it as you see it applied in examples and as you apply it yourself in working end-of-chapter problems. This book has a number of additional features and supplements, discussed in the Preface, to help you develop your problem-solving skills.

CHAPTER 1 SUMMARY

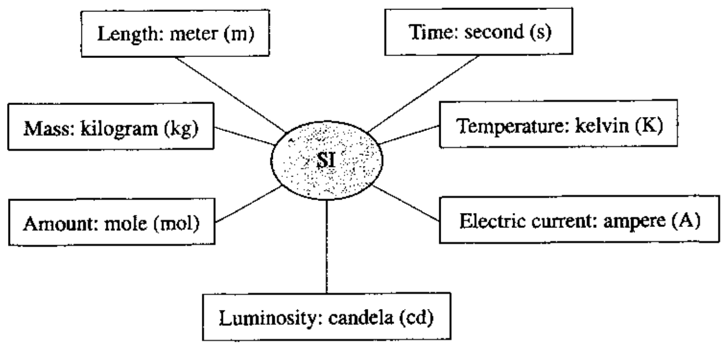
Big Idea

Physics is the fundamental science. It's convenient to consider several realms of physics, which together describe all that's known about physical reality:



Key Concepts and Equations

Numbers describing physical quantities must have units. The SI unit system comprises seven fundamental units:



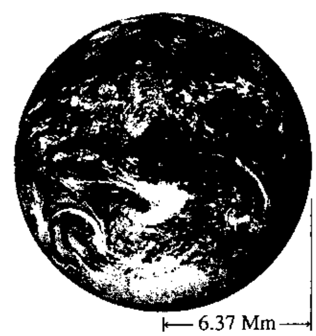
In addition, physics uses geometric measures of angle.

Numbers are often written with prefixes or in scientific notation to express powers of 10. Precision is shown by the number of significant figures:

Power of 10

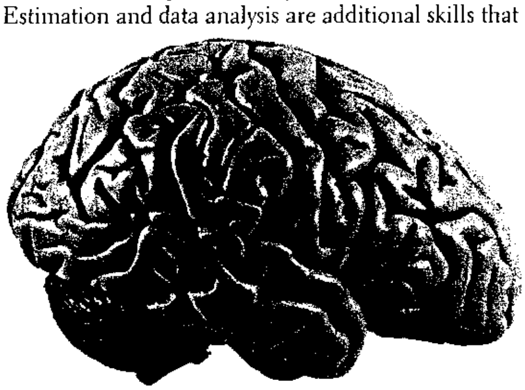
Earth's radius $6.37 \times 10^6\,\text{m} = 6.37\,\text{Mm}$

Three significant figures SI prefix for $\times 10^6$

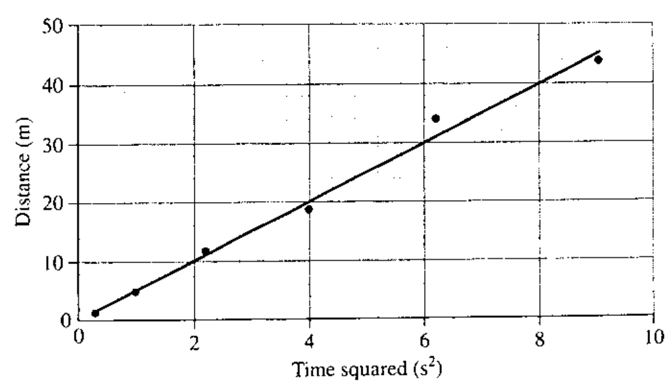


Applications

The IDEA strategy for solving physics problems consists of four steps: Interpret, Develop, Evaluate, and Assess. Estimation and data analysis are additional skills that help with physics.



$$N = \frac{10^{-3}\ \text{m}^3/\text{brain}}{10^{-15}\ \text{m}^3/\text{cell}} = 10^{12}\ \text{cells/brain}$$



MP For homework assigned on MasteringPhysics, go to www.masteringphysics.com

BIO *Biology and/or medicine-related problems* **DATA** *Data problems* **ENV** *Environmental problems* **CH** *Challenge problems* **COMP** *Computer problems*

For Thought and Discussion

1. Explain why measurement standards based on laboratory procedures are preferable to those based on specific objects such as the international prototype kilogram.
2. When a computer that carries seven significant figures adds 1.000000 and 2.5×10^{-15}, what's its answer? Why?
3. Why doesn't Earth's rotation provide a suitable time standard?
4. To raise a power of 10 to another power, you multiply the exponent by the power. Explain why this works.
5. What facts might a scientist use in estimating Earth's age?
6. How would you determine the length of a curved line?
7. Write $1/x$ as x to some power.
8. Emissions of carbon dioxide from fossil-fuel combustion are often expressed in gigatonnes per year, where 1 tonne = 1000 kg. But sometimes CO_2 emissions are given in petagrams per year. How are the two units related?
9. In Chapter 3, you'll learn that the range of a projectile launched over level ground is given by $x = v_0^2 \sin 2\theta/g$, where v_0 is the initial speed, θ is the launch angle, and g is the acceleration of gravity. If you did an experiment that involved launching projectiles with the same speed v_0 but different launch angles, what quantity would you plot the range x against in order to get a straight line and thus verify this relationship?
10. What is meant by an *explicit-constant* definition of a unit?
11. You're asked to make a rough estimate of the total mass of all the students in your university. You report your answer as 1.16×10^6 kg. Why isn't this an appropriate answer?

Exercises and Problems

Exercises

Section 1.2 Measurements and Units

12. The power output of a typical large power plant is 1000 megawatts (MW). Express this result in (a) W, (b) kW, and (c) GW.
13. The diameter of a hydrogen atom is about 0.1 nm, and the diameter of a proton is about 1 fm. How many times bigger than a proton is a hydrogen atom?
14. Use the definition of the meter to determine how far light travels in 1 ns.
15. In nanoseconds, how long is the period of the cesium-133 radiation used to define the second?
16. Lake Baikal in Siberia holds the world's largest quantity of fresh water, about 14 Eg. How many kilograms is that?
17. A hydrogen atom is about 0.1 nm in diameter. How many hydrogen atoms lined up side by side would make a line 1 cm long?
18. How long a piece of wire would you need to form a circular arc subtending an angle of 1.4 rad, if the radius of the arc is 8.1 cm?
19. Making a turn, a jetliner flies 2.1 km on a circular path of radius 3.4 km. Through what angle does it turn?
20. A car is moving at 35.0 mi/h. Express its speed in (a) m/s and (b) ft/s.
21. You have postage for a 1-oz letter but only a metric scale. What's the maximum mass your letter can have, in grams?
22. A year is very nearly $\pi \times 10^7$ s. By what percentage is this figure in error?
23. How many cubic centimeters are in a cubic meter?
24. Since the start of the industrial era, humankind has emitted about half an exagram of carbon to the atmosphere. What's that in tonnes (t, where 1 t = 1000 kg)?
25. A gallon of paint covers 350 ft^2. What's its coverage in m^2/L?
26. Highways in Canada have speed limits of 100 km/h. How does this compare with the 65 mi/h speed limit common in the United States?
27. One m/s is how many km/h?
28. A 3.0-lb box of grass seed will seed 2100 ft^2 of lawn. Express this coverage in m^2/kg.
29. A radian is how many degrees?
30. Convert the following to SI units: (a) 55 mi/h; (b) 40.0 km/h; (c) 1 week (take that 1 as an exact number); (d) the period of Mars's orbit (consult Appendix E).
31. The distance to the Andromeda galaxy, the nearest large neighbor galaxy of our Milky Way, is about 2.4×10^{22} m. Express this more succinctly using SI prefixes.

Section 1.3 Working with Numbers

32. Add 3.6×10^5m and 2.1×10^3 km.
33. Divide 4.2×10^3m/s by 0.57 ms, and express your answer in m/s^2.
34. Add 5.1×10^{-2} cm and 6.8×10^3 μm, and multiply the result by 1.8×10^4 N (N is the SI unit of force).
35. Find the cube root of 6.4×10^{19} without a calculator.
36. Add 1.46 m and 2.3 cm.
37. You're asked to specify the length of an updated aircraft model for a sales brochure. The original plane was 41 m long; the new model has a 3.6-cm-long radio antenna added to its nose. What length do you put in the brochure?
38. Repeat the preceding exercise, this time using 41.05 m as the airplane's original length.

Problems

39. To see why it's important to carry more digits in intermediate calculations, determine $(\sqrt{3})^3$ to three significant figures in two ways: (a) Find $\sqrt{3}$ and round to three significant figures, then cube and again round; and (b) find $\sqrt{3}$ to four significant figures, then cube and round to three significant figures.
40. You've been hired as an environmental watchdog for a big-city newspaper. You're asked to estimate the number of trees that go into one day's printing, given that half the newsprint comes from recycling, the rest from new wood pulp. What do you report?
41. The average dairy cow produces about 10^4 kg of milk per year. Estimate the number of dairy cows needed to keep the United States supplied with milk.
42. How many Earths would fit inside the Sun?
43. The average American uses electrical energy at the rate of about 1.5 kilowatts (kW). Solar energy reaches Earth's surface at an average rate of about 300 watts on every square meter (a value that accounts for night and clouds). What fraction of the United States' land area would have to be covered with 20% efficient solar cells to provide all of our electrical energy?
44. You're writing a biography of the physicist Enrico Fermi, who was fond of estimation problems. Here's one problem Fermi posed: What's the number of piano tuners in Chicago? Give your estimate, and explain to your readers how you got it.
45. (a) Estimate the volume of water going over Niagara Falls each second. (b) The falls provides the outlet for Lake Erie; if the

falls were shut off, estimate how long it would take Lake Erie to rise 1 m.

46. Estimate the number of air molecules in your dorm room.
47. A human hair is about 100 μm across. Estimate the number of hairs in a typical braid.
48. You're working in the fraud protection division of a credit-card company, and you're asked to estimate the chances that a 16-digit number chosen at random will be a valid credit-card number. What do you answer?
49. Bubble gum's density is about 1 g/cm^3. You blow an 8-g wad of gum into a bubble 10 cm in diameter. What's the bubble's thickness? (*Hint*: Think about spreading the bubble into a flat sheet. The surface area of a sphere is $4\pi r^2$.)
50. The Moon barely covers the Sun during a solar eclipse. Given that Moon and Sun are, respectively, 4×10^5 km and 1.5×10^8 km from Earth, determine how much bigger the Sun's diameter is than the Moon's. If the Moon's radius is 1800 km, how big is the Sun?
51. The semiconductor chip at the heart of a personal computer is a square 4 mm on a side and contains 10^{10} electronic components. (a) What's the size of each component, assuming they're square? (b) If a calculation requires that electrical impulses traverse 10^4 components on the chip, each a million times, how many such calculations can the computer perform each second? (*Hint*: The maximum speed of an electrical impulse is about two-thirds the speed of light.)
52. Estimate the number of (a) atoms and (b) cells in your body.
53. When we write the number 3.6 as typical of a number with two significant figures, we're saying that the actual value is closer to 3.6 than to 3.5 or 3.7; that is, the actual value lies between 3.55 and 3.65. Show that the percent uncertainty implied by such two-significant-figure precision varies with the value of the number, being the lowest for numbers beginning with 9 and the highest for numbers beginning with 1. In particular, what is the percent uncertainty implied by the numbers (a) 1.1, (b) 5.0, and (c) 9.9?
54. Continental drift occurs at about the rate your fingernails grow. Estimate the age of the Atlantic Ocean, given that the eastern and western hemispheres have been drifting apart.
55. You're driving into Canada and trying to decide whether to fill your gas tank before or after crossing the border. Gas in the United States costs \$3.67/gallon, in Canada it's \$1.32/L, and the Canadian dollar is worth 95¢ in U.S. currency. Where should you fill up?
56. In the 1908 London Olympics, the intended 26-mile marathon was extended 385 yards to put the end in front of the royal reviewing stand. This distance subsequently became standard. What's the marathon distance in kilometers, to the nearest meter?
57. **ENV** An environmental group is lobbying to shut down a coal-burning power plant that produces electrical energy at the rate of 1 GW (a watt, W, is a unit of power—the rate of energy production or consumption). They suggest replacing the plant with wind turbines that can produce 1.5 MW each but that, due to intermittent wind, average only 30% of that power. Estimate the number of wind turbines needed.
58. If you're working from the print version of this book, estimate the thickness of each page.
59. **BIO** Estimate the area of skin on your body.
60. Estimate the mass of water in the world's oceans, and express it with SI prefixes.
61. Express the following with appropriate units and significant figures: (a) 1.0 m plus 1 mm, (b) 1.0 m times 1 mm, (c) 1.0 m minus 999 mm, and (d) 1.0 m divided by 999 mm.
62. You're shopping for a new computer, and a salesperson claims the microprocessor chip in the model you're looking at contains 50 billion electronic components. The chip measures 5 mm on a side and uses 14-nm technology, meaning each component is 14 nm across. Is the salesperson right?
63. Café Milagro sells coffee online. A half-kilogram bag of coffee costs \$8.95, excluding shipping. If you order six bags, the shipping costs \$6.90. What's the cost per bag when you include shipping?
64. The world consumes energy at the rate of about 500 EJ per year, where the joule (J) is the SI energy unit. Convert this figure to watts (W), where 1 W = 1 J/s, and then estimate the average per capita energy consumption rate in watts.
65. **DATA** The volume of a sphere is given by $V = \frac{4}{3}\pi r^3$, where r is the sphere's radius. For solid spheres with the same density—made, for example, from the same material—mass is proportional to volume. The table below lists measures of diameter and mass for different steel balls. (a) Determine a quantity which, when you plot mass against it, should yield a straight line. (b) Make your plot, establish a best-fit line, and determine its slope (which in this case is proportional to the spheres' density).

Diameter (cm)	0.75	1.00	1.54	2.16	2.54
Mass (g)	1.81	3.95	15.8	38.6	68.2

Passage Problems

BIO The human body contains about 10^{14} cells, and the diameter of a typical cell is about 10 μm Like all ordinary matter, cells are made of atoms; a typical atomic diameter is 0.1 nm.

66. How does the number of atoms in a cell compare with the number of cells in the body?
    a. greater
    b. smaller
    c. about the same
67. The volume of a cell is about
    a. 10^{-10} m^3.
    b. 10^{-15} m^3.
    c. 10^{-20} m^3.
    d. 10^{-30} m^3.
68. The mass of a cell is about
    a. 10^{-10} kg.
    b. 10^{-12} kg.
    c. 10^{-14} kg.
    d. 10^{-16} kg.
69. The number of atoms in the body is closest to
    a. 10^{14}.
    b. 10^{20}.
    c. 10^{30}.
    d. 10^{40}.

Answers to Chapter Questions

Answer to Chapter Opening Question

All of them!

Answers to GOT IT? Questions

1.1 (c)

1.2 (1) 2.998×10^{-9}, 0.0008, 3.14×10^7, 0.041×10^9, 55×10^6
(2) 0.0008, 0.041×10^9 and 55×10^6 (with two significant figures each), 3.14×10^7, 2.998×10^{-9}