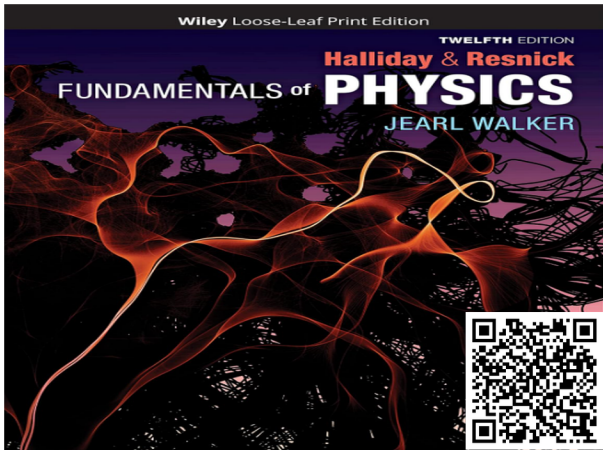


Fundamentals of Physics 12th Edition PDF

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As requested by instructors, here is a new edition of the textbook originated by David Halliday and Robert Resnick in 1963 and that I used as a first-year student at MIT. (Gosh, time has flown by.) Constructing this new edition allowed me to discover many delightful new examples and revisit a few favorites from my earlier eight editions. Here below are some highlights of this 12th edition.



Entertainment Pictures/Zuma Press

Figure 10.39 What tension was required by the Achilles tendons in Michael Jackson in his gravity-defying 45° lean during his video *Smooth Criminals*?



Evgeniy Skripnichenko/123RF

Figure 10.72 What is the increase in the tension of the Achilles tendons when high heels are worn?



Sergii Gnatiuk/123 RF

Figure 9.65 Falling is a chronic and serious condition among skateboarders, in-line skaters, elderly people, people with seizures, and many others. Often, they fall onto one outstretched hand, fracturing the wrist. What fall height can result in such fracture?



Bloomberg/Getty Images

Figure 34.5.4 In functional near infrared spectroscopy (fNIRS), a person wears a close-fitting cap with LEDs emitting in the near infrared range. The light can penetrate into the outer layer of the brain and reveal when that portion is activated by a given activity, from playing baseball to flying an airplane.



Fermilab/Science Source

Figure 28.5.2 Fast-neutron therapy is a promising weapon against salivary gland malignancies. But how can electrically neutral particles be accelerated to high speeds?



ZUMA Press Inc./Alamy Stock Photo

Figure 29.63 Parkinson's disease and other brain disorders have been treated with transcranial magnetic stimulation in which pulsed magnetic fields force neurons several centimeters deep to discharge.

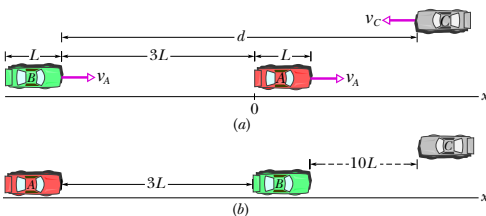


Figure 2.37 How should autonomous car *B* be programmed so that it can safely pass car *A* without being in danger from oncoming car *C*?

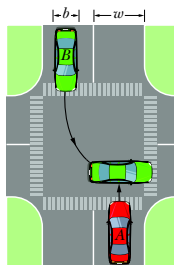


Figure 4.39 In a Pittsburgh left, a driver in the opposite lane anticipates the onset of the green light and rapidly pulls in front of your car during the red light. In a crash reconstruction, how soon before the green did the other driver start the turn?



Tracy Fox/123 RF

Figure 9.6.4 The most dangerous car crash is a head-on crash. In a head-on crash of cars of identical mass, by how much does the probability of a fatality of a driver decrease if the driver has a passenger in the car?

In addition, there are problems dealing with

- remote detection of the fall of an elderly person,
- the illusion of a rising fastball,
- hitting a fastball in spite of momentary vision loss,
- ship squat in which a ship rides lower in the water in a channel,
- the common danger of a bicyclist disappearing from view at an intersection,
- measurement of thunderstorm potentials with muons,

and more.

WHAT'S IN THE BOOK

- Checkpoints, one for every module
- Sample problems
- Review and summary at the end of each chapter
- Nearly 300 new end-of-chapter problems

In constructing this new edition, I focused on several areas of research that intrigue me and wrote new text discussions and many new homework problems. Here are a few research areas:

We take a look at the first image of a black hole (for which I have waited my entire life), and then we examine gravitational waves (something I discussed with Rainer Weiss at MIT when I worked in his lab several years before he came up with the idea of using an interferometer as a wave detector).

I wrote a new sample problem and several homework problems on autonomous cars where a computer system must calculate safe driving procedures, such as passing a slow car with an oncoming car in the passing lane.

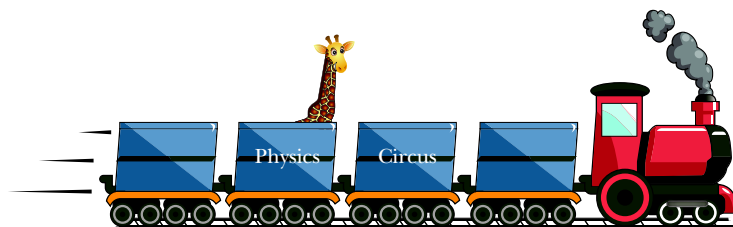
I explored cancer radiation therapy, including the use of Augur-Meitner electrons that were first understood by Lise Meitner.

I combed through many thousands of medical, engineering, and physics research articles to find clever ways of looking inside the human body without major invasive surgery. Some are listed in the index under “medical procedures and equipment.” Here are three examples:

(1) Robotic surgery using single-port incisions and optical fibers now allows surgeons to access internal organs, with patient recovery times of only hours instead of days or weeks as with previous surgery techniques.

(2) Transcranial magnetic stimulation is being used to treat chronic depression, Parkinson’s disease, and other brain malfunctions by applying pulsed magnetic fields from coils near the scalp to force neurons several centimeters deep to discharge.

(3) Magnetoencephalography (MEG) is being used to monitor a person’s brain as the person performs a task such as reading. The task causes weak electrical pulses to be sent along conducting paths between brain cells, and each pulse produces a weak magnetic field that is detected by extremely sensitive SQUIDS.



WileyPLUS THE WILEYPLUS ADVANTAGE

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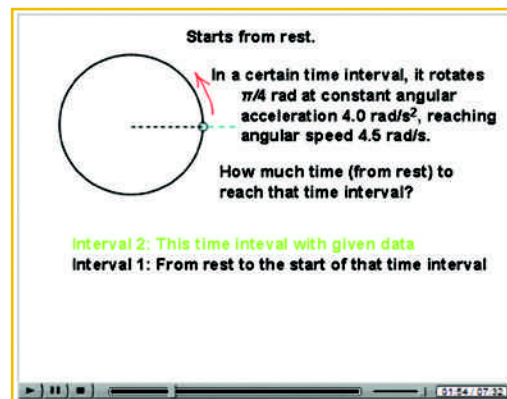
Links Between Homework Problems and Learning Objectives In *WileyPLUS*, every question and problem at the end of the chapter is linked to a learning objective, to answer the (usually unspoken) questions, “Why am I working this problem? What am I supposed to learn from it?” By being explicit about a problem’s purpose, I believe that a student might better transfer the learning objective to other problems with a different wording but the same key idea. Such transference would help defeat the common trouble that a student learns to work a particular problem but cannot then apply its key idea to a problem in a different setting.

Animations of one of the key figures in each chapter. Here in the book, those figures are flagged with the swirling icon. In the online chapter in *WileyPLUS*, a mouse click begins the animation. I have chosen the figures that are rich in information so that a student can see the physics in action and played out over a minute or two instead of just being flat on a printed page. Not only does this give life to the physics, but the animation can be repeated as many times as a student wants.



Video Illustrations David Maiullo of Rutgers University has created video versions of approximately 30 of the photographs and figures from the chapters. Much of physics is the study of things that move, and video can often provide better representation than a static photo or figure.

Videos I have made well over 1500 instructional videos, with more coming. Students can watch me draw or type on the screen as they hear me talk about a solution, tutorial, sample problem, or review, very much as they would experience were they sitting next to me in my office while I worked out something on a notepad. An instructor’s lectures and tutoring will always be the most valuable learning tools, but my videos are available 24 hours a day, 7 days a week, and can be repeated indefinitely.



- **Video tutorials on subjects in the chapters.** I chose the subjects that challenge the students the most, the ones that my students scratch their heads about.
- **Video reviews of high school math**, such as basic algebraic manipulations, trig functions, and simultaneous equations.
- **Video introductions to math**, such as vector multiplication, that will be new to the students.
- **Video presentations of sample problems.** My intent is to work out the physics, starting with the key ideas instead of just grabbing a formula. However, I also want to demonstrate how to read a sample problem, that is, how to read technical material to learn problem-solving procedures that can be transferred to other types of problems.
- **Video solutions to 20% of the end-of chapter problems.** The availability and timing of these solutions are controlled by the instructor. For example, they might be available after a homework deadline or a quiz. Each solution is not simply a plug-and-chug recipe. Rather I build a solution from the key ideas to the first step of reasoning and to a final solution. The student learns not just how to solve a particular problem but how to tackle any problem, even those that require *physics courage*.
- **Video examples of how to read data from graphs** (more than simply reading off a number with no comprehension of the physics).
- Many of the sample problems in the textbook are available online in both reading and video formats.

Problem-Solving Help I have written a large number of resources for *WileyPLUS* designed to help build the students' problem-solving skills.

- **Hundreds of additional sample problems.** These are available as stand-alone resources but (at the discretion of the instructor) they are also linked out of the homework problems. So, if a homework problem deals with, say, forces on a block on a ramp, a link to a related sample problem is provided. However, the sample problem is not just a replica of the homework problem and thus does not provide a solution that can be merely duplicated without comprehension.

GO Tutorial Close

This GO Tutorial will provide you with a step-by-step guide on how to approach this problem. When you are finished, go back and try the problem again on your own. To view the original question while you work, you can just drag this screen to the side. (This GO Tutorial consists of 4 steps).

Step 1: Solution Step 1 of GO Tutorial 10-30

KEY IDEAS:

(1) When an object rotates at constant angular acceleration, we can use the constant-acceleration equations of Table 10-1 modified for angular motion:

(1) $\omega = \omega_0 + \alpha t$

(2) $\theta - \theta_0 = \omega_0 t + \frac{1}{2} \alpha t^2$

(3) $\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$

(4) $\theta - \theta_0 = \frac{1}{2}(\omega_0 + \omega)t$

(5) $\theta - \theta_0 = \omega t - \frac{1}{2} \alpha t^2$

Counterclockwise is the positive direction of rotation, and clockwise is the negative direction.

(2) If a particle moves around a rotation axis at radius r , the magnitude of its radial (centripetal) acceleration a_r at any moment is related to its tangential speed v (the speed along the circular path) and its angular speed at that moment by

$$a_r = \frac{v^2}{r} = \omega^2 r$$

(3) If a particle moves around a rotation axis at radius r , the magnitude of its tangential acceleration a_t (the acceleration along the circular path) at any moment is related to angular acceleration α at that moment by

$$a_t = r\alpha$$

(4) If a particle moves around a rotation axis at radius r , the angular displacement through which it rotates is related to the distance s it moves along its circular path by

$$s = r\Delta\theta$$

GETTING STARTED: What is the radius of rotation (in meters) of a point on the rim of the flywheel?

Number Unit

exact number, no tolerance Check Your Input

Step 2: Solution Step 2 of GO Tutorial 10-30

What is the final angular speed in radians per second?

Number Unit

the tolerance is +/-2% Check Your Input

Step 3: Solution Step 3 of GO Tutorial 10-30

What was the initial angular speed?

Number Unit

exact number, no tolerance Check Your Input

Step 4: Solution Step 4 of GO Tutorial 10-30

Through what angular distance does the flywheel rotate to reach the final angular speed?

Number Unit

the tolerance is +/-2% Check Your Input

Now that you know how to solve the problem, go back and try again on your own. Close

- **GO Tutorials** for 15% of the end-of-chapter homework problems. In multiple steps, I lead a student through a homework problem, starting with the key ideas and giving hints when wrong answers are submitted. However, I purposely leave the last step (for the final answer) to the students so that they are responsible at the end. Some online tutorial systems trap a student when wrong answers are given, which can generate a lot of frustration. My GO Tutorials are not traps, because at any step along the way, a student can return to the main problem.

- **Hints on every end-of-chapter homework problem** are available (at the discretion of the instructor). I wrote these as true hints about the main ideas and the general procedure for a solution, not as recipes that provide an answer without any comprehension.

- **Pre-lecture videos.** At an instructor's discretion, a pre-lecture video is available for every module. Also, assignable questions are available to accompany these videos. The videos were produced by Melanie Good of the University of Pittsburgh.

Evaluation Materials

- **Pre-lecture reading questions are available in WileyPLUS for each chapter section.** I wrote these so that they do not require analysis or any deep understanding; rather they simply test whether a student has read the section. When a student opens up a section, a randomly chosen reading question (from a bank of questions) appears at the end. The instructor can decide whether the question is part of the grading for that section or whether it is just for the benefit of the student.

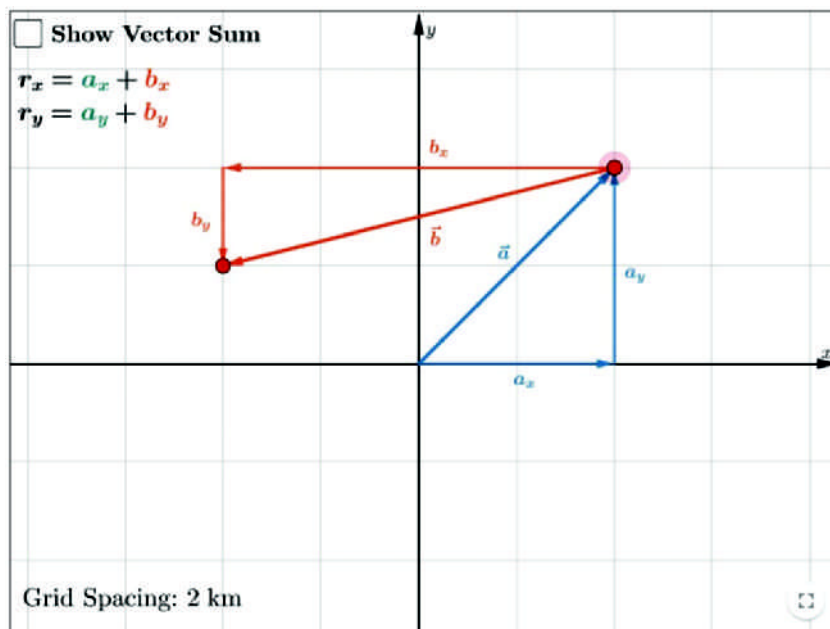
- **Checkpoints are available within each chapter module.** I wrote these so that they require analysis and decisions about the physics in the section. Answers are provided in the back of the book.

- **All end-of-chapter homework problems** (and many more problems) are available in *WileyPLUS*. The instructor can construct a homework assignment and control how it is graded when the answers are submitted online. For example, the instructor controls the deadline for submission and how many attempts a student is allowed on an answer. The instructor also controls which, if any, learning aids are available with each homework problem. Such links can include hints, sample problems, in-chapter reading materials, video tutorials, video math reviews, and even video solutions (which can be made available to the students after, say, a homework deadline).

- **Symbolic notation problems** that require algebraic answers are available in every chapter.

- **All end-of-chapter homework questions** are available for assignment in *WileyPLUS*. These questions (in a multiple-choice format) are designed to evaluate the students' conceptual understanding.

• **Interactive Exercises and Simulations** by Brad Trees of Ohio Wesleyan University. How do we help students understand challenging concepts in physics? How do we motivate students to engage with core content in a meaningful way? The simulations are intended to address these key questions. Each module in the Etext is linked to one or more simulations that convey concepts visually. A simulation depicts a physical situation in which time dependent phenomena are animated and information is presented in multiple representations including a visual representation of the physical system as well as a plot of related variables. Often, adjustable parameters allow the user to change a property of the system and to see the effects of that change on the subsequent behavior. For visual learners, the simulations provide an opportunity to “see” the physics in action. Each simulation is also linked to a set of interactive exercises, which guide the student through a deeper interaction with the physics underlying the simulation. The exercises consist of a series of practice questions with feedback and detailed solutions. Instructors may choose to assign the exercises for practice, to recommend the exercises to students as additional practice, and to show individual simulations during class time to demonstrate a concept and to motivate class discussion.



Icons for Additional Help When worked-out solutions are provided either in print or electronically for certain of the odd-numbered problems, the statements for those problems include an icon to alert both student and instructor. There are also icons indicating which problems have a GO Tutorial or a link to the *The Flying Circus of Physics*, which require calculus, and which involve a biomedical application. An icon guide is provided here and at the beginning of each set of problems.

Tutoring problem available (at instructor's discretion) in WileyPLUS	
Worked-out solution available in Student Solutions Manual	Requires calculus
Easy Medium Hard	Biomedical application
Additional information available in <i>The Flying Circus of Physics</i> and at flyingcircusofphysics.com	

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Fundamentals of Physics was designed to optimize students’ online learning experience. We highly recommend that students use the digital course within WileyPLUS as their primary course material. Here are students’ purchase options:

- 12th Edition WileyPLUS course
- *Fundamentals of Physics* Looseleaf Print Companion bundled with WileyPLUS

- *Fundamentals of Physics* volume 1 bundled with *WileyPLUS*
- *Fundamentals of Physics* volume 2 bundled with *WileyPLUS*
- *Fundamentals of Physics* VitalSource Etext

SUPPLEMENTARY MATERIALS AND ADDITIONAL RESOURCES

Supplements for the instructor can be obtained online through *WileyPLUS* or by contacting your Wiley representative. The following supplementary materials are available for this edition:

Instructor's Solutions Manual by Sen-Ben Liao, Lawrence Livermore National Laboratory. This manual provides worked-out solutions for all problems found at the end of each chapter. It is available in both MSWord and PDF.

- **Instructor's Manual** This resource contains lecture notes outlining the most important topics of each chapter; demonstration experiments; laboratory and computer projects; film and video sources; answers to all questions, exercises, problems, and checkpoints; and a correlation guide to the questions, exercises, and problems in the previous edition. It also contains a complete list of all problems for which solutions are available to students.
- **Classroom Response Systems ("Clicker") Questions** by David Marx, Illinois State University. There are two sets of questions available: Reading Quiz questions and Interactive Lecture questions. The Reading Quiz questions are intended to be relatively straightforward for any student who reads the assigned material. The Interactive Lecture questions are intended for use in an interactive lecture setting.
- **Wiley Physics Simulations** by Andrew Duffy, Boston University and John Gastineau, Vernier Software. This is a collection of 50 interactive simulations (Java applets) that can be used for classroom demonstrations.
- **Wiley Physics Demonstrations** by David Maiullo, Rutgers University. This is a collection of digital videos of 80 standard physics demonstrations. They can be shown in class or accessed from *WileyPLUS*. There is an accompanying Instructor's Guide that includes "clicker" questions.
- **Test Bank** by Suzanne Willis, Northern Illinois University. The Test Bank includes nearly 3,000 multiple-choice questions. These items are also available in the Computerized Test Bank, which provides full editing features to help you customize tests (available in both IBM and Macintosh versions).
- **All text illustrations** suitable for both classroom projection and printing.
- **Lecture PowerPoint Slides** These PowerPoint slides serve as a helpful starter pack for instructors, outlining key concepts and incorporating figures and equations from the text.

STUDENT SUPPLEMENTS

Student Solutions Manual (ISBN 9781119455127) by Sen-Ben Liao, Lawrence Livermore National Laboratory. This manual provides students with complete worked-out solutions to 15 percent of the problems found at the end of each chapter within the text. The Student Solutions Manual for the 12th edition is written using an innovative approach called TEAL, which stands for Think, Express, Analyze, and Learn. This learning strategy was originally developed at the Massachusetts Institute of Technology and has proven to be an effective learning tool for students. These problems with TEAL solutions are indicated with an SSM icon in the text.

Introductory Physics with Calculus as a Second Language (ISBN 9780471739104) *Mastering Problem Solving* by Thomas Barrett of Ohio State University. This brief paperback teaches the student how to approach problems more efficiently and effectively. The student will learn how to recognize common patterns in physics problems, break problems down into manageable steps, and apply appropriate techniques. The book takes the student step by step through the solutions to numerous examples.

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A great many people have contributed to this book. Sen-Ben Liao of Lawrence Livermore National Laboratory, James Whitenton of Southern Polytechnic State University, and Jerry Shi of Pasadena City College performed the Herculean task of working out solutions for every one of the homework problems in the book. At John Wiley publishers, the book received support from John LaVacca and Jennifer Yee, the editors who oversaw the entire project from start to finish, as well as Senior Managing Editor Mary Donovan and Editorial Assistant Samantha Hart. We thank Patricia Gutierrez and the Lumina team, for pulling all the pieces together during the complex production process, and Course Developers Corrina Santos and Kimberly Eskin, for masterfully developing the *WileyPLUS* course and online resources. We also thank Jon Boylan for the art and cover design; Helen Walden for her copyediting; and Donna Mulder for her proofreading.

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Measurement

1.1 MEASURING THINGS, INCLUDING LENGTHS

Learning Objectives

After reading this module, you should be able to . . .

- 1.1.1 Identify the base quantities in the SI system.
- 1.1.2 Name the most frequently used prefixes for SI units.
- 1.1.3 Change units (here for length, area, and volume) by using chain-link conversions.
- 1.1.4 Explain that the meter is defined in terms of the speed of light in a vacuum.

Key Ideas

- Physics is based on measurement of physical quantities. Certain physical quantities have been chosen as base quantities (such as length, time, and mass); each has been defined in terms of a standard and given a unit of measure (such as meter, second, and kilogram). Other physical quantities are defined in terms of the base quantities and their standards and units.
- The unit system emphasized in this book is the International System of Units (SI). The three physical quantities displayed in Table 1.1.1 are used in the early chapters. Standards, which must be both accessible and invariable, have been established for these base quantities by international agreement. These standards are used in all physical measurement, for both the base quantities and the quantities derived from them. Scientific notation and the prefixes of Table 1.1.2 are used to simplify measurement notation.
- Conversion of units may be performed by using chain-link conversions in which the original data are multiplied successively by conversion factors written as unity and the units are manipulated like algebraic quantities until only the desired units remain.
- The meter is defined as the distance traveled by light during a precisely specified time interval.

What Is Physics?

Science and engineering are based on measurements and comparisons. Thus, we need rules about how things are measured and compared, and we need experiments to establish the units for those measurements and comparisons. One purpose of physics (and engineering) is to design and conduct those experiments.

For example, physicists strive to develop clocks of extreme accuracy so that any time or time interval can be precisely determined and compared. You may wonder whether such accuracy is actually needed or worth the effort. Here is one example of the worth: Without clocks of extreme accuracy, the Global Positioning System (GPS) that is now vital to worldwide navigation would be useless.

Measuring Things

We discover physics by learning how to measure the quantities involved in physics. Among these quantities are length, time, mass, temperature, pressure, and electric current.

We measure each physical quantity in its own units, by comparison with a **standard**. The **unit** is a unique name we assign to measures of that quantity—for example, meter (m) for the quantity length. The standard corresponds to exactly 1.0 unit of the quantity. As you will see, the standard for length, which corresponds to exactly 1.0 m, is the distance traveled by light in a vacuum during a certain fraction of a second. We can define a unit and its standard in any way we care to. However, the important thing is to do so in such a way that scientists around the world will agree that our definitions are both sensible and practical.

Once we have set up a standard—say, for length—we must work out procedures by which any length whatever, be it the radius of a hydrogen atom, the wheelbase of a skateboard, or the distance to a star, can be expressed in terms of the standard. Rulers, which approximate our length standard, give us one such procedure for measuring length. However, many of our comparisons must be indirect. You cannot use a ruler, for example, to measure the radius of an atom or the distance to a star.

Base Quantities. There are so many physical quantities that it is a problem to organize them. Fortunately, they are not all independent; for example, speed is the ratio of a length to a time. Thus, what we do is pick out—by international agreement—a small number of physical quantities, such as length and time, and assign standards to them alone. We then define all other physical quantities in terms of these *base quantities* and their standards (called *base standards*). Speed, for example, is defined in terms of the base quantities length and time and their base standards.

Base standards must be both accessible and invariable. If we define the length standard as the distance between one’s nose and the index finger on an outstretched arm, we certainly have an accessible standard—but it will, of course, vary from person to person. The demand for precision in science and engineering pushes us to aim first for invariability. We then exert great effort to make duplicates of the base standards that are accessible to those who need them.

The International System of Units

In 1971, the 14th General Conference on Weights and Measures picked seven quantities as base quantities, thereby forming the basis of the International System of Units, abbreviated SI from its French name and popularly known as the *metric system*. Table 1.1.1 shows the units for the three base quantities—length, mass, and time—that we use in the early chapters of this book. These units were defined to be on a “human scale.”

Many SI *derived units* are defined in terms of these base units. For example, the SI unit for power, called the **watt** (W), is defined in terms of the base units for mass, length, and time. Thus, as you will see in Chapter 7,

$$1 \text{ watt} = 1 \text{ W} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^3, \quad (1.1.1)$$

where the last collection of unit symbols is read as kilogram-meter squared per second cubed.

To express the very large and very small quantities we often run into in physics, we use *scientific notation*, which employs powers of 10. In this notation,

$$3\,560\,000\,000 \text{ m} = 3.56 \times 10^9 \text{ m} \quad (1.1.2)$$

and
$$0.000\,000\,492 \text{ s} = 4.92 \times 10^{-7} \text{ s}. \quad (1.1.3)$$

Scientific notation on computers sometimes takes on an even briefer look, as in 3.56 E9 and 4.92 E–7, where E stands for “exponent of ten.” It is briefer still on some calculators, where E is replaced with an empty space.

Table 1.1.1 Units for Three SI Base Quantities

Quantity	Unit Name	Unit Symbol
Length	meter	m
Time	second	s
Mass	kilogram	kg

As a further convenience when dealing with very large or very small measurements, we use the prefixes listed in Table 1.1.2. As you can see, each prefix represents a certain power of 10, to be used as a multiplication factor. Attaching a prefix to an SI unit has the effect of multiplying by the associated factor. Thus, we can express a particular electric power as

$$1.27 \times 10^9 \text{ watts} = 1.27 \text{ gigawatts} = 1.27 \text{ GW} \quad (1.1.4)$$

or a particular time interval as

$$2.35 \times 10^{-9} \text{ s} = 2.35 \text{ nanoseconds} = 2.35 \text{ ns.} \quad (1.1.5)$$

Some prefixes, as used in milliliter, centimeter, kilogram, and megabyte, are probably familiar to you.

Changing Units

We often need to change the units in which a physical quantity is expressed. We do so by a method called *chain-link conversion*. In this method, we multiply the original measurement by a **conversion factor** (a ratio of units that is equal to unity). For example, because 1 min and 60 s are identical time intervals, we have

$$\frac{1 \text{ min}}{60 \text{ s}} = 1 \quad \text{and} \quad \frac{60 \text{ s}}{1 \text{ min}} = 1.$$

Thus, the ratios (1 min)/(60 s) and (60 s)/(1 min) can be used as conversion factors. This is *not* the same as writing $\frac{1}{60} = 1$ or $60 = 1$; each *number* and its *unit* must be treated together.

Because multiplying any quantity by unity leaves the quantity unchanged, we can introduce conversion factors wherever we find them useful. In chain-link conversion, we use the factors to cancel unwanted units. For example, to convert 2 min to seconds, we have

$$2 \text{ min} = (2 \text{ min})(1) = (2 \text{ min})\left(\frac{60 \text{ s}}{1 \text{ min}}\right) = 120 \text{ s.} \quad (1.1.6)$$

If you introduce a conversion factor in such a way that unwanted units do *not* cancel, invert the factor and try again. In conversions, the units obey the same algebraic rules as variables and numbers.

Appendix D gives conversion factors between SI and other systems of units, including non-SI units still used in the United States. However, the conversion factors are written in the style of “1 min = 60 s” rather than as a ratio. So, you need to decide on the numerator and denominator in any needed ratio.

Length

In 1792, the newborn Republic of France established a new system of weights and measures. Its cornerstone was the meter, defined to be one ten-millionth of the distance from the north pole to the equator. Later, for practical reasons, this Earth standard was abandoned and the meter came to be defined as the distance between two fine lines engraved near the ends of a platinum–iridium bar, the **standard meter bar**, which was kept at the International Bureau of Weights and Measures near Paris. Accurate copies of the bar were sent to standardizing laboratories throughout the world. These **secondary standards** were used to produce other, still more accessible standards, so that ultimately every

Table 1.1.2 Prefixes for SI Units

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

^aThe most frequently used prefixes are shown in bold type.

measuring device derived its authority from the standard meter bar through a complicated chain of comparisons.

Eventually, a standard more precise than the distance between two fine scratches on a metal bar was required. In 1960, a new standard for the meter, based on the wavelength of light, was adopted. Specifically, the standard for the meter was redefined to be 1 650 763.73 wavelengths of a particular orange-red light emitted by atoms of krypton-86 (a particular isotope, or type, of krypton) in a gas discharge tube that can be set up anywhere in the world. This awkward number of wavelengths was chosen so that the new standard would be close to the old meter-bar standard.

By 1983, however, the demand for higher precision had reached such a point that even the krypton-86 standard could not meet it, and in that year a bold step was taken. The meter was redefined as the distance traveled by light in a specified time interval. In the words of the 17th General Conference on Weights and Measures:



The meter is the length of the path traveled by light in a vacuum during a time interval of $1/299\,792\,458$ of a second.

This time interval was chosen so that the speed of light c is exactly

$$c = 299\,792\,458 \text{ m/s.}$$

Measurements of the speed of light had become extremely precise, so it made sense to adopt the speed of light as a defined quantity and to use it to redefine the meter.

Table 1.1.3 shows a wide range of lengths, from that of the universe (top line) to those of some very small objects.

Table 1.1.3 Some Approximate Lengths

Measurement	Length in Meters
Distance to the first galaxies formed	2×10^{26}
Distance to the Andromeda galaxy	2×10^{22}
Distance to the nearby star Proxima Centauri	4×10^{16}
Distance to Pluto	6×10^{12}
Radius of Earth	6×10^6
Height of Mt. Everest	9×10^3
Thickness of this page	1×10^{-4}
Length of a typical virus	1×10^{-8}
Radius of a hydrogen atom	5×10^{-11}
Radius of a proton	1×10^{-15}

Significant Figures and Decimal Places

Suppose that you work out a problem in which each value consists of two digits. Those digits are called **significant figures** and they set the number of digits that you can use in reporting your final answer. With data given in two significant figures, your final answer should have only two significant figures. However, depending on the mode setting of your calculator, many more digits might be displayed. Those extra digits are meaningless.

In this book, final results of calculations are often rounded to match the least number of significant figures in the given data. (However, sometimes an extra significant figure is kept.) When the leftmost of the digits to be discarded is 5 or more, the last remaining digit is rounded up; otherwise it is retained as is. For example, 11.3516 is rounded to three significant figures as 11.4 and 11.3279 is rounded to three significant figures as 11.3. (The answers to sample problems in this book are usually presented with the symbol = instead of \approx even if rounding is involved.)

When a number such as 3.15 or 3.15×10^3 is provided in a problem, the number of significant figures is apparent, but how about the number 3000? Is it known to only one significant figure (3×10^3)? Or is it known to as many as four significant figures (3.000×10^3)? In this book, we assume that all the zeros in such given numbers as 3000 are significant, but you had better not make that assumption elsewhere.

Don't confuse *significant figures* with *decimal places*. Consider the lengths 35.6 mm, 3.56 m, and 0.00356 m. They all have three significant figures but they have one, two, and five decimal places, respectively.

Sample Problem 1.1.1 Estimating order of magnitude, ball of string

The world's largest ball of string is about 2 m in radius. To the nearest order of magnitude, what is the total length L of the string in the ball?

KEY IDEA

We could, of course, take the ball apart and measure the total length L , but that would take great effort and make the ball's builder most unhappy. Instead, because we want only the nearest order of magnitude, we can estimate any quantities required in the calculation.

Calculations: Let us assume the ball is spherical with radius $R = 2$ m. The string in the ball is not closely packed (there are uncountable gaps between adjacent sections of string). To allow for these gaps, let us somewhat overestimate the cross-sectional area of the string by assuming the cross section is square, with an edge length $d = 4$ mm.

Then, with a cross-sectional area of d^2 and a length L , the string occupies a total volume of

$$V = (\text{cross-sectional area})(\text{length}) = d^2L.$$

This is approximately equal to the volume of the ball, given by $\frac{4}{3}\pi R^3$, which is about $4R^3$ because π is about 3. Thus, we have the following

$$d^2L = 4R^3,$$

$$\text{or } L = \frac{4R^3}{d^2} = \frac{4(2 \text{ m})^3}{(4 \times 10^{-3} \text{ m})^2} \\ = 2 \times 10^6 \text{ m} \approx 10^6 \text{ m} = 10^3 \text{ km}.$$

(Answer)

(Note that you do not need a calculator for such a simplified calculation.) To the nearest order of magnitude, the ball contains about 1000 km of string!

WileyPLUS Additional examples, video, and practice available at *WileyPLUS*

1.2 TIME

Learning Objectives

After reading this module, you should be able to . . .

1.2.1 Change units for time by using chain-link conversions.

1.2.2 Use various measures of time, such as for motion or as determined on different clocks.

Key Idea

● The second is defined in terms of the oscillations of light emitted by an atomic (cesium-133) source. Accurate

time signals are sent worldwide by radio signals keyed to atomic clocks in standardizing laboratories.

Time

Time has two aspects. For civil and some scientific purposes, we want to know the time of day so that we can order events in sequence. In much scientific work, we want to know how long an event lasts. Thus, any time standard must be able to answer two questions: “*When* did it happen?” and “*What is its duration?*” Table 1.2.1 shows some time intervals.

Any phenomenon that repeats itself is a possible time standard. Earth's rotation, which determines the length of the day, has been used in this way for centuries; Fig. 1.2.1 shows one novel example of a watch based on that rotation. A quartz clock, in which a quartz ring is made to vibrate continuously, can be calibrated against Earth's rotation via astronomical observations and used to measure time intervals in the laboratory. However, the calibration cannot be carried out with the accuracy called for by modern scientific and engineering technology.



Steven Pitkin

Figure 1.2.1 When the metric system was proposed in 1792, the hour was redefined to provide a 10-hour day. The idea did not catch on. The maker of this 10-hour watch wisely provided a small dial that kept conventional 12-hour time. Do the two dials indicate the same time?

Table 1.2.1 Some Approximate Time Intervals

Measurement	Time Interval in Seconds	Measurement	Time Interval in Seconds
Lifetime of the proton (predicted)	3×10^{40}	Time between human heartbeats	8×10^{-1}
Age of the universe	5×10^{17}	Lifetime of the muon	2×10^{-6}
Age of the pyramid of Cheops	1×10^{11}	Shortest lab light pulse	1×10^{-16}
Human life expectancy	2×10^9	Lifetime of the most unstable particle	1×10^{-23}
Length of a day	9×10^4	The Planck time ^a	1×10^{-43}

^aThis is the earliest time after the big bang at which the laws of physics as we know them can be applied.

To meet the need for a better time standard, atomic clocks have been developed. An atomic clock at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, is the standard for Coordinated Universal Time (UTC) in the United States. Its time signals are available by shortwave radio (stations WWV and WWVH) and by telephone (303-499-7111). Time signals (and related information) are also available from the United States Naval Observatory at website <https://www.usno.navy.mil/USNO/time>. (To set a clock extremely accurately at your particular location, you would have to account for the travel time required for these signals to reach you.)

Figure 1.2.2 shows variations in the length of one day on Earth over a 4-year period, as determined by comparison with a cesium (atomic) clock. Because the variation displayed by Fig. 1.2.2 is seasonal and repetitious, we suspect the rotating Earth when there is a difference between Earth and atom as timekeepers. The variation is due to tidal effects caused by the Moon and to large-scale winds.

The 13th General Conference on Weights and Measures in 1967 adopted a standard second based on the cesium clock:

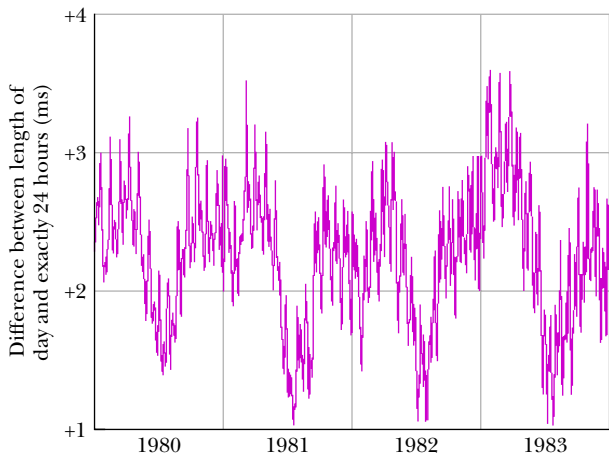


Figure 1.2.2 Variations in the length of the day over a 4-year period. Note that the entire vertical scale amounts to only 3 ms (= 0.003 s).



One second is the time taken by 9 192 631 770 oscillations of the light (of a specified wavelength) emitted by a cesium-133 atom.

Atomic clocks are so consistent that, in principle, two cesium clocks would have to run for 6000 years before their readings would differ by more than 1 s. Even such accuracy pales in comparison with that of clocks currently being developed; their precision may be 1 part in 10^{18} —that is, 1 s in 1×10^{18} s (which is about 3×10^{10} y).

1.3 MASS

Learning Objectives

After reading this module, you should be able to . . .

1.3.1 Change units for mass by using chain-link conversions.

1.3.2 Relate density to mass and volume when the mass is uniformly distributed.

Key Ideas

- The kilogram is defined in terms of a platinum–iridium standard mass kept near Paris. For measurements on an atomic scale, the atomic mass unit, defined in terms of the atom carbon-12, is usually used.
- The density ρ of a material is the mass per unit volume:

$$\rho = \frac{m}{V}.$$

Mass

The Standard Kilogram

The SI standard of mass is a cylinder of platinum and iridium (Fig. 1.3.1) that is kept at the International Bureau of Weights and Measures near Paris and assigned, by international agreement, a mass of 1 kilogram. Accurate copies have been sent to standardizing laboratories in other countries, and the masses of other bodies can be determined by balancing them against a copy. Table 1.3.1 shows some masses expressed in kilograms, ranging over about 83 orders of magnitude.

The U.S. copy of the standard kilogram is housed in a vault at NIST. It is removed, no more than once a year, for the purpose of checking duplicate copies that are used elsewhere. Since 1889, it has been taken to France twice for recomparison with the primary standard.

Kibble Balance

A far more accurate way of measuring mass is now being adopted. In a Kibble balance (named after its inventor Brian Kibble), a standard mass can be measured when the downward pull on it by gravity is balanced by an upward force from a magnetic field due to an electrical current. The precision of this technique comes from the fact that the electric and magnetic properties can be determined in terms of quantum mechanical quantities that have been precisely defined or measured. Once a standard mass is measured, it can be sent to other labs where the masses of other bodies can be determined from it.

A Second Mass Standard

The masses of atoms can be compared with one another more precisely than they can be compared with the standard kilogram. For this reason, we have a second mass standard. It is the carbon-12 atom, which, by international agreement, has been assigned a mass of 12 **atomic mass units** (u). The relation between the two units is

$$1 \text{ u} = 1.660\,538\,86 \times 10^{-27} \text{ kg}, \quad (1.3.1)$$

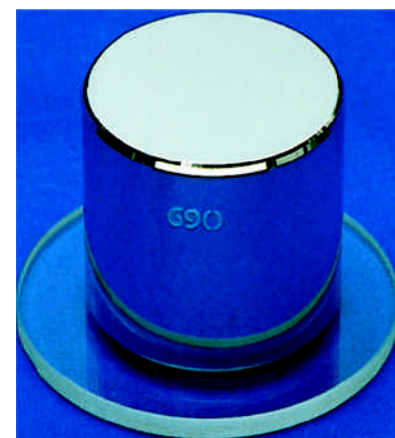
with an uncertainty of ± 10 in the last two decimal places. Scientists can, with reasonable precision, experimentally determine the masses of other atoms relative to the mass of carbon-12. What we presently lack is a reliable means of extending that precision to more common units of mass, such as a kilogram.

Density

As we shall discuss further in Chapter 14, **density** ρ (lowercase Greek letter rho) is the mass per unit volume:

$$\rho = \frac{m}{V}. \quad (1.3.2)$$

Densities are typically listed in kilograms per cubic meter or grams per cubic centimeter. The density of water (1.00 gram per cubic centimeter) is often used as a comparison. Fresh snow has about 10% of that density; platinum has a density that is about 21 times that of water.



Courtesy of Bureau International des Poids et Mesures. Reproduced with permission of the BIPM.

Figure 1.3.1 The international 1 kg standard of mass, a platinum–iridium cylinder 3.9 cm in height and in diameter.

Table 1.3.1 Some Approximate Masses

Object	Mass in Kilograms
Known universe	1×10^{53}
Our galaxy	2×10^{41}
Sun	2×10^{30}
Moon	7×10^{22}
Asteroid Eros	5×10^{15}
Small mountain	1×10^{12}
Ocean liner	7×10^7
Elephant	5×10^3
Grape	3×10^{-3}
Speck of dust	7×10^{-10}
Penicillin molecule	5×10^{-17}
Uranium atom	4×10^{-25}
Proton	2×10^{-27}
Electron	9×10^{-31}

Review & Summary

Measurement in Physics Physics is based on measurement of physical quantities. Certain physical quantities have been chosen as **base quantities** (such as length, time, and mass); each has been defined in terms of a **standard** and given a **unit** of measure (such as meter, second, and kilogram). Other physical quantities are defined in terms of the base quantities and their standards and units.

SI Units The unit system emphasized in this book is the International System of Units (SI). The three physical quantities displayed in Table 1.1.1 are used in the early chapters. Standards, which must be both accessible and invariable, have been established for these base quantities by international agreement. These standards are used in all physical measurement, for both the base quantities and the quantities derived from them. Scientific notation and the prefixes of Table 1.1.2 are used to simplify measurement notation.

Changing Units Conversion of units may be performed by using *chain-link conversions* in which the original data are

multiplied successively by conversion factors written as unity and the units are manipulated like algebraic quantities until only the desired units remain.

Length The meter is defined as the distance traveled by light during a precisely specified time interval.

Time The second is defined in terms of the oscillations of light emitted by an atomic (cesium-133) source. Accurate time signals are sent worldwide by radio signals keyed to atomic clocks in standardizing laboratories.

Mass The kilogram is defined in terms of a platinum-iridium standard mass kept near Paris. For measurements on an atomic scale, the atomic mass unit, defined in terms of the atom carbon-12, is usually used.

Density The density ρ of a material is the mass per unit volume:

$$\rho = \frac{m}{V}. \quad (1.3.2)$$

Problems

GO Tutoring problem available (at instructor's discretion) in *WileyPLUS*

SSM Worked-out solution available in Student Solutions Manual

E Easy **M** Medium **H** Hard

FCP Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

CALC Requires calculus

BIO Biomedical application

Module 1.1 Measuring Things, Including Lengths

1 E SSM Earth is approximately a sphere of radius 6.37×10^6 m. What are (a) its circumference in kilometers, (b) its surface area in square kilometers, and (c) its volume in cubic kilometers?

2 E A *gry* is an old English measure for length, defined as 1/10 of a *line*, where *line* is another old English measure for length, defined as 1/12 inch. A common measure for length in the publishing business is a *point*, defined as 1/72 inch. What is an area of 0.50 gry^2 in points squared (points^2)?

3 E The micrometer ($1 \mu\text{m}$) is often called the *micron*. (a) How many microns make up 1.0 km? (b) What fraction of a centimeter equals $1.0 \mu\text{m}$? (c) How many microns are in 1.0 yd?

4 E Spacing in this book was generally done in units of points and picas: 12 points = 1 pica, and 6 picas = 1 inch. If a figure was misplaced in the page proofs by 0.80 cm, what was the misplacement in (a) picas and (b) points?

5 E SSM Horses are to race over a certain English meadow for a distance of 4.0 furlongs. What is the race distance in (a) rods and (b) chains? (1 furlong = 201.168 m, 1 rod = 5.0292 m, and 1 chain = 20.117 m.)

6 M You can easily convert common units and measures electronically, but you still should be able to use a conversion table, such as those in Appendix D. Table 1.1 is part of a conversion table for a system of volume measures once common in Spain; a volume of 1 fanega is equivalent to 55.501 dm^3 (cubic decimeters). To complete the table, what numbers (to three significant

Table 1.1 Problem 6

	cahiz	fanega	cuartilla	almude	medio
1 cahiz =	1	12	48	144	288
1 fanega =		1	4	12	24
1 quartilla =			1	3	6
1 almude =				1	2
1 medio =					1

figures) should be entered in (a) the cahiz column, (b) the fanega column, (c) the quartilla column, and (d) the almude column, starting with the top blank? Express 7.00 almudes in (e) medios, (f) cahizes, and (g) cubic centimeters (cm^3).

7 M Hydraulic engineers in the United States often use, as a unit of volume of water, the *acre-foot*, defined as the volume of water that will cover 1 acre of land to a depth of 1 ft. A severe thunderstorm dumped 2.0 in. of rain in 30 min on a town of area 26 km^2 . What volume of water, in acre-feet, fell on the town?

8 M GO Harvard Bridge, which connects MIT with its fraternities across the Charles River, has a length of 364.4 Smoots plus one ear. The unit of one Smoot is based on the length of Oliver Reed Smoot, Jr., class of 1962, who was carried or dragged length by length across the bridge so that other pledge members of the Lambda Chi Alpha fraternity could mark off (with paint) 1-Smoot lengths along the bridge. The marks have

been repainted biannually by fraternity pledges since the initial measurement, usually during times of traffic congestion so that the police cannot easily interfere. (Presumably, the police were originally upset because the Smoot is not an SI base unit, but these days they seem to have accepted the unit.) Figure 1.1 shows three parallel paths, measured in Smoots (S), Willies (W), and Zeldas (Z). What is the length of 50.0 Smoots in (a) Willies and (b) Zeldas?



Figure 1.1 Problem 8.

9 M Antarctica is roughly semicircular, with a radius of 2000 km (Fig. 1.2). The average thickness of its ice cover is 3000 m. How many cubic centimeters of ice does Antarctica contain? (Ignore the curvature of Earth.)

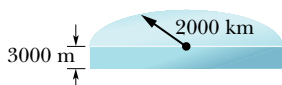


Figure 1.2 Problem 9.

Module 1.2 Time

10 E Until 1883, every city and town in the United States kept its own local time. Today, travelers reset their watches only when the time change equals 1.0 h. How far, on the average, must you travel in degrees of longitude between the time-zone boundaries at which your watch must be reset by 1.0 h? (Hint: Earth rotates 360° in about 24 h.)

11 E For about 10 years after the French Revolution, the French government attempted to base measures of time on multiples of ten: One week consisted of 10 days, one day consisted of 10 hours, one hour consisted of 100 minutes, and one minute consisted of 100 seconds. What are the ratios of (a) the French decimal week to the standard week and (b) the French decimal second to the standard second?

12 E The fastest growing plant on record is a *Hesperoyucca whipplei* that grew 3.7 m in 14 days. What was its growth rate in micrometers per second?

13 E GO Three digital clocks A, B, and C run at different rates and do not have simultaneous readings of zero. Figure 1.3 shows simultaneous readings on pairs of the clocks for four occasions. (At the earliest occasion, for example, B reads 25.0 s and C reads 92.0 s.) If two events are 600 s apart on clock A, how far apart are they on (a) clock B and (b) clock C? (c) When clock A reads 400 s, what does clock B read? (d) When clock C reads 15.0 s, what does clock B read? (Assume negative readings for prezero times.)

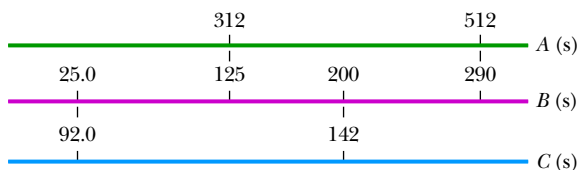


Figure 1.3 Problem 13.

14 E A lecture period (50 min) is close to 1 microcentury. (a) How long is a microcentury in minutes? (b) Using

$$\text{percentage difference} = \left(\frac{\text{actual} - \text{approximation}}{\text{actual}} \right) 100,$$

find the percentage difference from the approximation.

15 E A fortnight is a charming English measure of time equal to 2.0 weeks (the word is a contraction of “fourteen nights”). That is a nice amount of time in pleasant company but perhaps a painful string of microseconds in unpleasant company. How many microseconds are in a fortnight?

16 E Time standards are now based on atomic clocks. A promising second standard is based on *pulsars*, which are rotating neutron stars (highly compact stars consisting only of neutrons). Some rotate at a rate that is highly stable, sending out a radio beacon that sweeps briefly across Earth once with each rotation, like a lighthouse beacon. Pulsar PSR 1937 + 21 is an example; it rotates once every $1.557\,806\,448\,872\,75 \pm 3$ ms, where the trailing ± 3 indicates the uncertainty in the last decimal place (it does *not* mean ± 3 ms). (a) How many rotations does PSR 1937 + 21 make in 7.00 days? (b) How much time does the pulsar take to rotate exactly one million times and (c) what is the associated uncertainty?

17 E SSM Five clocks are being tested in a laboratory. Exactly at noon, as determined by the WWV time signal, on successive days of a week the clocks read as in the following table. Rank the five clocks according to their relative value as good timekeepers, best to worst. Justify your choice.

Clock	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
A	12:36:40	12:36:56	12:37:12	12:37:27	12:37:44	12:37:59	12:38:14
B	11:59:59	12:00:02	11:59:57	12:00:07	12:00:02	11:59:56	12:00:03
C	15:50:45	15:51:43	15:52:41	15:53:39	15:54:37	15:55:35	15:56:33
D	12:03:59	12:02:52	12:01:45	12:00:38	11:59:31	11:58:24	11:57:17
E	12:03:59	12:02:49	12:01:54	12:01:52	12:01:32	12:01:22	12:01:12

18 M Because Earth’s rotation is gradually slowing, the length of each day increases: The day at the end of 1.0 century is 1.0 ms longer than the day at the start of the century. In 20 centuries, what is the total of the daily increases in time?

19 H Suppose that, while lying on a beach near the equator watching the Sun set over a calm ocean, you start a stopwatch just as the top of the Sun disappears. You then stand, elevating your eyes by a height $H = 1.70$ m, and stop the watch when the top of the Sun again disappears. If the elapsed time is $t = 11.1$ s, what is the radius r of Earth?

Module 1.3 Mass

20 E GO The record for the largest glass bottle was set in 1992 by a team in Millville, New Jersey—they blew a bottle with a volume of 193 U.S. fluid gallons. (a) How much short of 1.0 million cubic centimeters is that? (b) If the bottle were filled with water at the leisurely rate of 1.8 g/min, how long would the filling take? Water has a density of 1000 kg/m³.

21 E Earth has a mass of 5.98×10^{24} kg. The average mass of the atoms that make up Earth is 40 u. How many atoms are there in Earth?

22 E Gold, which has a density of 19.32 g/cm^3 , is the most ductile metal and can be pressed into a thin leaf or drawn out into a long fiber. (a) If a sample of gold, with a mass of 27.63 g , is pressed into a leaf of $1.000 \mu\text{m}$ thickness, what is the area of the leaf? (b) If, instead, the gold is drawn out into a cylindrical fiber of radius $2.500 \mu\text{m}$, what is the length of the fiber?

23 E SSM (a) Assuming that water has a density of exactly 1 g/cm^3 , find the mass of one cubic meter of water in kilograms. (b) Suppose that it takes 10.0 h to drain a container of 5700 m^3 of water. What is the “mass flow rate,” in kilograms per second, of water from the container?

24 M GO Grains of fine California beach sand are approximately spheres with an average radius of $50 \mu\text{m}$ and are made of silicon dioxide, which has a density of 2600 kg/m^3 . What mass of sand grains would have a total surface area (the total area of all the individual spheres) equal to the surface area of a cube 1.00 m on an edge?

25 M FCP During heavy rain, a section of a mountainside measuring 2.5 km horizontally, 0.80 km up along the slope, and 2.0 m deep slips into a valley in a mud slide. Assume that the mud ends up uniformly distributed over a surface area of the valley measuring $0.40 \text{ km} \times 0.40 \text{ km}$ and that mud has a density of 1900 kg/m^3 . What is the mass of the mud sitting above a 4.0 m^2 area of the valley floor?

26 M One cubic centimeter of a typical cumulus cloud contains 50 to 500 water drops, which have a typical radius of $10 \mu\text{m}$. For that range, give the lower value and the higher value, respectively, for the following. (a) How many cubic meters of water are in a cylindrical cumulus cloud of height 3.0 km and radius 1.0 km ? (b) How many 1-liter pop bottles would that water fill? (c) Water has a density of 1000 kg/m^3 . How much mass does the water in the cloud have?

27 M Iron has a density of 7.87 g/cm^3 , and the mass of an iron atom is $9.27 \times 10^{-26} \text{ kg}$. If the atoms are spherical and tightly packed, (a) what is the volume of an iron atom and (b) what is the distance between the centers of adjacent atoms?

28 M A mole of atoms is 6.02×10^{23} atoms. To the nearest order of magnitude, how many moles of atoms are in a large domestic cat? The masses of a hydrogen atom, an oxygen atom, and a carbon atom are 1.0 u , 16 u , and 12 u , respectively. (*Hint:* Cats are sometimes known to kill a mole.)

29 M On a spending spree in Malaysia, you buy an ox with a weight of 28.9 piculs in the local unit of weights: $1 \text{ picul} = 100 \text{ gins}$, $1 \text{ gin} = 16 \text{ tahils}$, $1 \text{ tahl} = 10 \text{ chees}$, and $1 \text{ chee} = 10 \text{ hoons}$. The weight of 1 hoon corresponds to a mass of 0.3779 g . When you arrange to ship the ox home to your astonished family, how much mass in kilograms must you declare on the shipping manifest? (*Hint:* Set up multiple chain-link conversions.)

30 M CALC GO Water is poured into a container that has a small leak. The mass m of the water is given as a function of time t by $m = 5.00t^{0.8} - 3.00t + 20.00$, with $t \geq 0$, m in grams, and t in seconds. (a) At what time is the water mass greatest, and (b) what is that greatest mass? In kilograms per minute, what is the rate of mass change at (c) $t = 2.00 \text{ s}$ and (d) $t = 5.00 \text{ s}$?

31 H CALC A vertical container with base area measuring 14.0 cm by 17.0 cm is being filled with identical pieces of candy, each with a volume of 50.0 mm^3 and a mass of 0.0200 g . Assume that the volume of the empty spaces between the candies is

negligible. If the height of the candies in the container increases at the rate of 0.250 cm/s , at what rate (kilograms per minute) does the mass of the candies in the container increase?

Additional Problems

32 In the United States, a doll house has the scale of 1:12 of a real house (that is, each length of the doll house is $\frac{1}{12}$ that of the real house) and a miniature house (a doll house to fit within a doll house) has the scale of 1:144 of a real house. Suppose a real house (Fig. 1.4) has a front length of 20 m , a depth of 12 m , a height of 6.0 m , and a standard sloped roof (vertical triangular faces on the ends) of height 3.0 m . In cubic meters, what are the volumes of the corresponding (a) doll house and (b) miniature house?

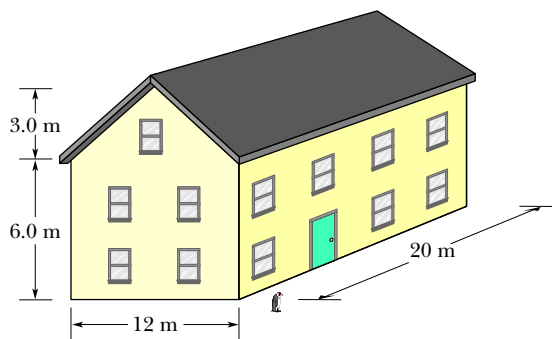


Figure 1.4 Problem 32.

33 SSM A ton is a measure of volume frequently used in shipping, but that use requires some care because there are at least three types of tons: A *displacement ton* is equal to 7 barrels bulk, a *freight ton* is equal to 8 barrels bulk, and a *register ton* is equal to 20 barrels bulk. A *barrel bulk* is another measure of volume: $1 \text{ barrel bulk} = 0.1415 \text{ m}^3$. Suppose you spot a shipping order for “73 tons” of M&M candies, and you are certain that the client who sent the order intended “ton” to refer to volume (instead of weight or mass, as discussed in Chapter 5). If the client actually meant displacement tons, how many extra U.S. bushels of the candies will you erroneously ship if you interpret the order as (a) 73 freight tons and (b) 73 register tons? ($1 \text{ m}^3 = 28.378 \text{ U.S. bushels}$.)

34 Two types of *barrel* units were in use in the 1920s in the United States. The apple barrel had a legally set volume of 7056 cubic inches; the cranberry barrel, 5826 cubic inches. If a merchant sells 20 cranberry barrels of goods to a customer who thinks he is receiving apple barrels, what is the discrepancy in the shipment volume in liters?

35 An old English children’s rhyme states, “Little Miss Muffet sat on a tuffet, eating her curds and whey, when along came a spider who sat down beside her. . . .” The spider sat down not because of the curds and whey but because Miss Muffet had a stash of 11 tuffets of dried flies. The volume measure of a tuffet is given by $1 \text{ tuffet} = 2 \text{ pecks} = 0.50 \text{ Imperial bushel}$, where $1 \text{ Imperial bushel} = 36.3687 \text{ liters (L)}$. What was Miss Muffet’s stash in (a) pecks, (b) Imperial bushels, and (c) liters?

36 Table 1.2 shows some old measures of liquid volume. To complete the table, what numbers (to three significant figures) should be entered in (a) the wey column, (b) the chaldron column, (c) the bag column, (d) the pottle column, and (e) the gill column, starting from the top down? (f) The volume of 1 bag is equal to 0.1091 m^3 . If an old story has a witch cooking up some

vile liquid in a cauldron of volume 1.5 chaldrons, what is the volume in cubic meters?

Table 1.2 Problem 36

	wey	chaldron	bag	pottle	gill
1 wey =	1	10/9	40/3	640	120 240
1 chaldron =					
1 bag =					
1 pottle =					
1 gill =					

37 A typical sugar cube has an edge length of 1 cm. If you had a cubical box that contained a mole of sugar cubes, what would its edge length be? (One mole = 6.02×10^{23} units.)

38 An old manuscript reveals that a landowner in the time of King Arthur held 3.00 acres of plowed land plus a livestock area of 25.0 perches by 4.00 perches. What was the total area in (a) the old unit of roods and (b) the more modern unit of square meters? Here, 1 acre is an area of 40 perches by 4 perches, 1 rood is an area of 40 perches by 1 perch, and 1 perch is the length 16.5 ft.

39 SSM A tourist purchases a car in England and ships it home to the United States. The car sticker advertised that the car's fuel consumption was at the rate of 40 miles per gallon on the open road. The tourist does not realize that the U.K. gallon differs from the U.S. gallon:

$$1 \text{ U.K. gallon} = 4.546\,090\,0 \text{ liters}$$

$$1 \text{ U.S. gallon} = 3.785\,411\,8 \text{ liters.}$$

For a trip of 750 miles (in the United States), how many gallons of fuel does (a) the mistaken tourist believe she needs and (b) the car actually require?

40 Using conversions and data in the chapter, determine the number of hydrogen atoms required to obtain 1.0 kg of hydrogen. A hydrogen atom has a mass of 1.0 u.

41 SSM A *cord* is a volume of cut wood equal to a stack 8 ft long, 4 ft wide, and 4 ft high. How many cords are in 1.0 m^3 ?

42 One molecule of water (H_2O) contains two atoms of hydrogen and one atom of oxygen. A hydrogen atom has a mass of 1.0 u and an atom of oxygen has a mass of 16 u, approximately. (a) What is the mass in kilograms of one molecule of water? (b) How many molecules of water are in the world's oceans, which have an estimated total mass of 1.4×10^{21} kg?

43 A person on a diet might lose 2.3 kg per week. Express the mass loss rate in milligrams per second, as if the dieter could sense the second-by-second loss.

44 What mass of water fell on the town in Problem 7? Water has a density of $1.0 \times 10^3 \text{ kg/m}^3$.

45 (a) A unit of time sometimes used in microscopic physics is the *shake*. One shake equals 10^{-8} s. Are there more shakes in a second than there are seconds in a year? (b) Humans have existed for about 10^6 years, whereas the universe is about 10^{10} years old. If the age of the universe is defined as 1 “universe day,” where a universe day consists of “universe seconds” as a normal day consists of normal seconds, how many universe seconds have humans existed?

46 A unit of area often used in measuring land areas is the *hectare*, defined as 10^4 m^2 . An open-pit coal mine consumes 75 hectares of land, down to a depth of 26 m, each year. What volume of earth, in cubic kilometers, is removed in this time?

47 SSM An astronomical unit (AU) is the average distance between Earth and the Sun, approximately $1.50 \times 10^8 \text{ km}$. The speed of light is about $3.0 \times 10^8 \text{ m/s}$. Express the speed of light in astronomical units per minute.

48 The common Eastern mole, a mammal, typically has a mass of 75 g, which corresponds to about 7.5 moles of atoms. (A mole of atoms is 6.02×10^{23} atoms.) In atomic mass units (u), what is the average mass of the atoms in the common Eastern mole?

49 A traditional unit of length in Japan is the ken (1 ken = 1.97 m). What are the ratios of (a) square kens to square meters and (b) cubic kens to cubic meters? What is the volume of a cylindrical water tank of height 5.50 kens and radius 3.00 kens in (c) cubic kens and (d) cubic meters?

50 You receive orders to sail due east for 24.5 mi to put your salvage ship directly over a sunken pirate ship. However, when your divers probe the ocean floor at that location and find no evidence of a ship, you radio back to your source of information, only to discover that the sailing distance was supposed to be 24.5 *nautical miles*, not regular miles. Use the Length table in Appendix D to calculate how far horizontally you are from the pirate ship in kilometers.

51 Density and liquefaction. A heavy object can sink into the ground during an earthquake if the shaking causes the ground to undergo *liquefaction*, in which the soil grains experience little friction as they slide over one another. The ground is then effectively quicksand. The possibility of liquefaction in sandy ground can be predicted in terms of the *void ratio* e for a sample of the ground: $e = V_{\text{voids}}/V_{\text{grains}}$. Here, V_{grains} is the total volume of the sand grains in the sample and V_{voids} is the total volume between the grains (in the *voids*). If e exceeds a critical value of 0.80, liquefaction can occur during an earthquake. What is the corresponding sand density ρ_{sand} ? Solid silicon dioxide (the primary component of sand) has a density of $\rho_{\text{SiO}_2} = 2.600 \times 10^3 \text{ kg/m}^3$.

52 Billion and trillion. Until 1974, the U.S. and the U.K. used the same names to mean different large numbers. Here are two examples: In American English a billion means a number with 9 zeros after the 1 and in British English it formerly meant a number with 12 zeros after the 1. In American English a trillion means a number with 12 zeros after the 1 and in British English it formerly meant a number with 18 zeros after the 1. In scientific notation with the prefixes in Table 1.1.2, what is 4.0 billion meters in (a) the American use and (b) the former British use? What is 5.0 trillion meters in (c) the American use and (d) the former British use?

53 Townships. In the United States, real estate can be measured in terms of *townships*: 1 township = 36 mi^2 , $1 \text{ mi}^2 = 640 \text{ acres}$, $1 \text{ acre} = 4840 \text{ yd}^2$, $1 \text{ yd}^2 = 9 \text{ ft}^2$. If you own 3.0 townships, how many square feet of real estate do you own?

54 Measures of a man. Leonardo da Vinci, renowned for his understanding of human anatomy, valued the measures of a man stated by Vitruvius Pollio, a Roman architect and engineer of the first century BC: four fingers make one palm, four palms make one foot, six palms make one cubit, and four cubits make a man's height. If we take a finger width to be 0.75 in., what then

are (a) the length of a man's foot and (b) the height of a man, both in centimeters?

55 Dog years. Dog owners like to convert the age of a dog (dubbed *dog years*) to the usual meaning of years to account for the more rapid aging of dogs. One measure of the aging process in both dogs and humans is the rate at which the DNA changes in a process called methylation. Research on that process shows that after the first year, the equivalent age of a dog is given by

$$\text{equivalent age} = 16 \ln(\text{dog years}) + 31,$$

where \ln is the natural logarithm. What then is the equivalent age of a dog on its 13th birthday?

56 Galactic years. The time the Solar System takes to circle around the center of the Milky Way galaxy, a galactic year, is about 230 My. In galactic years, how long ago did (a) the *Tyrannosaurus rex* dinosaurs live (67 My ago), (b) the first major ice age occur (2.2 Gy ago), and (c) Earth form (4.54 Gy ago)?

57 Planck time. The smallest time interval defined in physics is the Planck time $t_p = 5.39 \times 10^{-44}$ s, which is the time required for light to travel across a certain length in a vacuum. The universe began with the big bang 13.772 billion years ago. What is the number of Planck times since that beginning?

58 20,000 Leagues Under the Sea. In Jules Verne's classic science fiction story (published as a serial from 1869 to 1870), Captain Nemo travels in his underwater ship *Nautilus* through the seas of the world for a distance of 20,000 leagues, where a (metric) league is equal to 4.000 km. Assume Earth is spherical with a radius of 6378 km. How many times could Nemo have traveled around Earth?

59 Sea mile. A sea mile is a commonly used measure of distance in navigation but, unlike the *nautical mile*, it does not have a fixed value because it depends on the latitude at which it is measured. It is the distance measured along any given longitude that subtends 1 arc minute, as measured from Earth's center (Fig. 1.5). That distance depends on the radius r of Earth at that point, but because Earth is not a perfect sphere but is wider at the equator and has slightly flattened polar regions, the radius depends on the latitude. At the equator, the radius is 6378 km; at the pole it is 6356 km. What is the difference in a sea mile measured at the equator and at the pole?

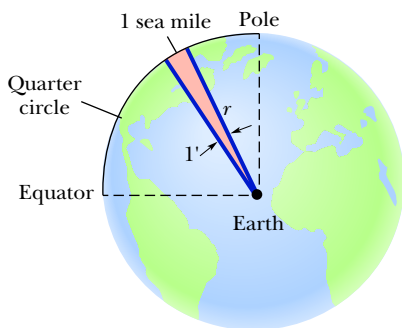


Figure 1.5 Problem 59.

60 Noctilucent clouds. Soon after the huge 1883 volcanic explosion of Krakatoa Island (near Java in the southeast Pacific), silvery, blue clouds began to appear nightly in the Northern Hemisphere early at night. The explosion was so violent that it hurled dust to the *mesosphere*, a cool portion of the atmosphere located well above the stratosphere. There water collected and froze on the dust to form the particles that made the first of these clouds. Termed *noctilucent clouds* (“night shining”), these clouds are now appearing frequently (Fig. 1.6a), signaling a major change in Earth's atmosphere, not because of volcanic explosions, but because of the increased production of methane by industries, rice paddies, landfills, and livestock flatulence.

The clouds are visible after sunset because they are in the upper portion of the atmosphere that is still illuminated by sunlight. Figure 1.6b shows the situation for an observer at point A who sees the clouds overhead 38 min after sunset. The two lines of light are tangent to Earth's surface at A and B , at radius r from Earth's center. Earth rotates through angle θ between the two lines of light. What is the height H of the clouds?



Noctilucent clouds over the Baltic Sea as viewed from Laboe, Germany, 2019. Source: Matthias Stüßen. Licensed under CC BY-SA 4.0

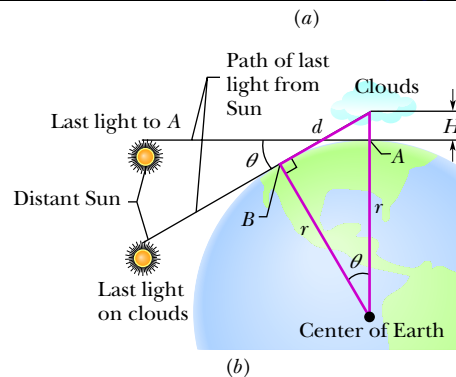


Figure 1.6 Problem 60. (a) Noctilucent clouds. (b) Sunlight reaching the observer and the clouds.

61 Class time, the long of it. For a common four-year undergraduate program, what are the total number of (a) hours and (b) seconds spent in class? Enter your answer in scientific notation.

Motion Along a Straight Line

2.1 POSITION, DISPLACEMENT, AND AVERAGE VELOCITY

Learning Objectives

After reading this module, you should be able to . . .

- 2.1.1** Identify that if all parts of an object move in the same direction and at the same rate, we can treat the object as if it were a (point-like) particle. (This chapter is about the motion of such objects.)
- 2.1.2** Identify that the position of a particle is its location as read on a scaled axis, such as an x axis.
- 2.1.3** Apply the relationship between a particle's displacement and its initial and final positions.
- 2.1.4** Apply the relationship between a particle's average velocity, its displacement, and the time interval for that displacement.
- 2.1.5** Apply the relationship between a particle's average speed, the total distance it moves, and the time interval for the motion.
- 2.1.6** Given a graph of a particle's position versus time, determine the average velocity between any two particular times.

Key Ideas

- The position x of a particle on an x axis locates the particle with respect to the origin, or zero point, of the axis.
- The position is either positive or negative, according to which side of the origin the particle is on, or zero if the particle is at the origin. The positive direction on an axis is the direction of increasing positive numbers; the opposite direction is the negative direction on the axis.
- The displacement Δx of a particle is the change in its position:

$$\Delta x = x_2 - x_1.$$

- Displacement is a vector quantity. It is positive if the particle has moved in the positive direction of the x axis and negative if the particle has moved in the negative direction.
- When a particle has moved from position x_1 to position x_2 during a time interval $\Delta t = t_2 - t_1$, its average velocity during that interval is

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}.$$

- The algebraic sign of v_{avg} indicates the direction of motion (v_{avg} is a vector quantity). Average velocity does not depend on the actual distance a particle moves, but instead depends on its original and final positions.
- On a graph of x versus t , the average velocity for a time interval Δt is the slope of the straight line connecting the points on the curve that represent the two ends of the interval.
- The average speed s_{avg} of a particle during a time interval Δt depends on the total distance the particle moves in that time interval:

$$s_{\text{avg}} = \frac{\text{total distance}}{\Delta t}.$$

What Is Physics?

One purpose of physics is to study the motion of objects—how fast they move, for example, and how far they move in a given amount of time. NASCAR engineers are fanatical about this aspect of physics as they determine the performance of their cars before and during a race. Geologists use this physics to measure tectonic-plate motion as they attempt to predict earthquakes. Medical researchers need this physics to map the blood flow through a patient when diagnosing a partially closed artery, and motorists use it to determine how they might slow sufficiently when their radar detector sounds a warning. There are countless other

examples. In this chapter, we study the basic physics of motion where the object (race car, tectonic plate, blood cell, or any other object) moves along a single axis. Such motion is called *one-dimensional motion*.

Motion

The world, and everything in it, moves. Even seemingly stationary things, such as a roadway, move with Earth's rotation, Earth's orbit around the Sun, the Sun's orbit around the center of the Milky Way galaxy, and that galaxy's migration relative to other galaxies. The classification and comparison of motions (called **kinematics**) is often challenging. What exactly do you measure, and how do you compare?

Before we attempt an answer, we shall examine some general properties of motion that is restricted in three ways.

1. The motion is along a straight line only. The line may be vertical, horizontal, or slanted, but it must be straight.
2. Forces (pushes and pulls) cause motion but will not be discussed until Chapter 5. In this chapter we discuss only the motion itself and changes in the motion. Does the moving object speed up, slow down, stop, or reverse direction? If the motion does change, how is time involved in the change?
3. The moving object is either a **particle** (by which we mean a point-like object such as an electron) or an object that moves like a particle (such that every portion moves in the same direction and at the same rate). A stiff pig slipping down a straight playground slide might be considered to be moving like a particle; however, a tumbling tumbleweed would not.

Position and Displacement

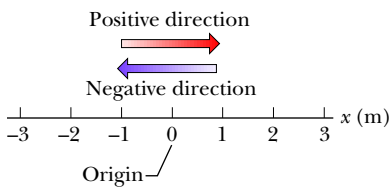


Figure 2.1.1 Position is determined on an axis that is marked in units of length (here meters) and that extends indefinitely in opposite directions. The axis name, here x , is always on the positive side of the origin.

To locate an object means to find its position relative to some reference point, often the **origin** (or zero point) of an axis such as the x axis in Fig. 2.1.1. The **positive direction** of the axis is in the direction of increasing numbers (coordinates), which is to the right in Fig. 2.1.1. The opposite is the **negative direction**.

For example, a particle might be located at $x = 5$ m, which means it is 5 m in the positive direction from the origin. If it were at $x = -5$ m, it would be just as far from the origin but in the opposite direction. On the axis, a coordinate of -5 m is less than a coordinate of -1 m, and both coordinates are less than a coordinate of $+5$ m. A plus sign for a coordinate need not be shown, but a minus sign must always be shown.

A change from position x_1 to position x_2 is called a **displacement** Δx , where

$$\Delta x = x_2 - x_1. \quad (2.1.1)$$

(The symbol Δ , the Greek uppercase delta, represents a change in a quantity, and it means the final value of that quantity minus the initial value.) When numbers are inserted for the position values x_1 and x_2 in Eq. 2.1.1, a displacement in the positive direction (to the right in Fig. 2.1.1) always comes out positive, and a displacement in the opposite direction (left in the figure) always comes out negative. For example, if the particle moves from $x_1 = 5$ m to $x_2 = 12$ m, then the displacement is $\Delta x = (12 \text{ m}) - (5 \text{ m}) = +7$ m. The positive result indicates that the motion is in the positive direction. If, instead, the particle moves from $x_1 = 5$ m to $x_2 = 1$ m, then $\Delta x = (1 \text{ m}) - (5 \text{ m}) = -4$ m. The negative result indicates that the motion is in the negative direction.

The actual number of meters covered for a trip is irrelevant; displacement involves only the original and final positions. For example, if the particle moves

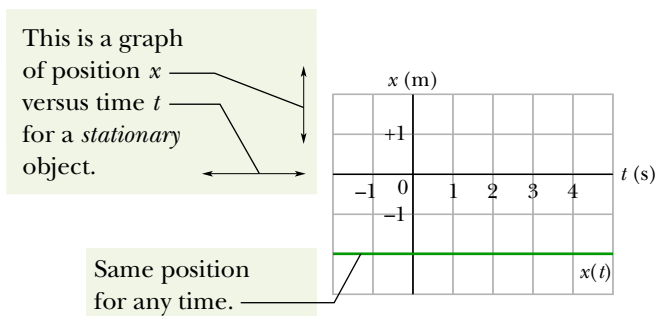


Figure 2.1.2 The graph of $x(t)$ for an armadillo that is stationary at $x = -2$ m. The value of x is -2 m for all times t .

from $x = 5$ m out to $x = 200$ m and then back to $x = 5$ m, the displacement from start to finish is $\Delta x = (5 \text{ m}) - (5 \text{ m}) = 0$.

Signs. A plus sign for a displacement need not be shown, but a minus sign must always be shown. If we ignore the sign (and thus the direction) of a displacement, we are left with the **magnitude** (or absolute value) of the displacement. For example, a displacement of $\Delta x = -4$ m has a magnitude of 4 m.

Displacement is an example of a **vector quantity**, which is a quantity that has both a direction and a magnitude. We explore vectors more fully in Chapter 3, but here all we need is the idea that displacement has two features: (1) Its *magnitude* is the distance (such as the number of meters) between the original and final positions. (2) Its *direction*, from an original position to a final position, can be represented by a plus sign or a minus sign if the motion is along a single axis.

Here is the first of many checkpoints where you can check your understanding with a bit of reasoning. The answers are in the back of the book.

Checkpoint 2.1.1

Here are three pairs of initial and final positions, respectively, along an x axis. Which pairs give a negative displacement: (a) -3 m, $+5$ m; (b) -3 m, -7 m; (c) 7 m, -3 m?

Average Velocity and Average Speed

A compact way to describe position is with a graph of position x plotted as a function of time t —a graph of $x(t)$. (The notation $x(t)$ represents a function x of t , not the product x times t .) As a simple example, Fig. 2.1.2 shows the position function $x(t)$ for a stationary armadillo (which we treat as a particle) over a 7 s time interval. The animal's position stays at $x = -2$ m.

Figure 2.1.3 is more interesting, because it involves motion. The armadillo is apparently first noticed at $t = 0$ when it is at the position $x = -5$ m. It moves toward $x = 0$, passes through that point at $t = 3$ s, and then moves on to increasingly larger positive values of x . Figure 2.1.3 also depicts the straight-line motion of the armadillo (at three times) and is something like what you would see. The graph in Fig. 2.1.3 is more abstract, but it reveals how fast the armadillo moves.

Actually, several quantities are associated with the phrase “how fast.” One of them is the **average velocity** v_{avg} , which is the ratio of the displacement Δx that occurs during a particular time interval Δt to that interval:

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}. \quad (2.1.2)$$

The notation means that the position is x_1 at time t_1 and then x_2 at time t_2 . A common unit for v_{avg} is the meter per second (m/s). You may see other units in the problems, but they are always in the form of length/time.

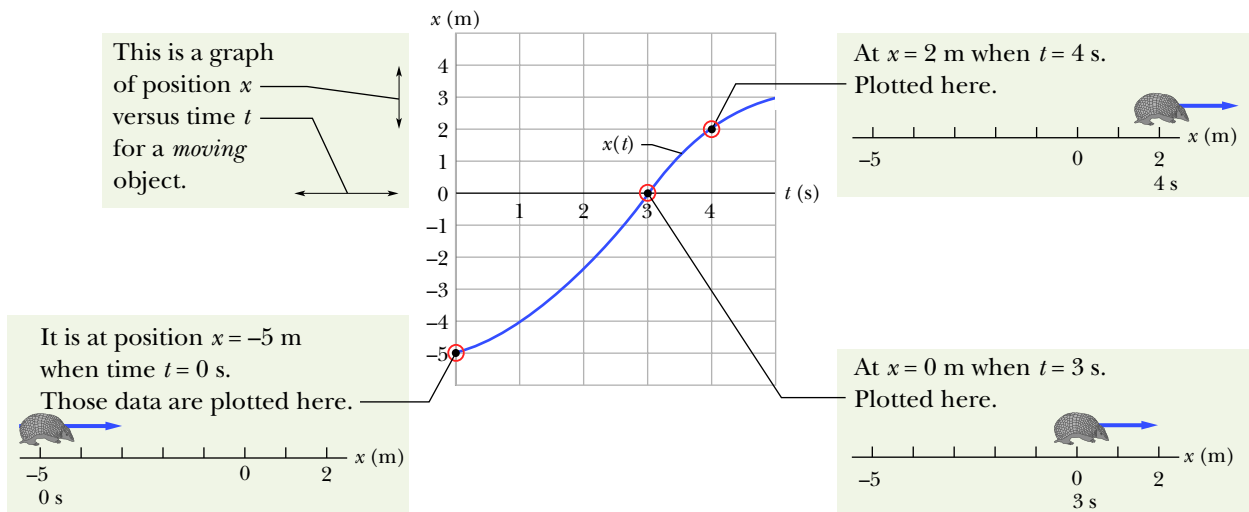


Figure 2.1.3 The graph of $x(t)$ for a moving armadillo. The path associated with the graph is also shown, at three times.

Graphs. On a graph of x versus t , v_{avg} is the **slope** of the straight line that connects two particular points on the $x(t)$ curve: one is the point that corresponds to x_2 and t_2 , and the other is the point that corresponds to x_1 and t_1 . Like displacement, v_{avg} has both magnitude and direction (it is another vector quantity). Its magnitude is the magnitude of the line's slope. A positive v_{avg} (and slope) tells us that the line slants upward to the right; a negative v_{avg} (and slope) tells us that the line slants downward to the right. The average velocity v_{avg} always has the same sign as the displacement Δx because Δt in Eq. 2.1.2 is always positive.

Figure 2.1.4 shows how to find v_{avg} in Fig. 2.1.3 for the time interval $t = 1$ s to $t = 4$ s. We draw the straight line that connects the point on the position curve at the beginning of the interval and the point on the curve at the end of the interval. Then we find the slope $\Delta x/\Delta t$ of the straight line. For the given time interval, the average velocity is

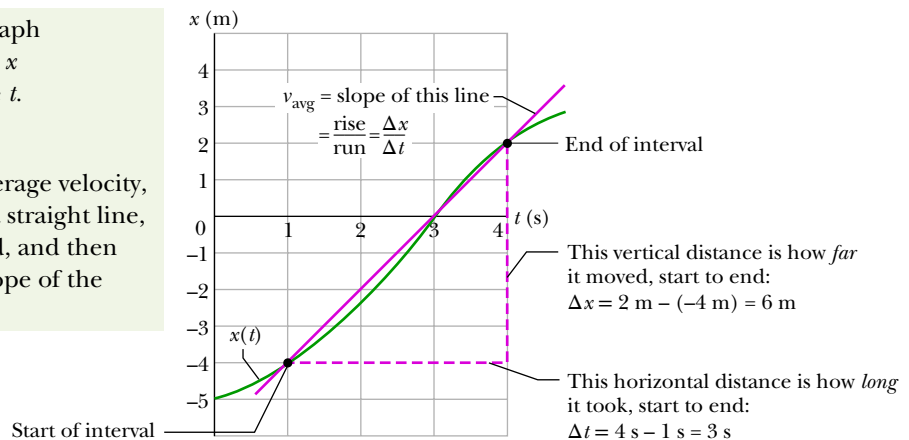
$$v_{\text{avg}} = \frac{6 \text{ m}}{3 \text{ s}} = 2 \text{ m/s.}$$



Figure 2.1.4 Calculation of the average velocity between $t = 1$ s and $t = 4$ s as the slope of the line that connects the points on the $x(t)$ curve representing those times. The swirling icon indicates that a figure is available in WileyPLUS as an animation with voiceover.

This is a graph of position x versus time t .

To find average velocity, first draw a straight line, start to end, and then find the slope of the line.



Average speed s_{avg} is a different way of describing “how fast” a particle moves. Whereas the average velocity involves the particle’s displacement Δx , the average speed involves the total distance covered (for example, the number of meters moved), independent of direction; that is,

$$s_{\text{avg}} = \frac{\text{total distance}}{\Delta t}. \quad (2.1.3)$$

Because average speed does *not* include direction, it lacks any algebraic sign. Sometimes s_{avg} is the same (except for the absence of a sign) as v_{avg} . However, the two can be quite different.

Sample Problem 2.1.1 Average velocity

You get a lift from a car service to take you to a state park along a straight road due east (directly toward the east) for 10.0 km at an average velocity of 40.0 km/h. From the drop-off point, you jog along a straight path due east for 3.00 km, which takes 0.500 h.

(a) What is your overall displacement from your starting point to the point where your jog ends?

KEY IDEA

For convenience, assume that you move in the positive direction of an x axis, from a first position of $x_1 = 0$ to a second position of x_2 at the end of the jog. That second position must be at $x_2 = 10.0 \text{ km} + 3.00 \text{ km} = 13.0 \text{ km}$. Then your displacement Δx along the x axis is the second position minus the first position.

Calculation: From Eq. 2.1.1, we have

$$\Delta x = x_2 - x_1 = 13.0 - 0 = 13.0 \text{ km}. \quad (\text{Answer})$$

Thus, your overall displacement is 13.0 km in the positive direction of the x axis.

(b) What is the time interval Δt from the beginning of your movement to the end of the jog?

KEY IDEA

We already know the jogging time interval $\Delta t_{\text{jog}} (= 0.500 \text{ h})$, but we lack the time interval Δt_{car} for the ride. However, we know that the displacement Δx_{car} is 10.0 km and the average velocity $v_{\text{avg,car}}$ is 40.0 km/h. That average velocity is the ratio of that displacement to the time interval for the ride, so we can find that time interval.

Calculations: We first write

$$v_{\text{avg,car}} = \frac{\Delta x_{\text{car}}}{\Delta t_{\text{car}}}.$$

Rearranging and substituting data then give us

$$\Delta t_{\text{car}} = \frac{\Delta x_{\text{car}}}{v_{\text{avg,car}}} = \frac{10.0 \text{ km}}{40.0 \text{ km/h}} = 0.250 \text{ h}.$$

$$\begin{aligned} \text{So,} \quad \Delta t &= \Delta t_{\text{car}} + \Delta t_{\text{jog}} \\ &= 0.250 \text{ h} + 0.500 \text{ h} = 0.750 \text{ h}. \quad (\text{Answer}) \end{aligned}$$

(c) What is your average velocity v_{avg} from the starting point to the end of the jog? Find it both numerically and graphically.

KEY IDEA

From Eq. 2.1.2 we know that v_{avg} for the entire trip is the ratio of the displacement of 13.0 km for the entire trip to the time interval of 0.750 h for the entire trip.

Calculation: Here we find

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{13.0 \text{ km}}{0.750 \text{ h}} = 17.3 \text{ km/h}. \quad (\text{Answer})$$

To find v_{avg} graphically, first we graph the function $x(t)$ as shown in Fig. 2.1.5, where the beginning and final points on the graph are the origin and the point labeled “Stop.”

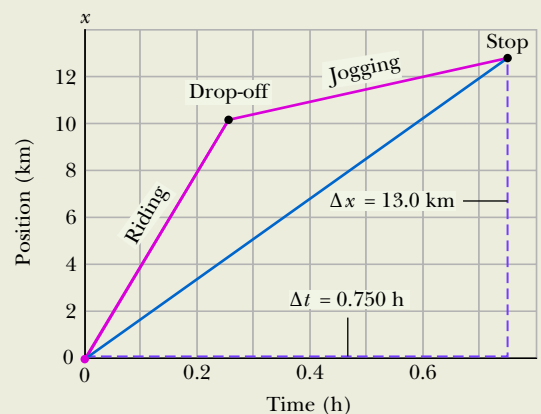


Figure 2.1.5 The lines marked “Riding” and “Jogging” are the position–time plots for the riding and jogging stages. The slope of the straight line joining the origin and the point labeled “Stop” is the average velocity for the motion from start to stop.

Your average velocity is the slope of the straight line connecting those points; that is, v_{avg} is the ratio of the *rise* ($\Delta x = 13.0 \text{ km}$) to the *run* ($\Delta t = 0.750 \text{ h}$), which gives us $v_{\text{avg}} = 17.3 \text{ km/h}$.

(d) Suppose you then jog back to the drop-off point for another 0.500 h. What is your average *speed* from the beginning of your trip to that return?

KEY IDEA

Your average speed is the ratio of the total distance you covered to the total time interval you took.

Calculation: The total distance is $10.0 \text{ km} + 3.00 \text{ km} + 3.00 \text{ km} = 16.0 \text{ km}$. The total time interval is $0.250 \text{ h} + 0.500 \text{ h} + 0.500 \text{ h} = 1.25 \text{ h}$. Thus, Eq. 2.1.3 gives us

$$s_{\text{avg}} = \frac{16.0 \text{ km}}{1.25 \text{ h}} = 12.8 \text{ km/h.} \quad (\text{Answer})$$

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2.2 INSTANTANEOUS VELOCITY AND SPEED

Learning Objectives

After reading this module, you should be able to . . .

2.2.1 Given a particle's position as a function of time, calculate the instantaneous velocity for any particular time.

2.2.2 Given a graph of a particle's position versus time, determine the instantaneous velocity for any particular time.

2.2.3 Identify speed as the magnitude of the instantaneous velocity.

Key Ideas

● The instantaneous velocity (or simply velocity) v of a moving particle is

$$v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt},$$

where $\Delta x = x_2 - x_1$ and $\Delta t = t_2 - t_1$.

● The instantaneous velocity (at a particular time) may be found as the slope (at that particular time) of the graph of x versus t .

● Speed is the magnitude of instantaneous velocity.

Instantaneous Velocity and Speed

You have now seen two ways to describe how fast something moves: average velocity and average speed, both of which are measured over a time interval Δt . However, the phrase “how fast” more commonly refers to how fast a particle is moving at a given instant—its **instantaneous velocity** (or simply **velocity**) v .

The velocity at any instant is obtained from the average velocity by shrinking the time interval Δt closer and closer to 0. As Δt dwindles, the average velocity approaches a limiting value, which is the velocity at that instant:

$$v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}. \quad (2.2.1)$$

Note that v is the rate at which position x is changing with time at a given instant; that is, v is the derivative of x with respect to t . Also note that v at any instant is the slope of the position–time curve at the point representing that instant. Velocity is another vector quantity and thus has an associated direction.

Speed is the magnitude of velocity; that is, speed is velocity that has been stripped of any indication of direction, either in words or via an algebraic sign. (*Caution:* Speed and average speed can be quite different.) A velocity of $+5 \text{ m/s}$ and one of -5 m/s both have an associated speed of 5 m/s . The speedometer in a car measures speed, not velocity (it cannot determine the direction).

Checkpoint 2.2.1

The following equations give the position $x(t)$ of a particle in four situations (in each equation, x is in meters, t is in seconds, and $t > 0$): (1) $x = 3t - 2$; (2) $x = -4t^2 - 2$; (3) $x = 2/t^2$; and (4) $x = -2$. (a) In which situation is the velocity v of the particle constant? (b) In which is v in the negative x direction?

Sample Problem 2.2.1 Velocity and slope of x versus t , elevator cab

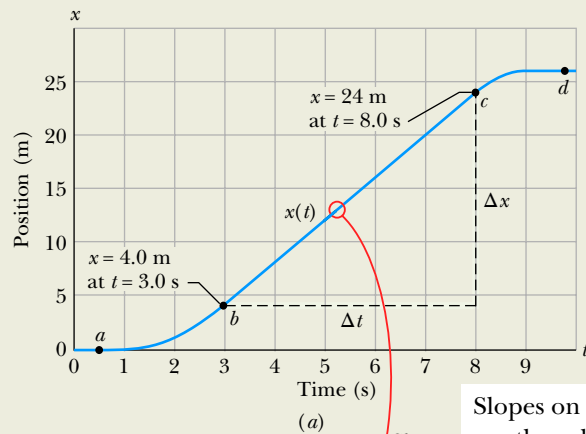
Figure 2.2.1a is an $x(t)$ plot for an elevator cab that is initially stationary, then moves upward (which we take to be the positive direction of x), and then stops. Plot $v(t)$.

KEY IDEA

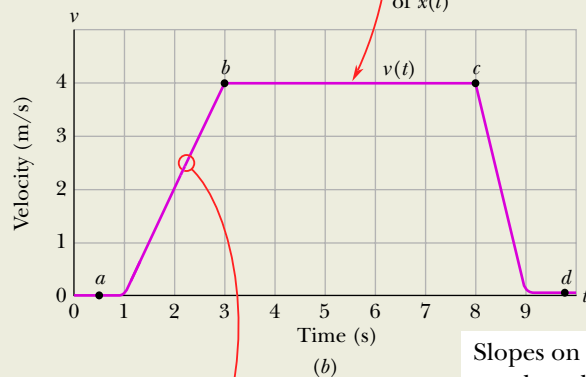
We can find the velocity at any time from the slope of the $x(t)$ curve at that time.

Calculations: The slope of $x(t)$, and so also the velocity, is zero in the intervals from 0 to 1 s and from 9 s on, so then the cab is stationary. During the interval bc , the slope is constant and nonzero, so then the cab moves with constant velocity. We calculate the slope of $x(t)$ then as

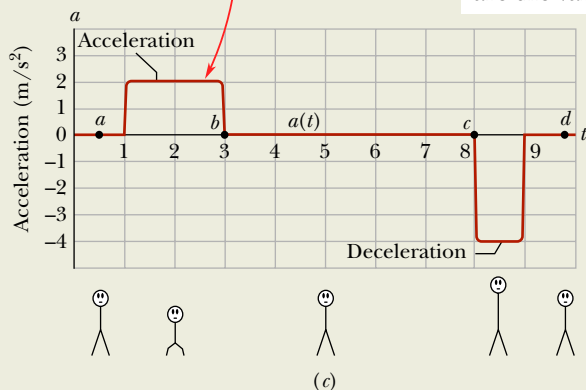
$$\frac{\Delta x}{\Delta t} = v = \frac{24 \text{ m} - 4.0 \text{ m}}{8.0 \text{ s} - 3.0 \text{ s}} = +4.0 \text{ m/s.} \quad (2.2.2)$$



Slopes on the x versus t graph are the values on the v versus t graph.



Slopes on the v versus t graph are the values on the a versus t graph.



What you would feel.

Figure 2.2.1 (a) The $x(t)$ curve for an elevator cab that moves upward along an x axis. (b) The $v(t)$ curve for the cab. Note that it is the derivative of the $x(t)$ curve ($v = dx/dt$). (c) The $a(t)$ curve for the cab. It is the derivative of the $v(t)$ curve ($a = dv/dt$). The stick figures along the bottom suggest how a passenger's body might feel during the accelerations.

The plus sign indicates that the cab is moving in the positive x direction. These intervals (where $v = 0$ and $v = 4$ m/s) are plotted in Fig. 2.2.1b. In addition, as the cab initially begins to move and then later slows to a stop, v varies as indicated in the intervals 1 s to 3 s and 8 s to 9 s. Thus, Fig. 2.2.1b is the required plot. (Figure 2.2.1c is considered in Module 2.3.)

Given a $v(t)$ graph such as Fig. 2.2.1b, we could “work backward” to produce the shape of the associated $x(t)$ graph (Fig. 2.2.1a). However, we would not know the actual values for x at various times, because the $v(t)$ graph indicates only *changes* in x . To find such a change in x during any interval, we must, in the language of

calculus, calculate the area “under the curve” on the $v(t)$ graph for that interval. For example, during the interval 3 s to 8 s in which the cab has a velocity of 4.0 m/s, the change in x is

$$\Delta x = (4.0 \text{ m/s})(8.0 \text{ s} - 3.0 \text{ s}) = +20 \text{ m}. \quad (2.2.3)$$

(This area is positive because the $v(t)$ curve is above the t axis.) Figure 2.2.1a shows that x does indeed increase by 20 m in that interval. However, Fig. 2.2.1b does not tell us the *values* of x at the beginning and end of the interval. For that, we need additional information, such as the value of x at some instant.

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2.3 ACCELERATION

Learning Objectives

After reading this module, you should be able to . . .

2.3.1 Apply the relationship between a particle’s average acceleration, its change in velocity, and the time interval for that change.

2.3.2 Given a particle’s velocity as a function of time, calculate the instantaneous acceleration for any particular time.

2.3.3 Given a graph of a particle’s velocity versus time, determine the instantaneous acceleration for any particular time and the average acceleration between any two particular times.

Key Ideas

● Average acceleration is the ratio of a change in velocity Δv to the time interval Δt in which the change occurs:

$$a_{\text{avg}} = \frac{\Delta v}{\Delta t}.$$

The algebraic sign indicates the direction of a_{avg} .

● Instantaneous acceleration (or simply acceleration) a is the first time derivative of velocity $v(t)$ and the second time derivative of position $x(t)$:

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}.$$

● On a graph of v versus t , the acceleration a at any time t is the slope of the curve at the point that represents t .

Acceleration

When a particle’s velocity changes, the particle is said to undergo **acceleration** (or to accelerate). For motion along an axis, the **average acceleration** a_{avg} over a time interval Δt is

$$a_{\text{avg}} = \frac{v_2 - v_1}{t_2 - t_1} = \frac{\Delta v}{\Delta t}, \quad (2.3.1)$$

where the particle has velocity v_1 at time t_1 and then velocity v_2 at time t_2 . The **instantaneous acceleration** (or simply **acceleration**) is

$$a = \frac{dv}{dt}. \quad (2.3.2)$$

In words, the acceleration of a particle at any instant is the rate at which its velocity is changing at that instant. Graphically, the acceleration at any point is the slope of the curve of $v(t)$ at that point. We can combine Eq. 2.3.2 with Eq. 2.2.1 to write

$$a = \frac{dv}{dt} = \frac{d}{dt} \left(\frac{dx}{dt} \right) = \frac{d^2x}{dt^2}. \quad (2.3.3)$$

In words, the acceleration of a particle at any instant is the second derivative of its position $x(t)$ with respect to time.

A common unit of acceleration is the meter per second per second: $\text{m}/(\text{s} \cdot \text{s})$ or m/s^2 . Other units are in the form of $\text{length}/(\text{time} \cdot \text{time})$ or $\text{length}/\text{time}^2$. Acceleration has both magnitude and direction (it is yet another vector quantity). Its algebraic sign represents its direction on an axis just as for displacement and velocity; that is, acceleration with a positive value is in the positive direction of an axis, and acceleration with a negative value is in the negative direction.

Figure 2.2.1 gives plots of the position, velocity, and acceleration of an elevator moving up a shaft. Compare the $a(t)$ curve with the $v(t)$ curve—each point on the $a(t)$ curve shows the derivative (slope) of the $v(t)$ curve at the corresponding time. When v is constant (at either 0 or 4 m/s), the derivative is zero and so also is the acceleration. When the cab first begins to move, the $v(t)$ curve has a positive derivative (the slope is positive), which means that $a(t)$ is positive. When the cab slows to a stop, the derivative and slope of the $v(t)$ curve are negative; that is, $a(t)$ is negative.

Next compare the slopes of the $v(t)$ curve during the two acceleration periods. The slope associated with the cab's slowing down (commonly called "deceleration") is steeper because the cab stops in half the time it took to get up to speed. The steeper slope means that the magnitude of the deceleration is larger than that of the acceleration, as indicated in Fig. 2.2.1c.

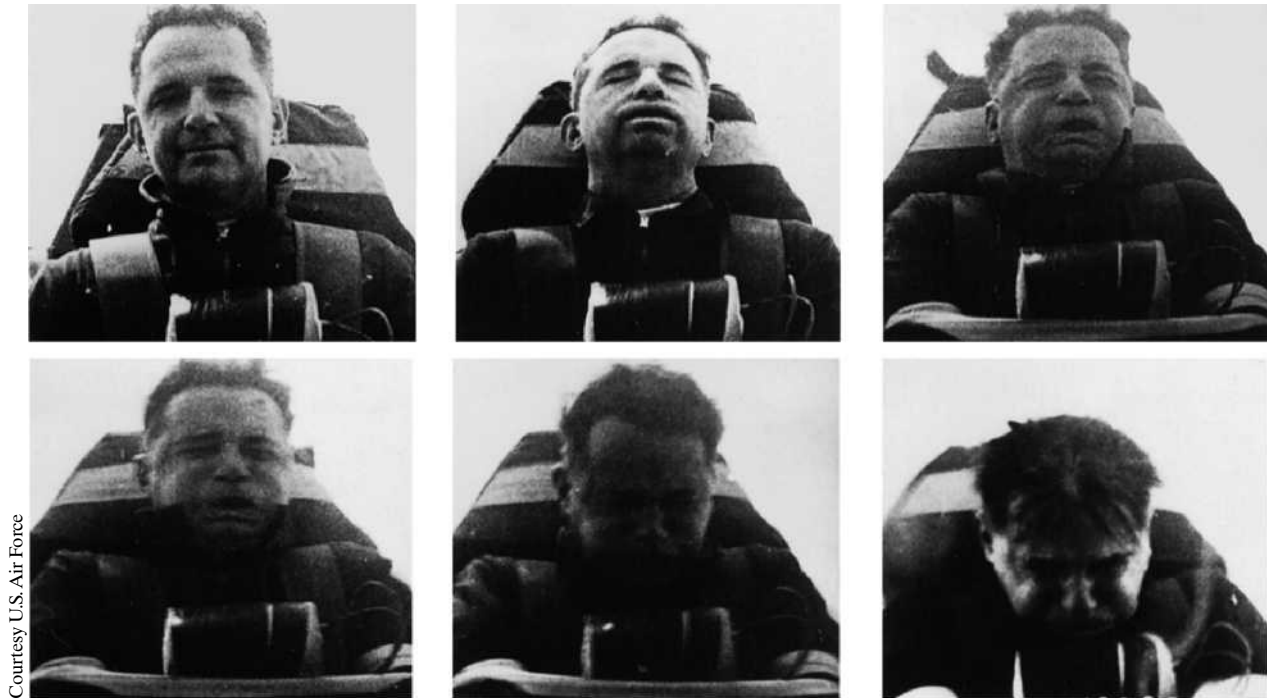
Sensations. The sensations you would feel while riding in the cab of Fig. 2.2.1 are indicated by the sketched figures at the bottom. When the cab first accelerates, you feel as though you are pressed downward; when later the cab is braked to a stop, you seem to be stretched upward. In between, you feel nothing special. In other words, your body reacts to accelerations (it is an accelerometer) but not to velocities (it is not a speedometer). When you are in a car traveling at 90 km/h or an airplane traveling at 900 km/h, you have no bodily awareness of the motion. However, if the car or plane quickly changes velocity, you may become keenly aware of the change, perhaps even frightened by it. Part of the thrill of an amusement park ride is due to the quick changes of velocity that you undergo (you pay for the accelerations, not for the speed). A more extreme example is shown in the photographs of Fig. 2.3.1, which were taken while a rocket sled was rapidly accelerated along a track and then rapidly braked to a stop. **FCP**

***g* Units.** Large accelerations are sometimes expressed in terms of g units, with

$$1g = 9.8 \text{ m/s}^2 \quad (\text{g unit}). \quad (2.3.4)$$

(As we shall discuss in Module 2.5, g is the magnitude of the acceleration of a falling object near Earth's surface.) On a roller coaster, you may experience brief accelerations up to $3g$, which is $(3)(9.8 \text{ m/s}^2)$, or about 29 m/s^2 , more than enough to justify the cost of the ride.

Signs. In common language, the sign of an acceleration has a nonscientific meaning: Positive acceleration means that the speed of an object is increasing, and negative acceleration means that the speed is decreasing (the object is decelerating). In this book, however, the sign of an acceleration indicates a direction, not whether an object's speed is increasing or decreasing. For example, if a car with an initial velocity $v = -25 \text{ m/s}$ is braked to a stop in 5.0 s, then $a_{\text{avg}} = +5.0 \text{ m/s}^2$. The acceleration is *positive*, but the car's speed has decreased. The reason is the difference in signs: The direction of the acceleration is opposite that of the velocity.



Courtesy U.S. Air Force

Figure 2.3.1 Colonel J. P. Stapp in a rocket sled as it is brought up to high speed (acceleration out of the page) and then very rapidly braked (acceleration into the page).

Here then is the proper way to interpret the signs:



If the signs of the velocity and acceleration of a particle are the same, the speed of the particle increases. If the signs are opposite, the speed decreases.

Checkpoint 2.3.1

A wombat moves along an x axis. What is the sign of its acceleration if it is moving (a) in the positive direction with increasing speed, (b) in the positive direction with decreasing speed, (c) in the negative direction with increasing speed, and (d) in the negative direction with decreasing speed?

Sample Problem 2.3.1 Acceleration and dv/dt

A particle's position on the x axis of Fig. 2.1.1 is given by

$$x = 4 - 27t + t^3,$$

with x in meters and t in seconds.

(a) Because position x depends on time t , the particle must be moving. Find the particle's velocity function $v(t)$ and acceleration function $a(t)$.

KEY IDEAS

(1) To get the velocity function $v(t)$, we differentiate the position function $x(t)$ with respect to time. (2) To get the

acceleration function $a(t)$, we differentiate the velocity function $v(t)$ with respect to time.

Calculations: Differentiating the position function, we find

$$v = -27 + 3t^2, \quad (\text{Answer})$$

with v in meters per second. Differentiating the velocity function then gives us

$$a = +6t, \quad (\text{Answer})$$

with a in meters per second squared.

(b) Is there ever a time when $v = 0$?

Calculation: Setting $v(t) = 0$ yields

$$0 = -27 + 3t^2,$$

which has the solution

$$t = \pm 3 \text{ s.} \quad (\text{Answer})$$

Thus, the velocity is zero both 3 s before and 3 s after the clock reads 0.

(c) Describe the particle's motion for $t \geq 0$.

Reasoning: We need to examine the expressions for $x(t)$, $v(t)$, and $a(t)$.

At $t = 0$, the particle is at $x(0) = +4 \text{ m}$ and is moving with a velocity of $v(0) = -27 \text{ m/s}$ —that is, in the negative direction of the x axis. Its acceleration is $a(0) = 0$ because just then the particle's velocity is not changing (Fig. 2.3.2a).

For $0 < t < 3 \text{ s}$, the particle still has a negative velocity, so it continues to move in the negative direction. However, its acceleration is no longer 0 but is increasing and positive. Because the signs of the velocity and the acceleration are opposite, the particle must be slowing (Fig. 2.3.2b).

Indeed, we already know that it stops momentarily at $t = 3 \text{ s}$. Just then the particle is as far to the left of the origin in Fig. 2.1.1 as it will ever get. Substituting $t = 3 \text{ s}$ into the expression for $x(t)$, we find that the particle's position just then is $x = -50 \text{ m}$ (Fig. 2.3.2c). Its acceleration is still positive.

For $t > 3 \text{ s}$, the particle moves to the right on the axis. Its acceleration remains positive and grows progressively larger in magnitude. The velocity is now positive, and it too grows progressively larger in magnitude (Fig. 2.3.2d).

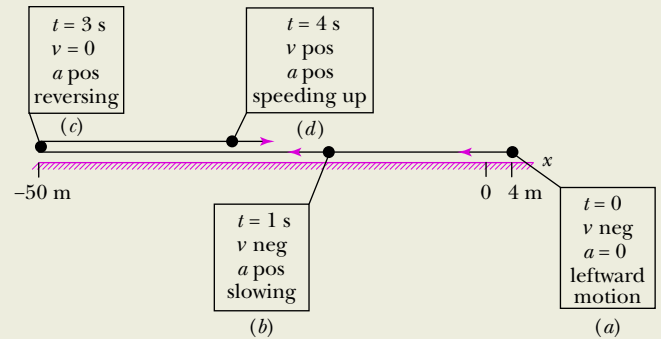


Figure 2.3.2 Four stages of the particle's motion.

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2.4 CONSTANT ACCELERATION

Learning Objectives

After reading this module, you should be able to . . .

2.4.1 For constant acceleration, apply the relationships between position, displacement, velocity, acceleration, and elapsed time (Table 2.4.1).

2.4.2 Calculate a particle's change in velocity by integrating its acceleration function with respect to time.

2.4.3 Calculate a particle's change in position by integrating its velocity function with respect to time.

Key Idea

• The following five equations describe the motion of a particle with constant acceleration:

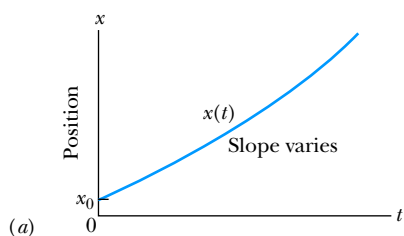
$$v = v_0 + at, \quad x - x_0 = v_0t + \frac{1}{2}at^2,$$

$$v^2 = v_0^2 + 2a(x - x_0), \quad x - x_0 = \frac{1}{2}(v_0 + v)t, \quad x - x_0 = vt - \frac{1}{2}at^2.$$

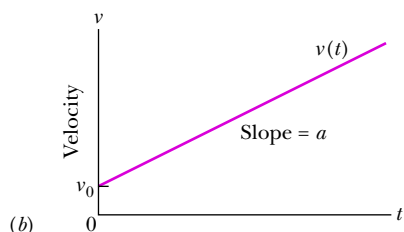
These are *not* valid when the acceleration is not constant.

Constant Acceleration: A Special Case

In many types of motion, the acceleration is either constant or approximately so. For example, you might accelerate a car at an approximately constant rate when a traffic light turns from red to green. Then graphs of your position, velocity,



Slopes of the position graph are plotted on the velocity graph.



Slope of the velocity graph is plotted on the acceleration graph.



Figure 2.4.1 (a) The position $x(t)$ of a particle moving with constant acceleration. (b) Its velocity $v(t)$, given at each point by the slope of the curve of $x(t)$. (c) Its (constant) acceleration, equal to the (constant) slope of the curve of $v(t)$.

and acceleration would resemble those in Fig. 2.4.1. (Note that $a(t)$ in Fig. 2.4.1c is constant, which requires that $v(t)$ in Fig. 2.4.1b have a constant slope.) Later when you brake the car to a stop, the acceleration (or deceleration in common language) might also be approximately constant.

Such cases are so common that a special set of equations has been derived for dealing with them. One approach to the derivation of these equations is given in this section. A second approach is given in the next section. Throughout both sections and later when you work on the homework problems, keep in mind that *these equations are valid only for constant acceleration (or situations in which you can approximate the acceleration as being constant)*.

First Basic Equation. When the acceleration is constant, the average acceleration and instantaneous acceleration are equal and we can write Eq. 2.3.1, with some changes in notation, as

$$a = a_{\text{avg}} = \frac{v - v_0}{t - 0}.$$

Here v_0 is the velocity at time $t = 0$ and v is the velocity at any later time t . We can recast this equation as

$$v = v_0 + at. \tag{2.4.1}$$

As a check, note that this equation reduces to $v = v_0$ for $t = 0$, as it must. As a further check, take the derivative of Eq. 2.4.1. Doing so yields $dv/dt = a$, which is the definition of a . Figure 2.4.1b shows a plot of Eq. 2.4.1, the $v(t)$ function; the function is linear and thus the plot is a straight line.

Second Basic Equation. In a similar manner, we can rewrite Eq. 2.1.2 (with a few changes in notation) as

$$v_{\text{avg}} = \frac{x - x_0}{t - 0}$$

and then as

$$x = x_0 + v_{\text{avg}}t, \tag{2.4.2}$$

in which x_0 is the position of the particle at $t = 0$ and v_{avg} is the average velocity between $t = 0$ and a later time t .

For the linear velocity function in Eq. 2.4.1, the *average* velocity over any time interval (say, from $t = 0$ to a later time t) is the average of the velocity at the beginning of the interval ($= v_0$) and the velocity at the end of the interval ($= v$). For the interval from $t = 0$ to the later time t then, the average velocity is

$$v_{\text{avg}} = \frac{1}{2}(v_0 + v). \tag{2.4.3}$$

Substituting the right side of Eq. 2.4.1 for v yields, after a little rearrangement,

$$v_{\text{avg}} = v_0 + \frac{1}{2}at. \tag{2.4.4}$$

Finally, substituting Eq. 2.4.4 into Eq. 2.4.2 yields

$$x - x_0 = v_0t + \frac{1}{2}at^2. \tag{2.4.5}$$

As a check, note that putting $t = 0$ yields $x = x_0$, as it must. As a further check, taking the derivative of Eq. 2.4.5 yields Eq. 2.4.1, again as it must. Figure 2.4.1a shows a plot of Eq. 2.4.5; the function is quadratic and thus the plot is curved.

Three Other Equations. Equations 2.4.1 and 2.4.5 are the *basic equations for constant acceleration*; they can be used to solve any constant acceleration problem

in this book. However, we can derive other equations that might prove useful in certain specific situations. First, note that as many as five quantities can possibly be involved in any problem about constant acceleration—namely, $x - x_0$, v , t , a , and v_0 . Usually, one of these quantities is *not* involved in the problem, *either as a given or as an unknown*. We are then presented with three of the remaining quantities and asked to find the fourth.

Equations 2.4.1 and 2.4.5 each contain four of these quantities, but not the same four. In Eq. 2.4.1, the “missing ingredient” is the displacement $x - x_0$. In Eq. 2.4.5, it is the velocity v . These two equations can also be combined in three ways to yield three additional equations, each of which involves a different “missing variable.” First, we can eliminate t to obtain

$$v^2 = v_0^2 + 2a(x - x_0). \quad (2.4.6)$$

This equation is useful if we do not know t and are not required to find it. Second, we can eliminate the acceleration a between Eqs. 2.4.1 and 2.4.5 to produce an equation in which a does not appear:

$$x - x_0 = \frac{1}{2}(v_0 + v)t. \quad (2.4.7)$$

Finally, we can eliminate v_0 , obtaining

$$x - x_0 = vt - \frac{1}{2}at^2. \quad (2.4.8)$$

Note the subtle difference between this equation and Eq. 2.4.5. One involves the initial velocity v_0 ; the other involves the velocity v at time t .

Table 2.4.1 lists the basic constant-acceleration equations (Eqs. 2.4.1 and 2.4.5) as well as the specialized equations that we have derived. To solve a simple constant-acceleration problem, you can usually use an equation from this list (*if you have the list with you*). Choose an equation for which the only unknown variable is the variable requested in the problem. A simpler plan is to remember only Eqs. 2.4.1 and 2.4.5, and then solve them as simultaneous equations whenever needed.

Checkpoint 2.4.1

The following equations give the position $x(t)$ of a particle in four situations: (1) $x = 3t - 4$; (2) $x = -5t^3 + 4t^2 + 6$; (3) $x = 2/t^2 - 4/t$; (4) $x = 5t^2 - 3$. To which of these situations do the equations of Table 2.4.1 apply?

Table 2.4.1 Equations for Motion with Constant Acceleration^a

Equation Number	Equation	Missing Quantity
2.4.1	$v = v_0 + at$	$x - x_0$
2.4.5	$x - x_0 = v_0t + \frac{1}{2}at^2$	v
2.4.6	$v^2 = v_0^2 + 2a(x - x_0)$	t
2.4.7	$x - x_0 = \frac{1}{2}(v_0 + v)t$	a
2.4.8	$x - x_0 = vt - \frac{1}{2}at^2$	v_0

^aMake sure that the acceleration is indeed constant before using the equations in this table.

Sample Problem 2.4.1 Autonomous car passing slower car

In Fig. 2.4.2a, you are riding in a car controlled by an autonomous driving system and trail a slower car that you want to pass. Figure 2.4.2b shows the initial situation, with you in car B . Your system’s radar detects the speed and location of slow car A . Both cars have length $L = 4.50$ m, speed $v_0 = 22.0$ m/s (49 mi/h, slower than the speed limit), and travel on a straight road with one lane in each direction. Your car initially trails A by distance $3.00L$ when you ask it to pass the slow car. That would require you to move into the other lane where there can be an oncoming vehicle. Your system must determine the time required for passing A , to see if passing would be

safe. So, the first step in the system’s control is to calculate that passing time.

We want B to pull into the other lane, accelerate at a constant $a = 3.50$ m/s² until it reaches a speed of $v = 27.0$ m/s (60 mi/h, the speed limit) and then, when it is at distance $3.00L$ ahead of A , pull back into the initial lane (it will then maintain 27.0 m/s). Assume that the lane changing takes negligible time. Figure 2.4.2c shows the situation at the onset of the acceleration, with the rear of car B at $x_{B1} = 0$ and the rear of car A at $x_{A1} = 4L$. Figure 2.4.2d shows the situation when car B is about to pull back into the initial lane. Let t_1 and d_1 be the time required for the acceleration

and the distance traveled during the acceleration. Let t_2 be the time from the end of the acceleration to when B is ahead of A by $3L$ and ready to pull back. We want the total time $t_{\text{tot}} = t_1 + t_2$. Here are the pieces in the calculation. What are the values of (a) t_1 and (b) d_1 ? (c) In terms of L, v_0, t_1 , and t_2 , what is the coordinate x_{B2} of the rear of car B when B is ready to pull back? (d) In terms of L, v_0, t_1 , and t_2 , what is the coordinate x_{A2} of the rear of car A just then? (e) What is x_{B2} in terms of x_{A2} and L ? Putting the pieces together, find the values of (f) t_2 and (g) t_{tot} .

KEY IDEA

We can apply the equations of constant acceleration to both stages of passing: when car B has acceleration $a = 3.50 \text{ m/s}^2$ and when it travels at constant speed (thus, with constant $a = 0$).

Calculations: (a) In the passing lane, B accelerates at the constant rate $a = 3.50 \text{ m/s}^2$ from initial speed $v_0 = 22.0 \text{ m/s}$ to final speed $v = 27.0 \text{ m/s}$. From Eq. 2.4.1, we find the time t_1 required for the acceleration:

$$t_1 = \frac{v - v_0}{a} = \frac{(27.0 \text{ m/s}) - (22.0 \text{ m/s})}{3.50 \text{ m/s}^2} = 1.4285 \text{ s} \approx 1.43 \text{ s.} \quad (\text{Answer})$$

(b) In Eq. 2.4.6, let $x - x_0$ be the distance d_1 traveled by B during the acceleration. We can then write

$$v^2 = v_0^2 + 2ad_1$$

$$d_1 = \frac{v^2 - v_0^2}{2a} = \frac{(27.0 \text{ m/s})^2 - (22.0 \text{ m/s})^2}{2(3.50 \text{ m/s}^2)} = 35.0 \text{ m} \quad (\text{Answer})$$

(c) After the acceleration through displacement d_1 from its initial position of $x_{B1} = 0$, the rear of car B moves at constant speed v for the unknown time t_2 . Its position is then

$$x_{B2} = d_1 + vt_2. \quad (\text{Answer})$$

(d) From its initial position of $x_{A1} = 4L$, the rear of car A moves at constant speed v_0 for the total time $t_1 + t_2$. Thus, its position is then

$$x_{A2} = 4L + v_0(t_1 + t_2). \quad (\text{Answer})$$

(e) The rear of car B is then $3L$ from the front of A and thus $4L$ from the rear of A . So,

$$x_{B2} = x_{A2} + 4L. \quad (\text{Answer})$$

(f) Putting the pieces together, we find

$$x_{B2} = x_{A2} + 4L$$

$$d_1 + vt_2 = 4L + v_0(t_1 + t_2) + 4L$$

$$t_2(v - v_0) = 8L + v_0t_1 - d_1$$

$$t_2 = \frac{8L + v_0t_1 - d_1}{v - v_0} = \frac{8(4.50) + (22.0 \text{ m/s})(1.4285 \text{ s}) - 35.0 \text{ m}}{(27.0 \text{ m/s}) - (22.0 \text{ m/s})} = 6.4854 \text{ s} \approx 6.49 \text{ s.} \quad (\text{Answer})$$

(g) The total time is

$$t_{\text{tot}} = t_1 + t_2 = 1.4285 \text{ s} + 6.4854 \text{ s} = 7.91 \text{ s.} \quad (\text{Answer})$$

As explored in one of the end-of-chapter problems, the next step for your car's control system is to detect the speed and distance of any oncoming car, to see if this much time is safe.

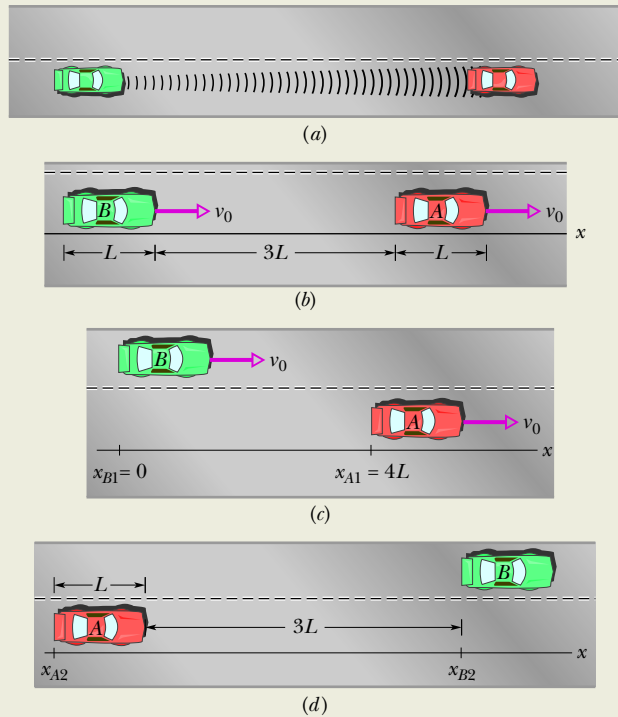


Figure 2.4.2 (a) Trailing car's radar system detects distance and speed of lead car. (b) Initial situation. (c) Trailing car B pulls into passing lane. (d) Car B is about to pull back into initial lane.

Another Look at Constant Acceleration*

The first two equations in Table 2.4.1 are the basic equations from which the others are derived. Those two can be obtained by integration of the acceleration with the condition that a is constant. To find Eq. 2.4.1, we rewrite the definition of acceleration (Eq. 2.3.2) as

$$dv = a dt.$$

We next write the *indefinite integral* (or *antiderivative*) of both sides:

$$\int dv = \int a dt.$$

Since acceleration a is a constant, it can be taken outside the integration. We obtain

$$\int dv = a \int dt$$

or
$$v = at + C. \quad (2.4.9)$$

To evaluate the constant of integration C , we let $t = 0$, at which time $v = v_0$. Substituting these values into Eq. 2.4.9 (which must hold for all values of t , including $t = 0$) yields

$$v_0 = (a)(0) + C = C.$$

Substituting this into Eq. 2.4.9 gives us Eq. 2.4.1.

To derive Eq. 2.4.5, we rewrite the definition of velocity (Eq. 2.2.1) as

$$dx = v dt$$

and then take the indefinite integral of both sides to obtain

$$\int dx = \int v dt.$$

Next, we substitute for v with Eq. 2.4.1:

$$\int dx = \int (v_0 + at) dt.$$

Since v_0 is a constant, as is the acceleration a , this can be rewritten as

$$\int dx = v_0 \int dt + a \int t dt.$$

Integration now yields

$$x = v_0 t + \frac{1}{2} at^2 + C', \quad (2.4.10)$$

where C' is another constant of integration. At time $t = 0$, we have $x = x_0$. Substituting these values in Eq. 2.4.10 yields $x_0 = C'$. Replacing C' with x_0 in Eq. 2.4.10 gives us Eq. 2.4.5.

*This section is intended for students who have had integral calculus.

2.5 FREE-FALL ACCELERATION

Learning Objectives

After reading this module, you should be able to . . .

2.5.1 Identify that if a particle is in free flight (whether upward or downward) and if we can neglect the effects of air on its motion, the particle has a

constant downward acceleration with a magnitude g that we take to be 9.8 m/s^2 .

2.5.2 Apply the constant-acceleration equations (Table 2.4.1) to free-fall motion.

Key Idea

● An important example of straight-line motion with constant acceleration is that of an object rising or falling freely near Earth's surface. The constant-acceleration equations describe this motion, but we make two changes in notation: (1) We refer the

motion to the vertical y axis with $+y$ vertically up; (2) we replace a with $-g$, where g is the magnitude of the free-fall acceleration. Near Earth's surface,

$$g = 9.8 \text{ m/s}^2 = 32 \text{ ft/s}^2.$$

Free-Fall Acceleration

If you tossed an object either up or down and could somehow eliminate the effects of air on its flight, you would find that the object accelerates downward at a certain constant rate. That rate is called the **free-fall acceleration**, and its magnitude is represented by g . The acceleration is independent of the object's characteristics, such as mass, density, or shape; it is the same for all objects.

Two examples of free-fall acceleration are shown in Fig. 2.5.1, which is a series of stroboscopic photos of a feather and an apple. As these objects fall, they accelerate downward—both at the same rate g . Thus, their speeds increase at the same rate, and they fall together.

The value of g varies slightly with latitude and with elevation. At sea level in Earth's midlatitudes the value is 9.8 m/s^2 (or 32 ft/s^2), which is what you should use as an exact number for the problems in this book unless otherwise noted.

The equations of motion in Table 2.4.1 for constant acceleration also apply to free fall near Earth's surface; that is, they apply to an object in vertical flight, either up or down, when the effects of the air can be neglected. However, note that for free fall: (1) The directions of motion are now along a vertical y axis instead of the x axis, with the positive direction of y upward. (This is important for later chapters when combined horizontal and vertical motions are examined.) (2) The free-fall acceleration is negative—that is, downward on the y axis, toward Earth's center—and so it has the value $-g$ in the equations.



The free-fall acceleration near Earth's surface is $a = -g = -9.8 \text{ m/s}^2$, and the magnitude of the acceleration is $g = 9.8 \text{ m/s}^2$. Do not substitute -9.8 m/s^2 for g .

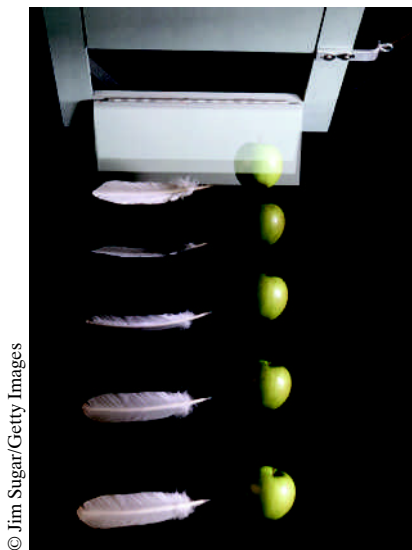


Figure 2.5.1 A feather and an apple free fall in vacuum at the same magnitude of acceleration g . The acceleration increases the distance between successive images. In the absence of air, the feather and apple fall together.

Suppose you toss a tomato directly upward with an initial (positive) velocity v_0 and then catch it when it returns to the release level. During its *free-fall flight* (from just after its release to just before it is caught), the equations of Table 2.4.1 apply to its motion. The acceleration is always $a = -g = -9.8 \text{ m/s}^2$, negative and thus downward. The velocity, however, changes, as indicated by Eqs. 2.4.1

and 2.4.6: During the ascent, the magnitude of the positive velocity decreases, until it momentarily becomes zero. Because the tomato has then stopped, it is at its maximum height. During the descent, the magnitude of the (now negative) velocity increases.

Checkpoint 2.5.1

(a) If you toss a ball straight up, what is the sign of the ball's displacement for the ascent, from the release point to the highest point? (b) What is it for the descent, from the highest point back to the release point? (c) What is the ball's acceleration at its highest point?

Sample Problem 2.5.1 Time for full up-down flight, baseball toss

In Fig. 2.5.2, a pitcher tosses a baseball up along a y axis, with an initial speed of 12 m/s. **FCP**

(a) How long does the ball take to reach its maximum height?

KEY IDEAS

(1) Once the ball leaves the pitcher and before it returns to his hand, its acceleration is the free-fall acceleration $a = -g$. Because this is constant, Table 2.4.1 applies to the motion. (2) The velocity v at the maximum height must be 0.

Calculation: Knowing v , a , and the initial velocity $v_0 = 12$ m/s, and seeking t , we solve Eq. 2.4.1, which contains those four variables. This yields

$$t = \frac{v - v_0}{a} = \frac{0 - 12 \text{ m/s}}{-9.8 \text{ m/s}^2} = 1.2 \text{ s.} \quad (\text{Answer})$$

(b) What is the ball's maximum height above its release point?

Calculation: We can take the ball's release point to be $y_0 = 0$. We can then write Eq. 2.4.6 in y notation, set $y - y_0 = y$ and $v = 0$ (at the maximum height), and solve for y . We get

$$y = \frac{v^2 - v_0^2}{2a} = \frac{0 - (12 \text{ m/s})^2}{2(-9.8 \text{ m/s}^2)} = 7.3 \text{ m.} \quad (\text{Answer})$$

(c) How long does the ball take to reach a point 5.0 m above its release point?

Calculations: We know v_0 , $a = -g$, and displacement $y - y_0 = 5.0$ m, and we want t , so we choose Eq. 2.4.5. Rewriting it for y and setting $y_0 = 0$ give us

$$y = v_0 t - \frac{1}{2} g t^2,$$

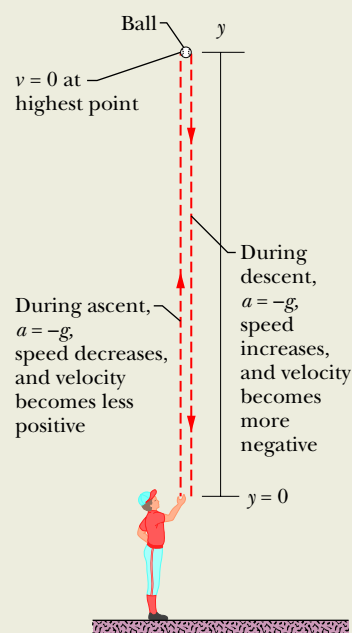


Figure 2.5.2 A pitcher tosses a baseball straight up into the air. The equations of free fall apply for rising as well as for falling objects, provided any effects from the air can be neglected.

$$\text{or} \quad 5.0 \text{ m} = (12 \text{ m/s})t - \left(\frac{1}{2}\right)(9.8 \text{ m/s}^2)t^2.$$

If we temporarily omit the units (having noted that they are consistent), we can rewrite this as

$$4.9t^2 - 12t + 5.0 = 0.$$

Solving this quadratic equation for t yields

$$t = 0.53 \text{ s} \quad \text{and} \quad t = 1.9 \text{ s.} \quad (\text{Answer})$$

There are two such times! This is not really surprising because the ball passes twice through $y = 5.0$ m, once on the way up and once on the way down.

2.6 GRAPHICAL INTEGRATION IN MOTION ANALYSIS

Learning Objectives

After reading this module, you should be able to . . .

2.6.1 Determine a particle's change in velocity by graphical integration on a graph of acceleration versus time.

2.6.2 Determine a particle's change in position by graphical integration on a graph of velocity versus time.

Key Ideas

● On a graph of acceleration a versus time t , the change in the velocity is given by

$$v_1 - v_0 = \int_{t_0}^{t_1} a \, dt.$$

● On a graph of velocity v versus time t , the change in the position is given by

$$x_1 - x_0 = \int_{t_0}^{t_1} v \, dt,$$

The integral amounts to finding an area on the graph:

$$\int_{t_0}^{t_1} a \, dt = \left(\begin{array}{l} \text{area between acceleration curve} \\ \text{and time axis, from } t_0 \text{ to } t_1 \end{array} \right).$$

where the integral can be taken from the graph as

$$\int_{t_0}^{t_1} v \, dt = \left(\begin{array}{l} \text{area between velocity curve} \\ \text{and time axis, from } t_0 \text{ to } t_1 \end{array} \right).$$

Graphical Integration in Motion Analysis

Integrating Acceleration. When we have a graph of an object's acceleration a versus time t , we can integrate on the graph to find the velocity at any given time. Because a is defined as $a = dv/dt$, the Fundamental Theorem of Calculus tells us that

$$v_1 - v_0 = \int_{t_0}^{t_1} a \, dt. \tag{2.6.1}$$

The right side of the equation is a definite integral (it gives a numerical result rather than a function), v_0 is the velocity at time t_0 , and v_1 is the velocity at later time t_1 . The definite integral can be evaluated from an $a(t)$ graph, such as in Fig. 2.6.1a. In particular,

$$\int_{t_0}^{t_1} a \, dt = \left(\begin{array}{l} \text{area between acceleration curve} \\ \text{and time axis, from } t_0 \text{ to } t_1 \end{array} \right). \tag{2.6.2}$$

If a unit of acceleration is 1 m/s^2 and a unit of time is 1 s , then the corresponding unit of area on the graph is

$$(1 \text{ m/s}^2)(1 \text{ s}) = 1 \text{ m/s},$$

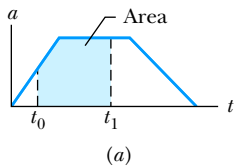
which is (properly) a unit of velocity. When the acceleration curve is above the time axis, the area is positive; when the curve is below the time axis, the area is negative.

Integrating Velocity. Similarly, because velocity v is defined in terms of the position x as $v = dx/dt$, then

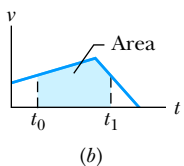
$$x_1 - x_0 = \int_{t_0}^{t_1} v \, dt, \tag{2.6.3}$$

where x_0 is the position at time t_0 and x_1 is the position at time t_1 . The definite integral on the right side of Eq. 2.6.3 can be evaluated from a $v(t)$ graph, like that shown in Fig. 2.6.1b. In particular,

$$\int_{t_0}^{t_1} v \, dt = \left(\begin{array}{l} \text{area between velocity curve} \\ \text{and time axis, from } t_0 \text{ to } t_1 \end{array} \right). \tag{2.6.4}$$



This area gives the change in velocity.



This area gives the change in position.

Figure 2.6.1 The area between a plotted curve and the horizontal time axis, from time t_0 to time t_1 , is indicated for (a) a graph of acceleration a versus t and (b) a graph of velocity v versus t .

If the unit of velocity is 1 m/s and the unit of time is 1 s, then the corresponding unit of area on the graph is

$$(1 \text{ m/s})(1 \text{ s}) = 1 \text{ m},$$

which is (properly) a unit of position and displacement. Whether this area is positive or negative is determined as described for the $a(t)$ curve of Fig. 2.6.1a.

Checkpoint 2.6.1

(a) To get the change in position function Δx from a graph of velocity v versus time t , do you graphically integrate the graph or find the slope of the graph? (b) Which do you do to get the acceleration?

Sample Problem 2.6.1 Graphical integration a versus t , whiplash injury

“Whiplash injury” commonly occurs in a rear-end collision where a front car is hit from behind by a second car. In the 1970s, researchers concluded that the injury was due to the occupant’s head being whipped back over the top of the seat as the car was slammed forward. As a result of this finding, head restraints were built into cars, yet neck injuries in rear-end collisions continued to occur.

In a recent test to study neck injury in rear-end collisions, a volunteer was strapped to a seat that was then moved abruptly to simulate a collision by a rear car moving at 10.5 km/h. Figure 2.6.2a gives the accelerations of the volunteer’s torso and head during the collision, which began at time $t = 0$. The torso acceleration was delayed by 40 ms because during that time interval the seat back had to compress against the volunteer. The head acceleration was delayed by an additional 70 ms. What was the torso speed when the head began to accelerate? **FCP**

KEY IDEA

We can calculate the torso speed at any time by finding an area on the torso $a(t)$ graph.

Calculations: We know that the initial torso speed is $v_0 = 0$ at time $t_0 = 0$, at the start of the “collision.” We want the torso speed v_1 at time $t_1 = 110$ ms, which is when the head begins to accelerate.

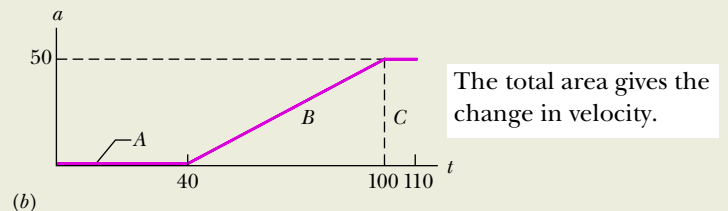
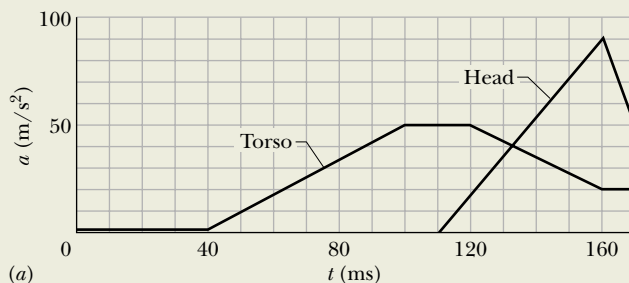


Figure 2.6.2 (a) The $a(t)$ curve of the torso and head of a volunteer in a simulation of a rear-end collision. (b) Breaking up the region between the plotted curve and the time axis to calculate the area.

Combining Eqs. 2.6.1 and 2.6.2, we can write

$$v_1 - v_0 = \left(\begin{array}{l} \text{area between acceleration curve} \\ \text{and time axis, from } t_0 \text{ to } t_1 \end{array} \right). \quad (2.6.5)$$

For convenience, let us separate the area into three regions (Fig. 2.6.2b). From 0 to 40 ms, region A has no area:

$$\text{area}_A = 0.$$

From 40 ms to 100 ms, region B has the shape of a triangle, with area

$$\text{area}_B = \frac{1}{2}(0.060 \text{ s})(50 \text{ m/s}^2) = 1.5 \text{ m/s}.$$

From 100 ms to 110 ms, region C has the shape of a rectangle, with area

$$\text{area}_C = (0.010 \text{ s})(50 \text{ m/s}^2) = 0.50 \text{ m/s}.$$

Substituting these values and $v_0 = 0$ into Eq. 2.6.5 gives us

$$v_1 - 0 = 0 + 1.5 \text{ m/s} + 0.50 \text{ m/s},$$

or $v_1 = 2.0 \text{ m/s} = 7.2 \text{ km/h}$. (Answer)

Comments: When the head is just starting to move forward, the torso already has a speed of 7.2 km/h. Researchers argue that it is this difference in speeds during the early stage of a rear-end collision that injures the neck. The backward whipping of the head happens later and could, especially if there is no head restraint, increase the injury.

Review & Summary

Position The *position* x of a particle on an x axis locates the particle with respect to the **origin**, or zero point, of the axis. The position is either positive or negative, according to which side of the origin the particle is on, or zero if the particle is at the origin. The **positive direction** on an axis is the direction of increasing positive numbers; the opposite direction is the **negative direction** on the axis.

Displacement The *displacement* Δx of a particle is the change in its position:

$$\Delta x = x_2 - x_1. \quad (2.1.1)$$

Displacement is a vector quantity. It is positive if the particle has moved in the positive direction of the x axis and negative if the particle has moved in the negative direction.

Average Velocity When a particle has moved from position x_1 to position x_2 during a time interval $\Delta t = t_2 - t_1$, its *average velocity* during that interval is

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_2 - x_1}{t_2 - t_1}. \quad (2.1.2)$$

The algebraic sign of v_{avg} indicates the direction of motion (v_{avg} is a vector quantity). Average velocity does not depend on the actual distance a particle moves, but instead depends on its original and final positions.

On a graph of x versus t , the average velocity for a time interval Δt is the slope of the straight line connecting the points on the curve that represent the two ends of the interval.

Average Speed The *average speed* s_{avg} of a particle during a time interval Δt depends on the total distance the particle moves in that time interval:

$$s_{\text{avg}} = \frac{\text{total distance}}{\Delta t}. \quad (2.1.3)$$

Instantaneous Velocity The *instantaneous velocity* (or simply **velocity**) v of a moving particle is

$$v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}, \quad (2.2.1)$$

where Δx and Δt are defined by Eq. 2.1.2. The instantaneous velocity (at a particular time) may be found as the slope (at that particular time) of the graph of x versus t . **Speed** is the magnitude of instantaneous velocity.

Average Acceleration *Average acceleration* is the ratio of a change in velocity Δv to the time interval Δt in which the change occurs:

$$a_{\text{avg}} = \frac{\Delta v}{\Delta t}. \quad (2.3.1)$$

The algebraic sign indicates the direction of a_{avg} .

Instantaneous Acceleration *Instantaneous acceleration* (or simply **acceleration**) a is the first time derivative of velocity $v(t)$ and the second time derivative of position $x(t)$:

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}. \quad (2.3.2, 2.3.3)$$

On a graph of v versus t , the acceleration a at any time t is the slope of the curve at the point that represents t .

Constant Acceleration The five equations in Table 2.4.1 describe the motion of a particle with constant acceleration:

$$v = v_0 + at, \quad (2.4.1)$$

$$x - x_0 = v_0t + \frac{1}{2}at^2, \quad (2.4.5)$$

$$v^2 = v_0^2 + 2a(x - x_0), \quad (2.4.6)$$

$$x - x_0 = \frac{1}{2}(v_0 + v)t, \quad (2.4.7)$$

$$x - x_0 = vt - \frac{1}{2}at^2. \quad (2.4.8)$$

These are *not* valid when the acceleration is not constant.

Free-Fall Acceleration An important example of straight-line motion with constant acceleration is that of an object rising or falling freely near Earth's surface. The constant-acceleration equations describe this motion, but we make two changes in notation: (1) We refer the motion to the vertical y axis with $+y$ vertically *up*; (2) we replace a with $-g$, where g is the magnitude of the free-fall acceleration. Near Earth's surface, $g = 9.8 \text{ m/s}^2 (= 32 \text{ ft/s}^2)$.

Questions

1 Figure 2.1 gives the velocity of a particle moving on an x axis. What are (a) the initial and (b) the final directions of travel? (c) Does the particle stop momentarily? (d) Is the acceleration positive or negative? (e) Is it constant or varying?

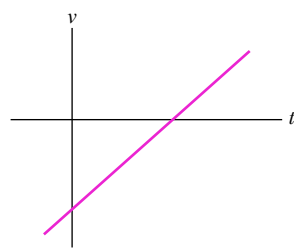


Figure 2.1 Question 1.

2 Figure 2.2 gives the acceleration $a(t)$ of a Chihuahua as it chases a German shepherd

along an axis. In which of the time periods indicated does the Chihuahua move at constant speed?

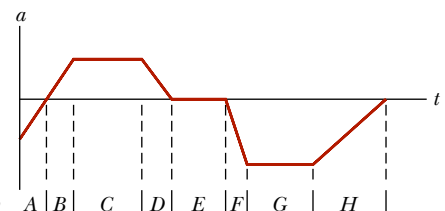


Figure 2.2 Question 2.

3 Figure 2.3 shows four paths along which objects move from a starting point to a final point, all in the same time interval. The paths pass over a grid of equally spaced straight lines. Rank the paths according to (a) the average velocity of the objects and (b) the average speed of the objects, greatest first.

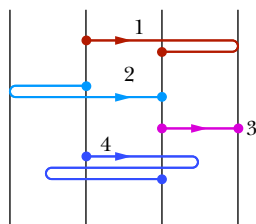


Figure 2.3 Question 3.

4 Figure 2.4 is a graph of a particle's position along an x axis versus time. (a) At time $t = 0$, what is the sign of the particle's position? Is the particle's velocity positive, negative, or 0 at (b) $t = 1$ s, (c) $t = 2$ s, and (d) $t = 3$ s? (e) How many times does the particle go through the point $x = 0$?

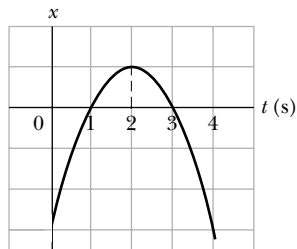


Figure 2.4 Question 4.

5 Figure 2.5 gives the velocity of a particle moving along an axis. Point 1 is at the highest point on the curve; point 4 is at the lowest point; and points 2 and 6 are at the same height. What is the direction of travel at (a) time $t = 0$ and (b) point 4? (c) At which of the six numbered points does the particle reverse its direction of travel? (d) Rank the six points according to the magnitude of the acceleration, greatest first.

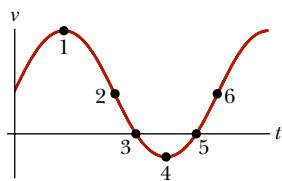


Figure 2.5 Question 5.

6 At $t = 0$, a particle moving along an x axis is at position $x_0 = -20$ m. The signs of the particle's initial velocity v_0 (at time t_0) and constant acceleration a are, respectively, for four situations: (1) +, +; (2) +, -; (3) -, +; (4) -, -. In which situations will the particle (a) stop momentarily, (b) pass through the origin, and (c) never pass through the origin?

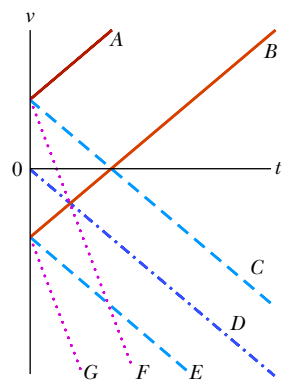


Figure 2.6 Question 7.

7 Hanging over the railing of a bridge, you drop an egg (no

initial velocity) as you throw a second egg downward. Which curves in Fig. 2.6 give the velocity $v(t)$ for (a) the dropped egg and (b) the thrown egg? (Curves A and B are parallel; so are C, D, and E; so are F and G.)

8 The following equations give the velocity $v(t)$ of a particle in four situations: (a) $v = 3$; (b) $v = 4t^2 + 2t - 6$; (c) $v = 3t - 4$; (d) $v = 5t^2 - 3$. To which of these situations do the equations of Table 2.4.1 apply?

9 In Fig. 2.7, a cream tangerine is thrown directly upward past three evenly spaced windows of equal heights. Rank the windows according to (a) the average speed of the cream tangerine while passing them, (b) the time the cream tangerine takes to pass them, (c) the magnitude of the acceleration of the cream tangerine while passing them, and (d) the change Δv in the speed of the cream tangerine during the passage, greatest first.

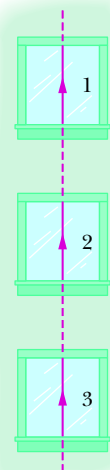


Figure 2.7 Question 9.

10 Suppose that a passenger intent on lunch during his first ride in a hot-air balloon accidentally drops an apple over the side during the balloon's liftoff. At the moment of the apple's release, the balloon is accelerating upward with a magnitude of 4.0 m/s^2 and has an upward velocity of magnitude 2 m/s . What are the (a) magnitude and (b) direction of the acceleration of the apple just after it is released? (c) Just then, is the apple moving upward or downward, or is it stationary? (d) What is the magnitude of its velocity just then? (e) In the next few moments, does the speed of the apple increase, decrease, or remain constant?

11 Figure 2.8 shows that a particle moving along an x axis undergoes three periods of acceleration. Without written computation, rank the acceleration periods according to the increases they produce in the particle's velocity, greatest first.

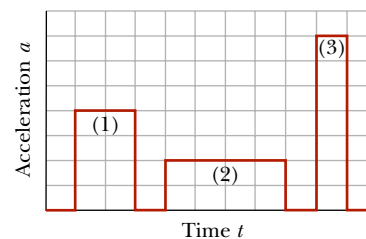


Figure 2.8 Question 11.

Problems

GO Tutoring problem available (at instructor's discretion) in WileyPLUS

SSM Worked-out solution available in Student Solutions Manual

E Easy **M** Medium **H** Hard

FCP Additional information available in *The Flying Circus of Physics* and at flyingcircusofphysics.com

CALC Requires calculus

BIO Biomedical application

Module 2.1 Position, Displacement, and Average Velocity

1 E While driving a car at 90 km/h , how far do you move while your eyes shut for 0.50 s during a hard sneeze?

2 E Compute your average velocity in the following two cases: (a) You walk 73.2 m at a speed of 1.22 m/s and then run 73.2 m at a speed of 3.05 m/s along a straight track. (b) You walk for 1.00 min at a speed of 1.22 m/s and then run for 1.00 min at 3.05 m/s

along a straight track. (c) Graph x versus t for both cases and indicate how the average velocity is found on the graph.

3 E SSM An automobile travels on a straight road for 40 km at 30 km/h. It then continues in the same direction for another 40 km at 60 km/h. (a) What is the average velocity of the car during the full 80 km trip? (Assume that it moves in the positive x direction.) (b) What is the average speed? (c) Graph x versus t and indicate how the average velocity is found on the graph.

4 E A car moves uphill at 40 km/h and then back downhill at 60 km/h. What is the average speed for the round trip?

5 E CALC SSM The position of an object moving along an x axis is given by $x = 3t - 4t^2 + t^3$, where x is in meters and t in seconds. Find the position of the object at the following values of t : (a) 1 s, (b) 2 s, (c) 3 s, and (d) 4 s. (e) What is the object's displacement between $t = 0$ and $t = 4$ s? (f) What is its average velocity for the time interval from $t = 2$ s to $t = 4$ s? (g) Graph x versus t for $0 \leq t \leq 4$ s and indicate how the answer for (f) can be found on the graph.

6 E BIO The 1992 world speed record for a bicycle (human-powered vehicle) was set by Chris Huber. His time through the measured 200 m stretch was a sizzling 6.509 s, at which he commented, "Cogito ergo zoom!" (I think, therefore I go fast!). In 2001, Sam Whittingham beat Huber's record by 19.0 km/h. What was Whittingham's time through the 200 m?

7 M Two trains, each having a speed of 30 km/h, are headed at each other on the same straight track. A bird that can fly 60 km/h flies off the front of one train when they are 60 km apart and heads directly for the other train. On reaching the other train, the (crazy) bird flies directly back to the first train, and so forth. What is the total distance the bird travels before the trains collide?

8 M FCP GO *Panic escape.* Figure 2.9 shows a general situation in which a stream of people attempt to escape through an exit door that turns out to be locked. The people move toward the door at speed $v_s = 3.50$ m/s, are each $d = 0.25$ m in depth, and are separated by $L = 1.75$ m. The arrangement in Fig. 2.9 occurs at time $t = 0$. (a) At what average rate does the layer of people at the door increase? (b) At what time does the layer's depth reach 5.0 m? (The answers reveal how quickly such a situation becomes dangerous.)

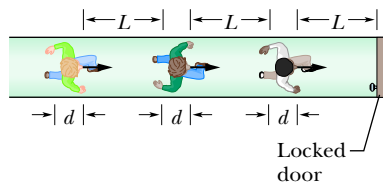


Figure 2.9 Problem 8.

9 M BIO In 1 km races, runner 1 on track 1 (with time 2 min, 27.95 s) appears to be faster than runner 2 on track 2 (2 min, 28.15 s). However, length L_2 of track 2 might be slightly greater than length L_1 of track 1. How large can $L_2 - L_1$ be for us still to conclude that runner 1 is faster?

10 M FCP To set a speed record in a measured (straight-line) distance d , a race car must be driven first in one direction (in time t_1) and then in the opposite direction (in time t_2). (a) To eliminate the effects of the wind and obtain the car's speed v_c in a windless situation, should we find the average of d/t_1 and d/t_2 (method 1) or should we divide d by the average of t_1 and t_2 ? (b) What is the fractional difference in the two methods when a steady wind blows along the car's route and the ratio of the wind speed v_w to the car's speed v_c is 0.0240?

11 M GO You are to drive 300 km to an interview. The interview is at 11:15 A.M. You plan to drive at 100 km/h, so you leave at 8:00 A.M. to allow some extra time. You drive at that speed for the first 100 km, but then construction work forces you to slow to 40 km/h for 40 km. What would be the least speed needed for the rest of the trip to arrive in time for the interview?

12 H FCP *Traffic shock wave.* An abrupt slowdown in concentrated traffic can travel as a pulse, termed a *shock wave*, along the line of cars, either downstream (in the traffic direction) or upstream, or it can be stationary. Figure 2.10 shows a uniformly spaced line of cars moving at speed $v = 25.0$ m/s toward a uniformly spaced line of slow cars moving at speed $v_s = 5.00$ m/s. Assume that each faster car adds length $L = 12.0$ m (car length plus buffer zone) to the line of slow cars when it joins the line, and assume it slows abruptly at the last instant. (a) For what separation distance d between the faster cars does the shock wave remain stationary? If the separation is twice that amount, what are the (b) speed and (c) direction (upstream or downstream) of the shock wave?

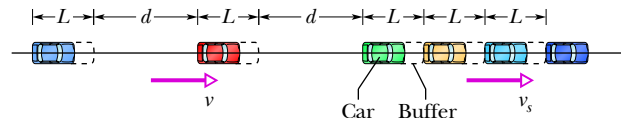


Figure 2.10 Problem 12.

13 H You drive on Interstate 10 from San Antonio to Houston, half the *time* at 55 km/h and the other half at 90 km/h. On the way back you travel half the *distance* at 55 km/h and the other half at 90 km/h. What is your average speed (a) from San Antonio to Houston, (b) from Houston back to San Antonio, and (c) for the entire trip? (d) What is your average velocity for the entire trip? (e) Sketch x versus t for (a), assuming the motion is all in the positive x direction. Indicate how the average velocity can be found on the sketch.

Module 2.2 Instantaneous Velocity and Speed

14 E GO CALC An electron moving along the x axis has a position given by $x = 16te^{-t}$ m, where t is in seconds. How far is the electron from the origin when it momentarily stops?

15 E GO CALC (a) If a particle's position is given by $x = 4 - 12t + 3t^2$ (where t is in seconds and x is in meters), what is its velocity at $t = 1$ s? (b) Is it moving in the positive or negative direction of x just then? (c) What is its speed just then? (d) Is the speed increasing or decreasing just then? (Try answering the next two questions without further calculation.) (e) Is there ever an instant when the velocity is zero? If so, give the time t ; if not, answer no. (f) Is there a time after $t = 3$ s when the particle is moving in the negative direction of x ? If so, give the time t ; if not, answer no.

16 E CALC The position function $x(t)$ of a particle moving along an x axis is $x = 4.0 - 6.0t^2$, with x in meters and t in seconds. (a) At what time and (b) where does the particle (momentarily) stop? At what (c) negative time and (d) positive time does the particle pass through the origin? (e) Graph x versus t for the range -5 s to $+5$ s. (f) To shift the curve rightward on the graph, should we include the term $+20t$ or the term $-20t$ in $x(t)$? (g) Does that inclusion increase or decrease the value of x at which the particle momentarily stops?

17 M CALC The position of a particle moving along the x axis is given in centimeters by $x = 9.75 + 1.50t^3$, where t is in seconds. Calculate (a) the average velocity during the time interval $t = 2.00$ s to $t = 3.00$ s; (b) the instantaneous velocity at $t = 2.00$ s; (c) the instantaneous velocity at $t = 3.00$ s; (d) the instantaneous velocity at $t = 2.50$ s; and (e) the instantaneous velocity when the particle is midway between its positions at $t = 2.00$ s and $t = 3.00$ s. (f) Graph x versus t and indicate your answers graphically.

Module 2.3 Acceleration

18 E CALC The position of a particle moving along an x axis is given by $x = 12t^2 - 2t^3$, where x is in meters and t is in seconds. Determine (a) the position, (b) the velocity, and (c) the acceleration of the particle at $t = 3.0$ s. (d) What is the maximum positive coordinate reached by the particle and (e) at what time is it reached? (f) What is the maximum positive velocity reached by the particle and (g) at what time is it reached? (h) What is the acceleration of the particle at the instant the particle is not moving (other than at $t = 0$)? (i) Determine the average velocity of the particle between $t = 0$ and $t = 3$ s.

19 E SSM At a certain time a particle had a speed of 18 m/s in the positive x direction, and 2.4 s later its speed was 30 m/s in the opposite direction. What is the average acceleration of the particle during this 2.4 s interval?

20 E CALC (a) If the position of a particle is given by $x = 20t - 5t^3$, where x is in meters and t is in seconds, when, if ever, is the particle's velocity zero? (b) When is its acceleration a zero? (c) For what time range (positive or negative) is a negative? (d) Positive? (e) Graph $x(t)$, $v(t)$, and $a(t)$.

21 M From $t = 0$ to $t = 5.00$ min, a man stands still, and from $t = 5.00$ min to $t = 10.0$ min, he walks briskly in a straight line at a constant speed of 2.20 m/s. What are (a) his average velocity v_{avg} and (b) his average acceleration a_{avg} in the time interval 2.00 min to 8.00 min? What are (c) v_{avg} and (d) a_{avg} in the time interval 3.00 min to 9.00 min? (e) Sketch x versus t and v versus t , and indicate how the answers to (a) through (d) can be obtained from the graphs.

22 M CALC The position of a particle moving along the x axis depends on the time according to the equation $x = ct^2 - bt^3$, where x is in meters and t is in seconds. What are the units of (a) constant c and (b) constant b ? Let their numerical values be 3.0 and 2.0, respectively. (c) At what time does the particle reach its maximum positive x position? From $t = 0.0$ s to $t = 4.0$ s, (d) what distance does the particle move and (e) what is its displacement? Find its velocity at times (f) 1.0 s, (g) 2.0 s, (h) 3.0 s, and (i) 4.0 s. Find its acceleration at times (j) 1.0 s, (k) 2.0 s, (l) 3.0 s, and (m) 4.0 s.

Module 2.4 Constant Acceleration

23 E SSM An electron with an initial velocity $v_0 = 1.50 \times 10^5$ m/s enters a region of length $L = 1.00$ cm where it is electrically accelerated (Fig. 2.11). It emerges with $v = 5.70 \times 10^6$ m/s. What is its acceleration, assumed constant?

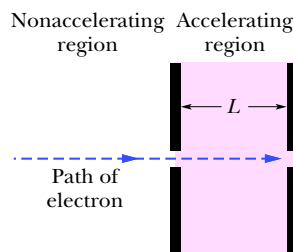


Figure 2.11 Problem 23.

24 E BIO FCP *Catapulting mushrooms.* Certain mushrooms launch their spores by a catapult mechanism. As water condenses

from the air onto a spore that is attached to the mushroom, a drop grows on one side of the spore and a film grows on the other side. The spore is bent over by the drop's weight, but when the film reaches the drop, the drop's water suddenly spreads into the film and the spore springs upward so rapidly that it is slung off into the air. Typically, the spore reaches a speed of 1.6 m/s in a $5.0 \mu\text{m}$ launch; its speed is then reduced to zero in 1.0 mm by the air. Using those data and assuming constant accelerations, find the acceleration in terms of g during (a) the launch and (b) the speed reduction.

25 E An electric vehicle starts from rest and accelerates at a rate of 2.0 m/s^2 in a straight line until it reaches a speed of 20 m/s. The vehicle then slows at a constant rate of 1.0 m/s^2 until it stops. (a) How much time elapses from start to stop? (b) How far does the vehicle travel from start to stop?

26 E A muon (an elementary particle) enters a region with a speed of 5.00×10^6 m/s and then is slowed at the rate of $1.25 \times 10^{14} \text{ m/s}^2$. (a) How far does the muon take to stop? (b) Graph x versus t and v versus t for the muon.

27 E An electron has a constant acceleration of $+3.2 \text{ m/s}^2$. At a certain instant its velocity is $+9.6 \text{ m/s}$. What is its velocity (a) 2.5 s earlier and (b) 2.5 s later?

28 E On a dry road, a car with good tires may be able to brake with a constant deceleration of 4.92 m/s^2 . (a) How long does such a car, initially traveling at 24.6 m/s, take to stop? (b) How far does it travel in this time? (c) Graph x versus t and v versus t for the deceleration.

29 E A certain elevator cab has a total run of 190 m and a maximum speed of 305 m/min, and it accelerates from rest and then back to rest at 1.22 m/s^2 . (a) How far does the cab move while accelerating to full speed from rest? (b) How long does it take to make the nonstop 190 m run, starting and ending at rest?

30 E The brakes on your car can slow you at a rate of 5.2 m/s^2 . (a) If you are going 137 km/h and suddenly see a state trooper, what is the minimum time in which you can get your car under the 90 km/h speed limit? (The answer reveals the futility of braking to keep your high speed from being detected with a radar or laser gun.) (b) Graph x versus t and v versus t for such a slowing.

31 E SSM Suppose a rocket ship in deep space moves with constant acceleration equal to 9.8 m/s^2 , which gives the illusion of normal gravity during the flight. (a) If it starts from rest, how long will it take to acquire a speed one-tenth that of light, which travels at $3.0 \times 10^8 \text{ m/s}$? (b) How far will it travel in so doing?

32 E BIO FCP A world's land speed record was set by Colonel John P. Stapp when in March 1954 he rode a rocket-propelled sled that moved along a track at 1020 km/h. He and the sled were brought to a stop in 1.4 s. (See Fig. 2.3.1.) In terms of g , what acceleration did he experience while stopping?

33 E SSM A car traveling 56.0 km/h is 24.0 m from a barrier when the driver slams on the brakes. The car hits the barrier 2.00 s later. (a) What is the magnitude of the car's constant acceleration before impact? (b) How fast is the car traveling at impact?

34 M GO In Fig. 2.12, a red car and a green car, identical except for the color, move toward each other in adjacent lanes and parallel to an x axis. At time $t = 0$, the red car is at $x_r = 0$ and the green car is at $x_g = 220$ m. If the red car has a constant velocity

of 20 km/h, the cars pass each other at $x = 44.5$ m, and if it has a constant velocity of 40 km/h, they pass each other at $x = 76.6$ m. What are (a) the initial velocity and (b) the constant acceleration of the green car?



Figure 2.12 Problems 34 and 35.

35 M Figure 2.12 shows a red car and a green car that move toward each other. Figure 2.13 is a graph of their motion, showing the positions $x_{g0} = 270$ m and $x_{r0} = -35.0$ m at time $t = 0$. The green car has a constant speed of 20.0 m/s and the red car begins from rest. What is the acceleration magnitude of the red car?

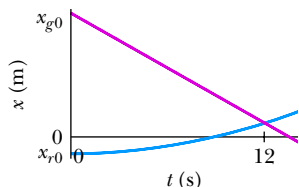


Figure 2.13 Problem 35.

36 M A car moves along an x axis through a distance of 900 m, starting at rest (at $x = 0$) and ending at rest (at $x = 900$ m). Through the first $\frac{1}{4}$ of that distance, its acceleration is $+2.25$ m/s². Through the rest of that distance, its acceleration is -0.750 m/s². What are (a) its travel time through the 900 m and (b) its maximum speed? (c) Graph position x , velocity v , and acceleration a versus time t for the trip.

37 M Figure 2.14 depicts the motion of a particle moving along an x axis with a constant acceleration. The figure's vertical scaling is set by $x_s = 6.0$ m. What are the (a) magnitude and (b) direction of the particle's acceleration?

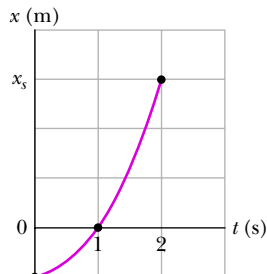


Figure 2.14 Problem 37.

38 M (a) If the maximum acceleration that is tolerable for passengers in a subway train is 1.34 m/s² and subway stations are located 806 m apart, what is the maximum speed a subway train can attain between stations? (b) What is the travel time between stations? (c) If a subway train stops for 20 s at each station, what is the maximum average speed of the train, from one start-up to the next? (d) Graph x , v , and a versus t for the interval from one start-up to the next.

39 M Cars A and B move in the same direction in adjacent lanes. The position x of car A is given in Fig. 2.15, from time $t = 0$ to $t = 7.0$ s. The figure's vertical scaling is set by $x_s = 32.0$ m. At $t = 0$, car B is at $x = 0$, with a velocity of 12 m/s and a negative constant acceleration a_B .

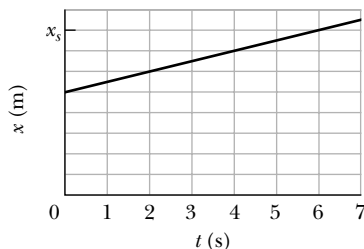


Figure 2.15 Problem 39.

(a) What must a_B be such that the cars are (momentarily) side by side (momentarily at the same value of x) at $t = 4.0$ s? (b) For that value of a_B , how many times are the cars side by side? (c) Sketch the position x of car B versus time t on Fig. 2.15.

How many times will the cars be side by side if the magnitude of acceleration a_B is (d) more than and (e) less than the answer to part (a)?

40 M FCP You are driving toward a traffic signal when it turns yellow. Your speed is the legal speed limit of $v_0 = 55$ km/h; your best deceleration rate has the magnitude $a = 5.18$ m/s². Your best reaction time to begin braking is $T = 0.75$ s. To avoid having the front of your car enter the intersection after the light turns red, should you brake to a stop or continue to move at 55 km/h if the distance to the intersection and the duration of the yellow light are (a) 40 m and 2.8 s, and (b) 32 m and 1.8 s? Give an answer of brake, continue, either (if either strategy works), or neither (if neither strategy works and the yellow duration is inappropriate).

41 M GO As two trains move along a track, their conductors suddenly notice that they are headed toward each other. Figure 2.16 gives their velocities v as functions of time t as the conductors slow the trains. The figure's vertical scaling is set by $v_s = 40.0$ m/s. The slowing processes begin when the trains are 200 m apart. What is their separation when both trains have stopped?

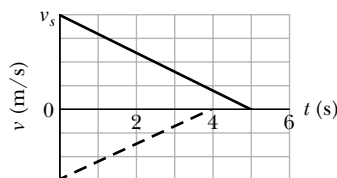


Figure 2.16 Problem 41.

42 H GO You are arguing over a cell phone while trailing an unmarked police car by 25 m; both your car and the police car are traveling at 110 km/h. Your argument diverts your attention from the police car for 2.0 s (long enough for you to look at the phone and yell, "I won't do that!"). At the beginning of that 2.0 s, the police officer begins braking suddenly at 5.0 m/s². (a) What is the separation between the two cars when your attention finally returns? Suppose that you take another 0.40 s to realize your danger and begin braking. (b) If you too brake at 5.0 m/s², what is your speed when you hit the police car?

43 H GO When a high-speed passenger train traveling at 161 km/h rounds a bend, the engineer is shocked to see that a locomotive has improperly entered onto the track from a siding and is a distance $D = 676$ m ahead (Fig. 2.17). The locomotive is moving at 29.0 km/h. The engineer of the high-speed train immediately applies the brakes. (a) What must be the magnitude of the resulting constant deceleration if a collision is to be just avoided? (b) Assume that the engineer is at $x = 0$ when, at $t = 0$, he first spots the locomotive. Sketch $x(t)$ curves for the locomotive and high-speed train for the cases in which a collision is just avoided and is not quite avoided.

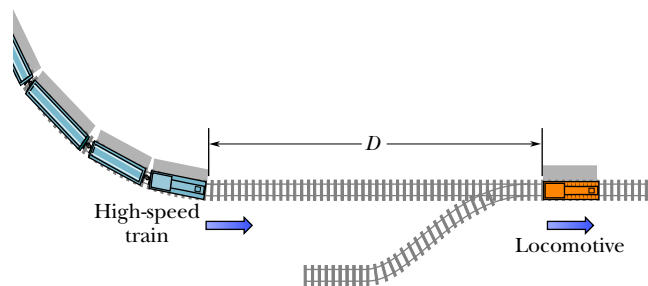


Figure 2.17 Problem 43.

Module 2.5 Free-Fall Acceleration

44 E When startled, an armadillo will leap upward. Suppose it rises 0.544 m in the first 0.200 s. (a) What is its initial speed as it leaves the ground? (b) What is its speed at the height of 0.544 m? (c) How much higher does it go?

45 E SSM (a) With what speed must a ball be thrown vertically from ground level to rise to a maximum height of 50 m? (b) How long will it be in the air? (c) Sketch graphs of y , v , and a versus t for the ball. On the first two graphs, indicate the time at which 50 m is reached.

46 E Raindrops fall 1700 m from a cloud to the ground. (a) If they were not slowed by air resistance, how fast would the drops be moving when they struck the ground? (b) Would it be safe to walk outside during a rainstorm?

47 E SSM At a construction site a pipe wrench struck the ground with a speed of 24 m/s. (a) From what height was it inadvertently dropped? (b) How long was it falling? (c) Sketch graphs of y , v , and a versus t for the wrench.

48 E A hoodlum throws a stone vertically downward with an initial speed of 12.0 m/s from the roof of a building, 30.0 m above the ground. (a) How long does it take the stone to reach the ground? (b) What is the speed of the stone at impact?

49 E SSM A hot-air balloon is ascending at the rate of 12 m/s and is 80 m above the ground when a package is dropped over the side. (a) How long does the package take to reach the ground? (b) With what speed does it hit the ground?

50 M At time $t = 0$, apple 1 is dropped from a bridge onto a roadway beneath the bridge; somewhat later, apple 2 is thrown down from the same height. Figure 2.18 gives the vertical positions y of the apples versus t during the falling, until both apples have hit the roadway. The scaling is set by $t_s = 2.0$ s. With approximately what speed is apple 2 thrown down?

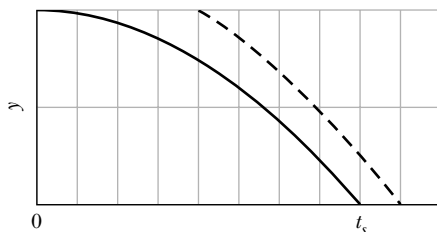


Figure 2.18 Problem 50.

51 M As a runaway scientific balloon ascends at 19.6 m/s, one of its instrument packages breaks free of a harness and free-falls. Figure 2.19 gives the vertical velocity of the package versus time, from before it breaks free to when it reaches the ground. (a) What maximum height above the break-free point does it rise? (b) How high is the break-free point above the ground?

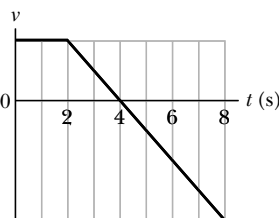


Figure 2.19 Problem 51.

52 M GO A bolt is dropped from a bridge under construction, falling 90 m to the valley below the bridge. (a) In how much time does it pass through the last 20% of its fall? What is its speed (b) when it begins that last 20% of its fall and (c) when it reaches the valley beneath the bridge?

53 M SSM A key falls from a bridge that is 45 m above the water. It falls directly into a model boat, moving with constant velocity, that is 12 m from the point of impact when the key is released. What is the speed of the boat?

54 M GO A stone is dropped into a river from a bridge 43.9 m above the water. Another stone is thrown vertically down 1.00 s after the first is dropped. The stones strike the water at the same time. (a) What is the initial speed of the second stone? (b) Plot velocity versus time on a graph for each stone, taking zero time as the instant the first stone is released.

55 M SSM A ball of moist clay falls 15.0 m to the ground. It is in contact with the ground for 20.0 ms before stopping. (a) What is the magnitude of the average acceleration of the ball during the time it is in contact with the ground? (Treat the ball as a particle.) (b) Is the average acceleration up or down?

56 M GO Figure 2.20 shows the speed v versus height y of a ball tossed directly upward, along a y axis. Distance d is 0.40 m. The speed at height y_A is v_A . The speed at height y_B is $\frac{1}{3}v_A$. What is speed v_A ?

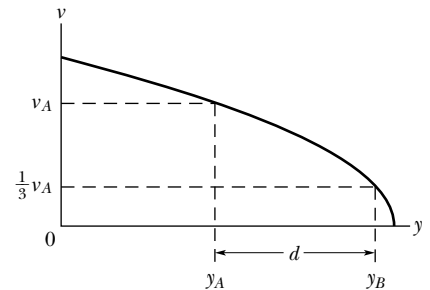


Figure 2.20 Problem 56.

57 M To test the quality of a tennis ball, you drop it onto the floor from a height of 4.00 m. It rebounds to a height of 2.00 m. If the ball is in contact with the floor for 12.0 ms, (a) what is the magnitude of its average acceleration during that contact and (b) is the average acceleration up or down?

58 M An object falls a distance h from rest. If it travels $0.50h$ in the last 1.00 s, find (a) the time and (b) the height of its fall. (c) Explain the physically unacceptable solution of the quadratic equation in t that you obtain.

59 M Water drips from the nozzle of a shower onto the floor 200 cm below. The drops fall at regular (equal) intervals of time, the first drop striking the floor at the instant the fourth drop begins to fall. When the first drop strikes the floor, how far below the nozzle are the (a) second and (b) third drops?

60 M GO A rock is thrown vertically upward from ground level at time $t = 0$. At $t = 1.5$ s it passes the top of a tall tower, and 1.0 s later it reaches its maximum height. What is the height of the tower?

61 H GO A steel ball is dropped from a building's roof and passes a window, taking 0.125 s to fall from the top to the bottom of the window, a distance of 1.20 m. It then falls to a sidewalk and bounces back past the window, moving from bottom to top in 0.125 s. Assume that the upward flight is an exact reverse of the fall. The time the ball spends below the bottom of the window is 2.00 s. How tall is the building?

62 H BIO FCP A basketball player grabbing a rebound jumps 76.0 cm vertically. How much total time (ascent and descent) does the player spend (a) in the top 15.0 cm of this jump and (b) in the bottom 15.0 cm? (The player seems to hang in the air at the top.)

63 H GO A drowsy cat spots a flowerpot that sails first up and then down past an open window. The pot is in view for a total of 0.50 s, and the top-to-bottom height of the window is 2.00 m. How high above the window top does the flowerpot go?

64 H A ball is shot vertically upward from the surface of another planet. A plot of y versus t for the ball is shown in Fig. 2.21, where y is the height of the ball above its starting point and $t = 0$ at the instant the ball is shot. The figure's vertical scaling is set by $y_s = 30.0$ m. What are the magnitudes of (a) the free-fall acceleration on the planet and (b) the initial velocity of the ball?

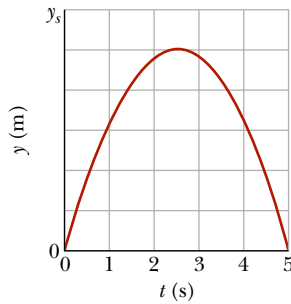


Figure 2.21 Problem 64.

Module 2.6 Graphical Integration in Motion Analysis

65 E BIO CALC FCP Figure 2.6.2a gives the acceleration of a volunteer's head and torso during a rear-end collision. At maximum head acceleration, what is the speed of (a) the head and (b) the torso?

66 M BIO CALC FCP In a forward punch in karate, the fist begins at rest at the waist and is brought rapidly forward until the arm is fully extended. The speed $v(t)$ of the fist is given in Fig. 2.22 for someone skilled in karate. The vertical scaling is set by $v_s = 8.0$ m/s. How far has the fist moved at (a) time $t = 50$ ms and (b) when the speed of the fist is maximum?

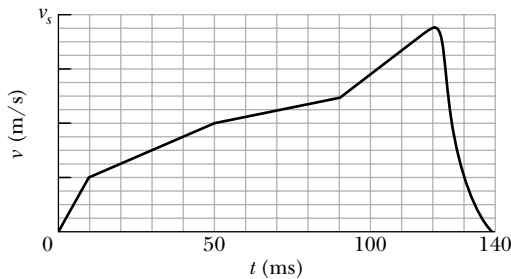


Figure 2.22 Problem 66.

67 M BIO CALC

When a soccer ball is kicked toward a player and the player deflects the ball by “heading” it, the acceleration of the head during the collision can be significant. Figure 2.23 gives the measured acceleration $a(t)$ of a soccer player's head for a bare head and a helmeted head, starting from rest. The scaling on the vertical axis is set by $a_s = 200$ m/s². At time $t = 7.0$ ms, what is the difference in the speed acquired by the bare head and the speed acquired by the helmeted head?

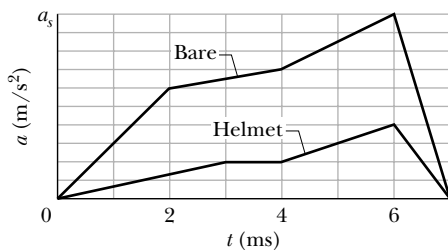


Figure 2.23 Problem 67.

68 M BIO CALC FCP A salamander of the genus *Hydromantes* captures prey by launching its tongue as a projectile: The skeletal part of the tongue is shot forward, unfolding the rest of the tongue, until the outer portion lands on the prey, sticking to it. Figure 2.24 shows the acceleration magnitude a versus time t for the acceleration phase of the launch in a typical situation. The indicated accelerations are $a_2 = 400$ m/s² and $a_1 = 100$ m/s². What is the outward speed of the tongue at the end of the acceleration phase?

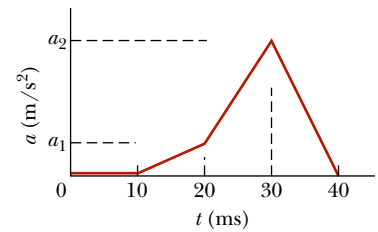


Figure 2.24 Problem 68.

69 M BIO CALC How far does the runner whose velocity–time graph is shown in Fig. 2.25 travel in 16 s? The figure's vertical scaling is set by $v_s = 8.0$ m/s.

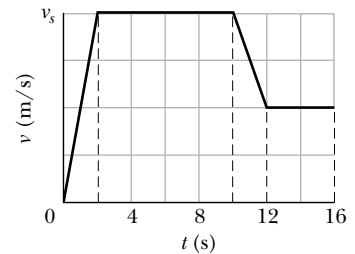


Figure 2.25 Problem 69.

70 H CALC Two particles move along an x axis. The position of particle 1 is given by $x = 6.00t^2 + 3.00t + 2.00$ (in meters and seconds); the acceleration of particle 2 is given by $a = -8.00t$ (in meters per second squared and seconds) and, at $t = 0$, its velocity is 20 m/s. When the velocities of the particles match, what is their velocity?

Additional Problems

71 CALC In an arcade video game, a spot is programmed to move across the screen according to $x = 9.00t - 0.750t^3$, where x is distance in centimeters measured from the left edge of the screen and t is time in seconds. When the spot reaches a screen edge, at either $x = 0$ or $x = 15.0$ cm, t is reset to 0 and the spot starts moving again according to $x(t)$. (a) At what time after starting is the spot instantaneously at rest? (b) At what value of x does this occur? (c) What is the spot's acceleration (including sign) when this occurs? (d) Is it moving right or left just prior to coming to rest? (e) Just after? (f) At what time $t > 0$ does it first reach an edge of the screen?

72 A rock is shot vertically upward from the edge of the top of a tall building. The rock reaches its maximum height above the top of the building 1.60 s after being shot. Then, after barely missing the edge of the building as it falls downward, the rock strikes the ground 6.00 s after it is launched. In SI units: (a) with what upward velocity is the rock shot, (b) what maximum height above the top of the building is reached by the rock, and (c) how tall is the building?

73 GO At the instant the traffic light turns green, an automobile starts with a constant acceleration a of 2.2 m/s². At the same instant a truck, traveling with a constant speed of 9.5 m/s, overtakes and passes the automobile. (a) How far beyond the traffic signal will the automobile overtake the truck? (b) How fast will the automobile be traveling at that instant?

74 A pilot flies horizontally at 1300 km/h, at height $h = 35$ m above initially level ground. However, at time $t = 0$, the pilot begins to fly over ground sloping upward at angle $\theta = 4.3^\circ$

(Fig. 2.26). If the pilot does not change the airplane's heading, at what time t does the plane strike the ground?

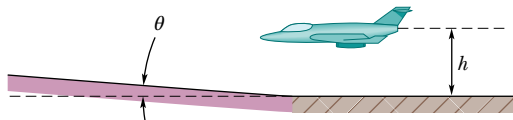


Figure 2.26 Problem 74.

75 GO To stop a car, first you require a certain reaction time to begin braking; then the car slows at a constant rate. Suppose that the total distance moved by your car during these two phases is 56.7 m when its initial speed is 80.5 km/h, and 24.4 m when its initial speed is 48.3 km/h. What are (a) your reaction time and (b) the magnitude of the acceleration?

76 GO FCP Figure 2.27 shows part of a street where traffic flow is to be controlled to allow a *platoon* of cars to move smoothly along the street. Suppose that the platoon leaders have just reached intersection 2, where the green light appeared when they were distance d from the intersection. They continue to travel at a certain speed v_p (the speed limit) to reach intersection 3, where the green appears when they are distance d from it. The intersections are separated by distances D_{23} and D_{12} . (a) What should be the time delay of the onset of green at intersection 3 relative to that at intersection 2 to keep the platoon moving smoothly?

Suppose, instead, that the platoon had been stopped by a red light at intersection 1. When the green comes on there, the leaders require a certain time t_r to respond to the change and an additional time to accelerate at some rate a to the cruising speed v_p . (b) If the green at intersection 2 is to appear when the leaders are distance d from that intersection, how long after the light at intersection 1 turns green should the light at intersection 2 turn green?

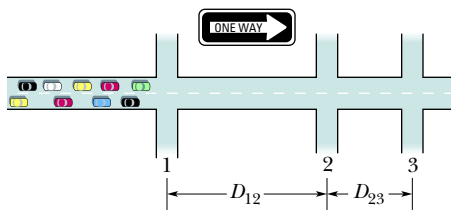


Figure 2.27 Problem 76.

77 SSM A hot rod can accelerate from 0 to 60 km/h in 5.4 s. (a) What is its average acceleration, in m/s^2 , during this time? (b) How far will it travel during the 5.4 s, assuming its acceleration is constant? (c) From rest, how much time would it require to go a distance of 0.25 km if its acceleration could be maintained at the value in (a)?

78 GO A red train traveling at 72 km/h and a green train traveling at 144 km/h are headed toward each other along a straight, level track. When they are 950 m apart, each engineer sees the other's train and applies the brakes. The brakes slow each train at the rate of 1.0 m/s^2 . Is there a collision? If so, answer yes and give the speed of the red train and the speed of the green train at impact, respectively. If not, answer no and give the separation between the trains when they stop.

79 GO At time $t = 0$, a rock climber accidentally allows a piton to fall freely from a high point on the rock wall to the valley below him. Then, after a short delay, his climbing partner, who is 10 m higher on the wall, throws a piton downward. The positions y of the pitons versus t during the falling are given in Fig. 2.28. With what speed is the second piton thrown?

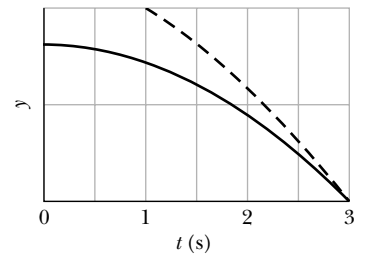


Figure 2.28 Problem 79.

80 A train started from rest and moved with constant acceleration. At one time it was traveling 30 m/s, and 160 m farther on it was traveling 50 m/s. Calculate (a) the acceleration, (b) the time required to travel the 160 m mentioned, (c) the time required to attain the speed of 30 m/s, and (d) the distance moved from rest to the time the train had a speed of 30 m/s. (e) Graph x versus t and v versus t for the train, from rest.

81 CALC SSM A particle's acceleration along an x axis is $a = 5.0t$, with t in seconds and a in meters per second squared. At $t = 2.0$ s, its velocity is +17 m/s. What is its velocity at $t = 4.0$ s?

82 CALC Figure 2.29 gives the acceleration a versus time t for a particle moving along an x axis. The a -axis scale is set by $a_s = 12.0 \text{ m/s}^2$. At $t = -2.0$ s, the particle's velocity is 7.0 m/s. What is its velocity at $t = 6.0$ s?

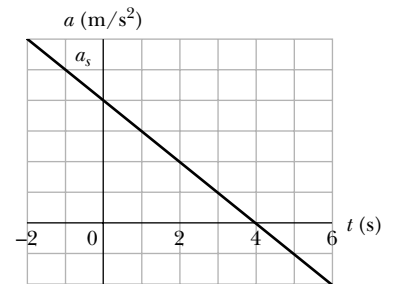


Figure 2.29 Problem 82.

83 BIO Figure 2.30 shows a simple device for measuring your reaction time.

It consists of a cardboard strip marked with a scale and two large dots. A friend holds the strip *vertically*, with thumb and forefinger at the dot on the right in Fig. 2.30. You then position your thumb and forefinger at the other dot (on the left in Fig. 2.30), being careful not to touch the strip. Your friend releases the strip, and you try to pinch it as soon as possible after you see it begin to fall. The mark at the place where you pinch the strip gives your reaction time. (a) How far from the lower dot should you place the 50.0 ms mark? How much higher should you place the marks for (b) 100, (c) 150, (d) 200, and (e) 250 ms? (For example, should the 100 ms marker be 2 times as far from the dot as the 50 ms marker? If so, give an answer of 2 times. Can you find any pattern in the answers?)

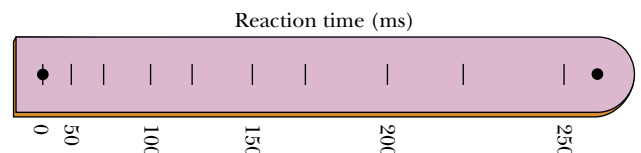


Figure 2.30 Problem 83.

84 BIO FCP A rocket-driven sled running on a straight, level track is used to investigate the effects of large accelerations on

humans. One such sled can attain a speed of 1600 km/h in 1.8 s, starting from rest. Find (a) the acceleration (assumed constant) in terms of g and (b) the distance traveled.

85 Fastball timing. In professional baseball, the *pitching distance* of 60 feet 6 inches is the distance from the front of the pitcher’s plate (or rubber) to the rear of the home plate. (a) Assuming that a 95 mi/h fastball travels that full distance horizontally, what is its flight time, which is the time a batter must judge if the ball is “hittable” and then swing the bat? (b) Research indicates that even an elite batter cannot track the ball for the full flight and yet many players have described seeing the ball–bat collision. One explanation is that the eyes track the ball in the early part of the flight and then undergo a *predictive saccade* in which they jump to an anticipated point later in the flight. A saccade suppresses vision for 20 ms. How far in feet does the fastball travel during that interval of no vision?

86 Measuring the free-fall acceleration. At the National Physical Laboratory in England, a measurement of the free-fall acceleration g was made by throwing a glass ball straight up in an evacuated tube and letting it return. Let ΔT_L in Fig. 2.31 be the time interval between the two passes of the ball across a certain lower level, ΔT_U the time interval between the two passages across an upper level, and H the distance between the two levels. What is g in terms of those quantities?

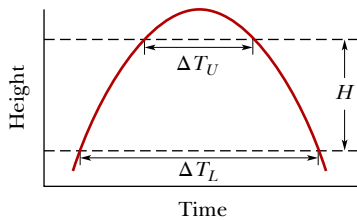


Figure 2.31 Problem 86.

87 CALC Velocity versus time. Figure 2.32 gives the velocity v (m/s) versus time t (s) for a particle moving along an x axis. The area between the time axis and the plotted curve is given for the two portions of the graph. At $t = t_A$ (at one of the crossing points in the plotted figure), the particle’s position is $x = 14$ m. What is its position at (a) $t = 0$ and (b) $t = t_B$?

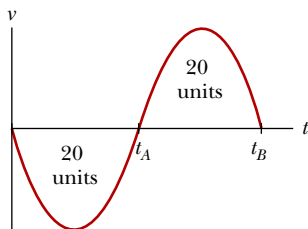


Figure 2.32 Problem 87.

88 CALC Hockey puck on frozen lake. At time $t = 0$, a hockey puck is sent sliding over a frozen lake, directly into a strong wind. Figure 2.33 gives the velocity v of the puck versus time,

as the puck moves along an x axis, starting at $x_0 = 0$. At $t = 14$ s, what is its coordinate?

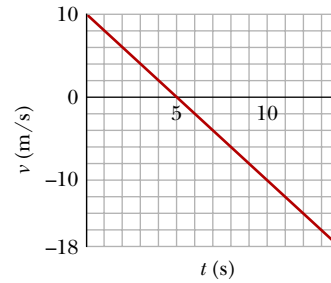


Figure 2.33 Problem 88.

89 Seafloor spread. Figure 2.34 is a plot of the age of ancient seafloor material, in millions of years, against the distance from a certain ocean ridge. Seafloor material extruded from that ridge moves away from it at approximately uniform speed. What is that speed in centimeters per year?

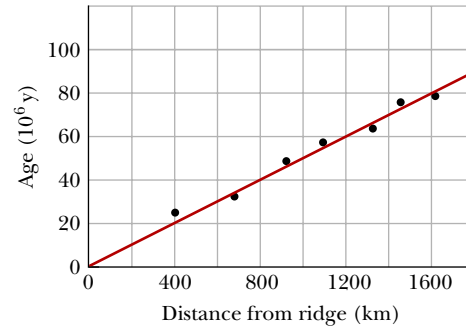


Figure 2.34 Problem 89.

90 Braking, no reaction time. Modern cars with a computer system using radar can eliminate the normal reaction time for a driver to recognize an upcoming danger and apply the brakes. For example, the system can detect the sudden stopping of a car in front of a driver by using radar signals that travel at the speed of light. Rapid processing then can almost immediately activate the braking. For a car traveling at $v = 31.3$ m/s (70 mi/h) and assuming a normal reaction time of 0.750 s, find the reduction in a car’s stopping distance with such a computer system.

91 100 m dash. The running event known as the 100 m dash consists of three stages. In the first, the runner accelerates to the maximum speed, which usually occurs at the 50 m to 70 m mark. That speed is then maintained until the last 10 m, when the runner slows. Consider three parts of the record-setting run by Usain Bolt in the 2008 Olympics: (a) from 10 m to 20 m, elapsed time of 1.02 s, (b) from 50 m to 60 m, elapsed time of 0.82 s, and (c) from 90 m to 100 m, elapsed time of 0.90 s. What was the average velocity for each part?

92 Drag race of car and motorcycle. A popular web video shows a jet airplane, a car, and a motorcycle racing from rest along a runway (Fig. 2.35). Initially the motorcycle takes the lead, but then the jet takes the lead, and finally the car blows past the motorcycle. Consider the motorcycle–car race. The

motorcycle's constant acceleration $a_m = 8.40 \text{ m/s}^2$ is greater than the car's constant acceleration $a_c = 5.60 \text{ m/s}^2$, but the motorcycle has an upper limit of $v_m = 58.8 \text{ m/s}$ to its speed while the car has an upper limit of $v_c = 106 \text{ m/s}$. Let the car and motorcycle race in the positive direction of an x axis, starting with their midpoints at $x = 0$ at $t = 0$. At what (a) time and (b) position are their midpoints again aligned?

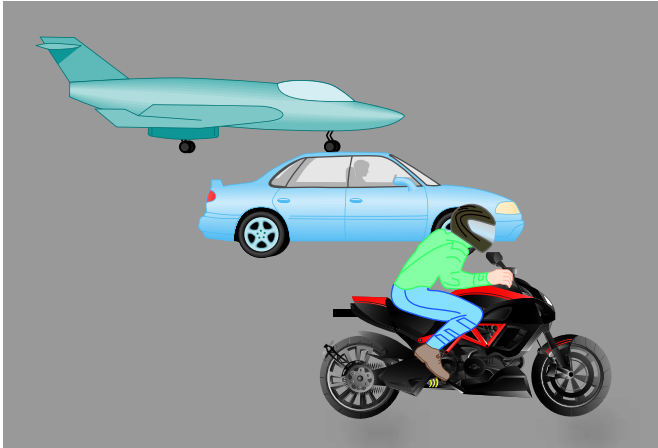


Figure 2.35 Problem 92.

93 Speedy ants. The silver ants of the Sahara Desert are the fastest ants in terms of their body length, which averages 7.92 mm . In the hottest part of the day, they run as fast as 0.855 m/s . In terms of body lengths per second, how fast do they run?

94 Car lengths in trailing. When trailing a car on a highway, you are advised to maintain a trailing distance that is often quoted in terms of car lengths, such as in “stay back by 3 car lengths.” Suppose the other car suddenly stops (it hits, say, a large stationary truck). Assume a car length L is 4.50 m , your car speed v_0 is 31.3 m/s (70 mi/h), your trailing distance is $nL = 10.0L$, and the acceleration magnitude at which your car can brake is 8.50 m/s^2 . What is your speed just before colliding with the other car if (a) your reaction time t_r to start braking is 0.750 s and (b) automatic braking is immediately started by your car's radar system that continuously monitors the road? What is the minimum value for n needed to avoid a collision with (c) the reaction time t_r and (d) automatic braking?

95 Speed limits. (a) The greatest speed limit in the United States is along the tolled section of Texas State Highway 130 where the limit is 85 mi/h . How much time would be saved in driving that 41 mi section at the speed limit instead of 60 mi/h ?

(b) The speed limit in residential areas is commonly 25 mi/h but some motorists drive at an average speed of 45 mi/h , perhaps by weaving through traffic and even driving through traffic lights that had just turned red. How much time would be saved in driving at that faster speed through 5.5 mi instead of the posted speed limit if the car does not stop at any intersections?

96 Autonomous car passing with following car. Figure 2.36a gives an overhead view of three cars with the same length $L = 4.50 \text{ m}$. Cars A and B are moving at $v_A = 22.0 \text{ m/s}$ (49 mi/h) along the right-hand lane of a long, straight road with two lanes in each direction, and car C is moving along the passing lane at $v_C = 27.0 \text{ m/s}$ (60 mi/h) at initial distance d behind B . Car B is autonomous and is equipped with a computer control system using radar to detect the speeds and distances of the other two cars. At time $t = 0$, the front of car B is $3.00L$ behind the rear of car A , which is at $x_{A1} = 0$ on the x axis. We want B to pull into the passing lane, speed up and pass A , and then pull back into the right-hand lane, $3.00L$ in front of A and at the initial speed. The computer control system will allow 15.0 s for the maneuver and only if the front of C will be no closer than $3.00L$ behind A at the end of the maneuver, as in Fig. 2.36b. What is the least value of d that the system will allow?

97 Freeway entrance ramps. When freeways were first built in the United States in the 1950s, entrance ramps were often too short for an entering car to safely merge into existing traffic. Consider an aggressive car acceleration of $a = 4.0 \text{ m/s}^2$ and an initial car speed of $v_0 = 25 \text{ mi/h}$ as the car enters the entrance ramp of a freeway where other cars are moving at 55 mi/h . (a) If the ramp has a length of $d = 40 \text{ yd}$, what is the car's speed v in miles per hour as it attempts to merge? (b) What is the minimum length d in yards needed for the car's speed to match the speed of the other cars?

98 Autonomous car passing with oncoming car. Figure 2.37a gives an overhead view of three cars with the same length $L = 4.50 \text{ m}$. Cars A and B are moving at $v_A = 22.0 \text{ m/s}$ (49 mi/h) along a long, straight road with one lane in each direction and car C is oncoming at $v_C = 27.0 \text{ m/s}$ (60 mi/h) at initial distance d in front of B . Car B is autonomous and is equipped with a computer and radar control system to detect the speeds and distances of the other two cars. At time $t = 0$, the front of car B is $3.00L$ behind the rear of car A , which is at $x_{A1} = 0$ on the x axis. We want B to pull into the other lane, speed up and pass A , and then pull back into the initial lane to be $3.00L$ in front of A and at the initial speed (Fig. 2.37b). The computer control system will allow 15.0 s for the maneuver but only if the front of C will be no closer than $10L$ in front of B at the end of the maneuver, as shown in the figure. What is the least value of d that the system will allow?

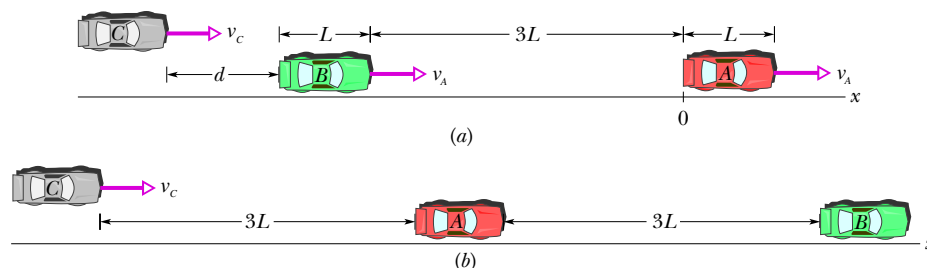


Figure 2.36 Problem 96.

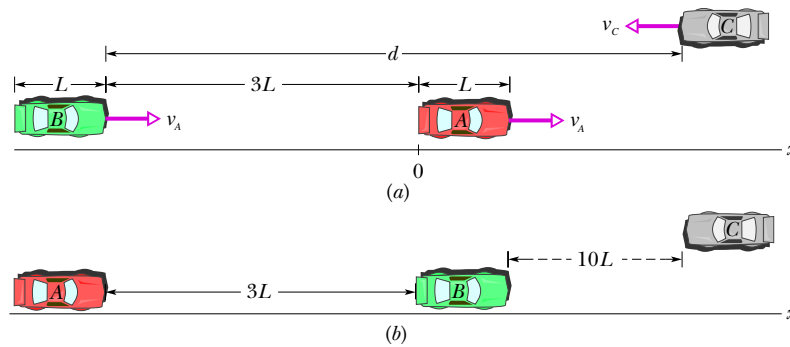


Figure 2.37 Problem 98.

99 Record accelerations. When Kitty O’Neil set the dragster records for the greatest speed and least elapsed time by reaching 392.54 mi/h in 3.72 s, what was her average acceleration in (a) meters per second squared and (b) g units? When Eli Beeding, Jr., reached 72.5 mi/h in 0.0400 s on a rocket sled, what was his average acceleration in (c) meters per second squared and (d) g units? For each person, assume the motion is in the positive direction of an x axis.

100 Travel to a star. How much time would be required for a starship to reach Proxima Centauri, the star closest to the Sun, at a distance of $L = 4.244$ light years (ly)? Assume that it starts from rest, maintains a comfortable acceleration magnitude of $1.000g$ for the first 0.0450 y and a deceleration (slowing) magnitude of $1.000g$ for the last 0.0450 y, and cruises at constant speed in between those periods.

101 CALC Bobsled acceleration. In the start of a four-person bobsled race, two drivers (a pilot and a brakeman) are already on board while two pushers accelerate the sled along the ice by pushing against the ice with spiked shoes. After pushing for 50 m along a straight course, the pushers jump on board. The acceleration during the pushing largely determines the time to slide through the rest of the course and thus decides the winner with the least run time, which often depends on differences of 1.0 ms. Consider an x axis along the 50 m, with the origin at the start position. If the position x versus time t in the pushing phase is given by $x = 0.3305t^2 + 4.2060t$ (in meters and seconds), then at the end of a 9.000 s push what are (a) the speed and (b) the acceleration?

102 Car-following stopping distance. When you drive behind another car, what is the minimum distance you should keep between the cars to avoid a rear-end collision if the other car were to suddenly stop (it hits, say, a stationary truck)? Some drivers use a “2 second rule” while others use a “3 second rule.” To apply such rules, pick out an object such as a tree alongside the road. When the front car passes it, begin to count off seconds. For the first rule, you want to pass that object at a count of 2 s, and for the second rule, 3 s. For the 2 s rule, what is the resulting car–car separation at a speed of (a) 15.6 m/s (35 mi/h, slow) and (b) 31.3 m/s (70 mi/h, fast)? For the 3 s rule, what is the car–car separation at a speed of (c) 15.6 m/s and (d) 31.3 m/s? To check if the results give safe trailing distances, find the stopping distance required of you at those initial speeds. Assume that your car’s braking acceleration is -8.50 m/s^2 and your reaction time to apply the brake upon seeing the danger is 0.750 s. What is your stopping distance at a speed of (e) 15.6 m/s and (f) 31.3 m/s? (g) For which is the 2 s rule adequate? (h) For which is the 3 s rule adequate?

103 Vehicle jerk indicating aggression. One common form of aggressive driving is for a trailing driver to repeat a pattern of accelerating suddenly to come close to the car in front and then braking suddenly to avoid a collision. One way to monitor such behavior, either remotely or with an onboard computer system, is to measure *vehicle jerk*, where jerk is the physics term for the time rate of change of an object’s acceleration along a straight path. Figure 2.38 is a graph of acceleration a versus time t in a typical situation for a car. Determine the jerk for each of the time periods: (a) gas pedal pushed down rapidly, 2.0 s interval, (b) gas pedal released, 1.5 s interval, (c) brake pedal pushed down rapidly, 1.5 s interval, (d) brake pedal released, 2.5 s interval.

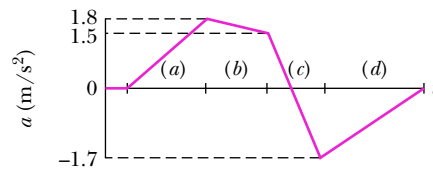


Figure 2.38 Problem 103.

104 Metal baseball bat danger. Wood bats are required in professional baseball but metal bats are sometimes allowed in youth and college baseball. One result is that the *exit speed* v of the baseball off a metal bat can be greater. In one set of measurements under the same circumstances, $v = 50.98 \text{ m/s}$ off a wood bat and $v = 61.50 \text{ m/s}$ off a metal bat. Consider a ball hit directly toward the pitcher. The regulation distance between pitcher and batter is $\Delta x = 60 \text{ ft } 6 \text{ in.}$ For those measured speeds, how much time Δt does the ball take to reach the pitcher for (a) the wood bat and (b) the metal bat? (c) By what percentage would Δt be reduced if professional baseball switched to metal bats? Because pitchers do not wear any protective equipment on face or body, the situation is already dangerous and the switch would add to that danger.

105 Falling wrench. A worker drops a wrench down the elevator shaft of a tall building. (a) Where is the wrench 1.5 s later? (b) How fast is the wrench falling just then?

106 Crash acceleration. A car crashes head on into a wall and stops, with the front collapsing by 0.500 m. The driver is firmly held to the seat by a seat belt and thus moves forward by 0.500 m during the crash. Assume that the acceleration is constant during the crash. What is the magnitude of the driver’s acceleration in g units if the initial speed of the car is (a) 35 mi/h and (b) 70 mi/h?

107 Billboard distraction. Highway billboards have long been a possible source of driver distraction, especially the modern

electronic billboards with moving parts or with flipping from one scene to another within a few seconds. If you are traveling at 31.3 m/s (70 mi/h), how far along the road do you move if you look at a colorful and animated billboard for (a) 0.20 s (a glancing look), (b) 0.80 s, and (c) 2.0 s? Answer in both meters and in yards (to give you a feel for how your travel would be along an American football field).

108 BIO CALC *Remote fall detection.* Falling is a chronic danger to the elderly and people subject to seizure. Researchers search for ways to detect a fall remotely so that a caretaker can go to the victim quickly. One way is to use a computer system that analyzes the motions of someone on CCTV in real time. The system monitors the vertical velocity of someone and then calculates the vertical acceleration when that velocity changes. If the system detects a large negative (downward) acceleration followed by a briefer positive acceleration and accompanied by a sound burst for the onset of the positive acceleration, a signal is sent to a caretaker. Figure 2.39 gives an idealized graph of vertical velocity v versus time t as determined by the system: $t_1 = 1.0$ s, $t_2 = 2.5$ s, $t_3 = 3.0$ s, $t_4 = 4.0$ s, $v_1 = -7.0$ m/s. (The plot on a more realistic graph would be curved.) What are (a) the acceleration during the descent and (b) the upward acceleration during the impact with the floor?

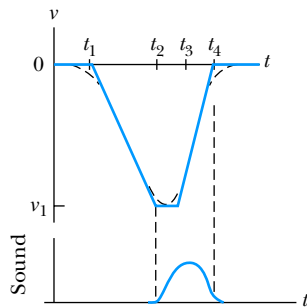


Figure 2.39 Problem 108.

109 *Ship speed in knots.* Before modern instrumentation, a ship's speed was measured with a line that had small knots tied along its length, separated by 47 feet 3 inches. The line was attached by three cords to a wood plate (a *clip log*) in the shape of a pie slice as shown in Fig. 2.40. One sailor threw the plate overboard and then allowed the force of the water against the plate to pull the line off a reel and through his hand so that he could detect the periodic passage of knots. Another sailor inverted a sandglass so that sand flowed from its upper chamber into the lower chamber in 28 s. During that interval the first sailor counted the number of knots passing through his hand. The result was the ship's speed in knots (abbreviated as kn). If 17 knots passed, what was the ship's speed in (a) knots, (b) miles per hour, and (c) kilometers per hour?

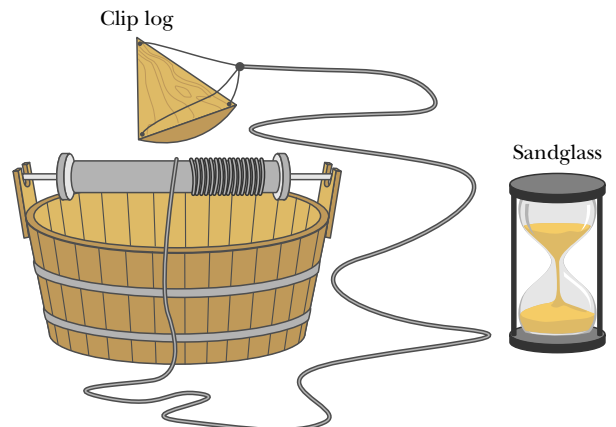


Figure 2.40 Problem 109.