McGraw-Hill Ryerson

Physics 11

CHAPTER 1 Physics: The Science of Matter and Energy

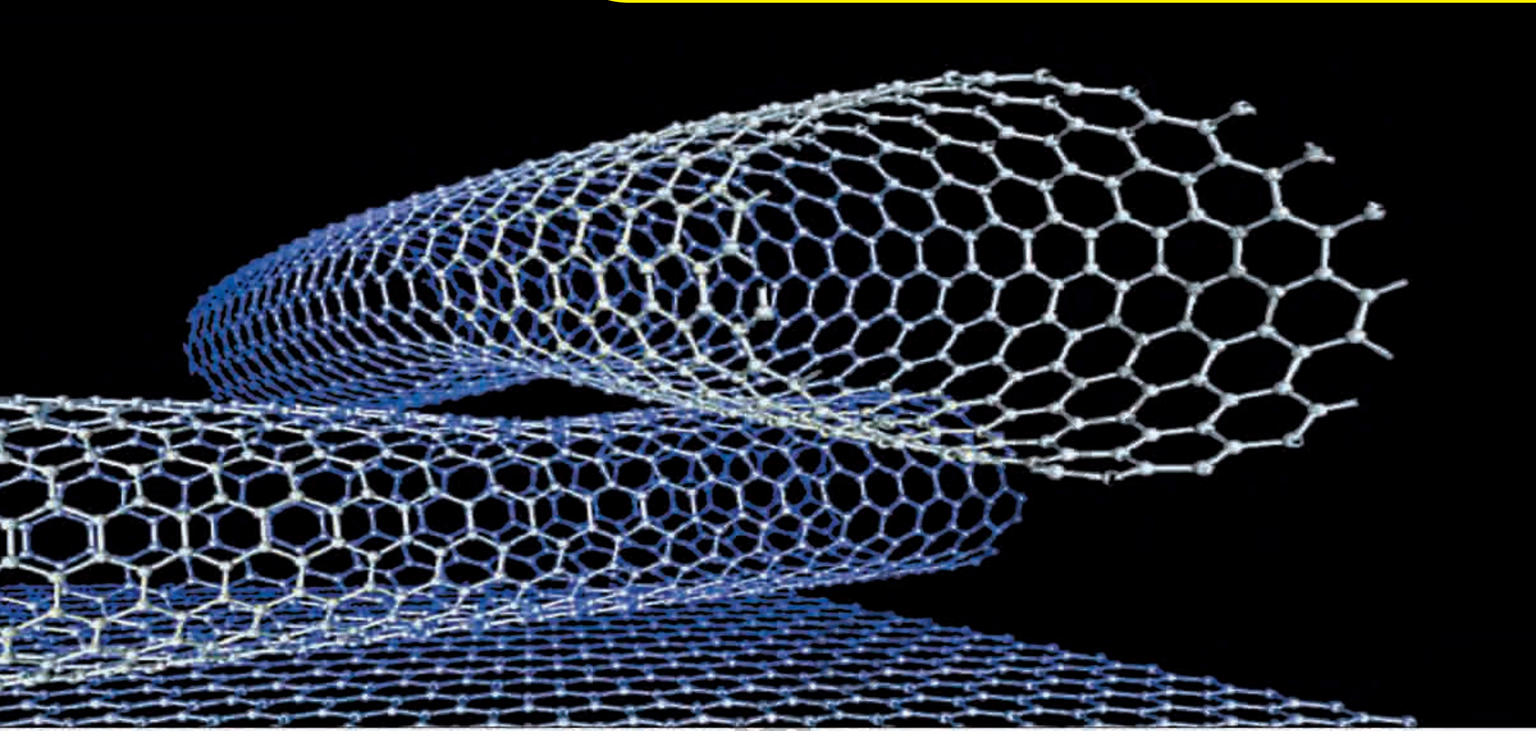
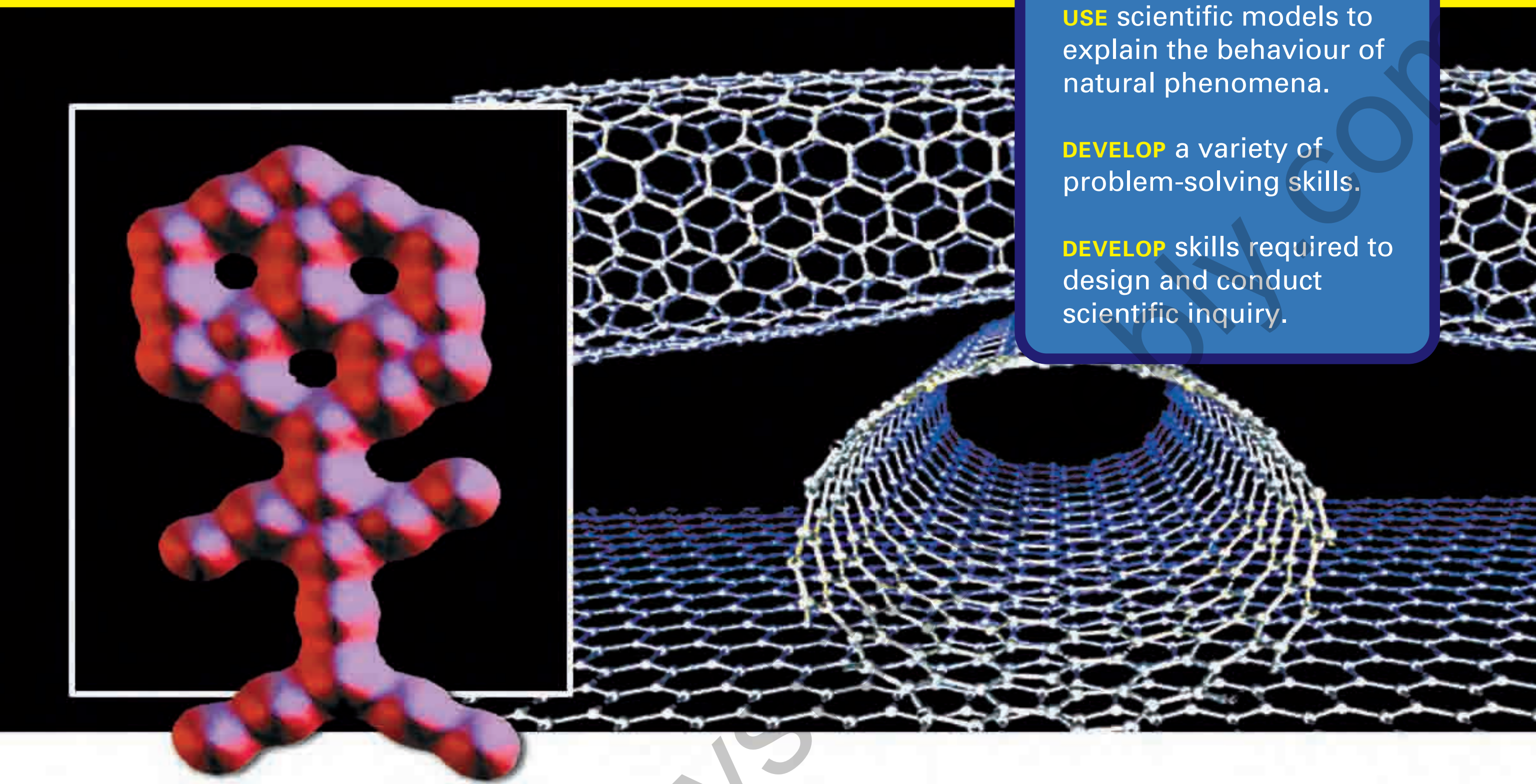


Image courtesy of IBM Research

CHAPTER CONTENTS

You are looking at two different views of a computer-generated model of a carbon nanotube — a straw on an atomic scale. Built one carbon atom at a time, this nanotube is a pioneering example of a new class of machines, so tiny they cannot be seen by the unaided eye, or even through most microscopes. Extraordinarily strong, yet only a few atoms in diameter, minuscule devices like this one may dramatically alter our lives in the years to come. In fact, some leading researchers believe the "nano age" has already begun. The inset "molecule man" made of 28 carbon monoxide molecules, and the "guitar" shown on page 10 are the results of researchers having fun with nanotechnology.

Nanotechnology, the emerging science and technology of building mechanical devices from single atoms, seeks to control energy and movement at an atomic level. Once perfected, nanotechnology would permit microscopic machines to perform complex tasks atom-by-atom, molecule-by-molecule. Imagine a tiny robotic device that could be programmed to produce specific products, like paper or steel, simply by extracting the required atoms from the atmosphere, in much the same way a potato plant absorbs nutrients from the soil, water, and air, and reorganizes them to create more potatoes.



OVERALL EXPECTATIONS

USE scientific models to explain the behaviour of natural phenomena.

DEVELOP a variety of problem-solving skills.

DEVELOP skills required to design and conduct scientific inquiry.

Imagine if a machine could produce diamonds by rearranging atoms of coal or produce fresh water by coupling atoms of hydrogen and oxygen. What if such a machine could be programmed to clean the air by rearranging atoms in common pollutants, or heal the sick by repairing damaged cells? It is difficult even to begin to understand the impact such technology could have on our everyday lives, and on the countless chemical, biological, and physical relationships and processes that govern our world. However, one thing is certain: nanotechnology represents a new way of harnessing and transforming matter and energy, making it an important application of the science we call physics.

Throughout this course you will be involved in the processes of doing physics. You will be asking questions, forming hypotheses, designing and carrying out investigations, creating models and using theories to explain your findings, and solving problems related to physics. In short, you will be learning to think like a physicist. The activities in this course will be carried out at many levels of sophistication. In science, as well as in other disciplines, the simplest questions and investigations often reveal the most interesting and important answers.

Web Link

www.school.mcgrawhill.ca/resources/

To learn more about nanotechnology and view pictures of nanomachines, go to the above site. Click on **Science Resources** and **Physics 11** to find out where to go next.

MULTI LAB

Think Physics!

TARGET SKILLS
- Predicting
- Hypothesizing
- Performing and recording
- Modelling concepts
- Analyzing and interpreting
- Communicating results

An important part of physics is creating models that allow us to develop explanations for phenomena. Models are helpful in making predictions based on observations. Try the following labs, creating your own models and making your own predictions based on what you already know. Keep these definitions in mind as you proceed.

Black Box

Pull the strings on the black box and observe what happens. Try several combinations, noting the motion and tension of the strings, any noises you hear, and anything else that strikes you. Record your observations.

1. Based on your observations, draw a model showing how you think the strings are connected inside the black box.
2. Test the accuracy of your prediction by once again pulling the strings on the black box.
3. How can this experiment be used to explain the process of scientific inquiry?

Beach Ball

With a partner, observe what happens to a beach ball when you throw it back and forth while applying various spins. Record your observations.

1. Describe the effects of each spin.
2. Draw a model representing what you observed.

Van de Graaff Generator

Place scraps of paper from a 3-hole punch onto the Van de Graaff generator as shown. Switch on the generator and observe what happens. Record your observations.

1. Based on your observations, draw a model showing what happened to the paper.

Super Ball

Drop a super ball from a specific height. Conduct several trials, changing variables like the initial velocity of the ball and its rate of spin. Record your observations. Then, develop rules that will allow you to predict whether the ball, based on its initial velocity and rate of spin, will bounce to a height above its starting point.

1. Test your predictions.
2. Describe the motion of the super ball using a model about the conservation of energy.

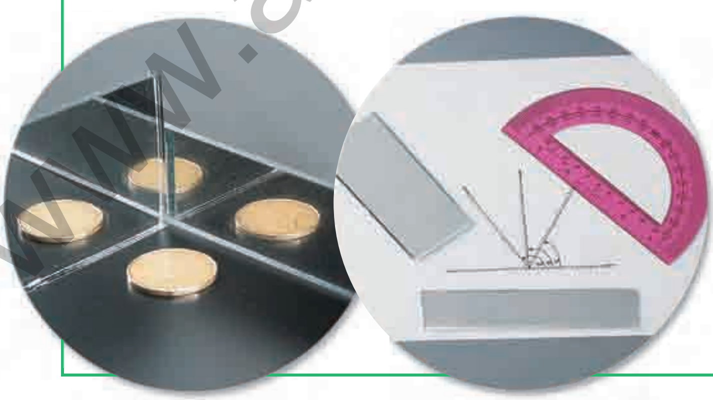
Radiometer

Shine a light on the radiometer and observe what happens. Repeat the process using a hair dryer on cool and hot settings. Record your observations.

1. What causes the vanes to spin? Formulate a hypothesis.
2. How was the energy transferred?
3. What similarities exist between heat and light?
4. Test your hypothesis.

Multiple Images with Two Plane Mirrors

Use a protractor to create a template similar to the one shown. Set up the mirrors and coin as shown. Then, create a table like this one. Count the number of images you see when the mirrors are set to specific angles. Record your observations.



Number of objects	Angle between mirrors	Number of images
1	180°	
1	120°	
1	90°	
1	60°	

1. Develop a mathematical equation that predicts the number of images that will appear when the angle between the plane mirrors is known. Hint: there are 360° in a circle.

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Go to the above web site for other Quick Labs to help you get started. Click on **Science Resources** and then **Physics 11.**

1.1 Physics: A Window on the Universe

SECTION EXPECTATIONS

- Use appropriate scientific models to explain and predict the behaviour of natural phenomena.
- Identify and describe science- and technology-based careers related to physics.

KEY TERMS

- physics
- scientific inquiry
- observation
- qualitative
- quantitative
- theory
- model

MISCONCEPTION

From X-rays to Nerve Impulses

Many people think that physics is very difficult and highly mathematical. While mathematics is very much a part of physics, the basics of physics need not be difficult to understand. No matter what field of study is most interesting to you, it is likely that physics concepts will help you better understand some facet of it. You may be especially interested in another science, such as biology or chemistry. As your study of science progresses, you will discover that each science depends on the others. For example, chemists use X-rays to study the structure of large molecules. Biologists use the theory of electricity to study the transmission of nerve impulses.

What makes physics so exciting is that you will be involved in thinking about how the universe works and why the universe behaves as it does. When asked to define science, Albert Einstein once replied, "science is nothing more than refinement of everyday thinking." If you substitute "physics" for "science" in Einstein's definition, just what is the refinement he is referring to? Using the language of mathematics to construct models and theories, **physics** attempts to explain and predict interactions between matter and energy. In physics, the search for the nature of these relationships takes us from the submicroscopic structure of the atom to the supermacroscopic structure of the universe. All endeavours in physics, however, have one thing in common; they all aim to formulate fundamental truths about the nature of the universe.

Your challenge in this course will be to develop a decision-making process for yourself that allows you to move from Einstein's "everyday thinking" to his "refinement of everyday thinking." This refinement, the systematic process of gathering data through observation, experimentation, organizing the data, and drawing conclusions, is often called **scientific inquiry**. The approach begins with the process of hypothesizing. A good scientist tries to find evidence that is *not* supported by a model. If contradictory evidence is found, the model was inadequate.

Throughout the textbook, you will find scientific misconceptions highlighted in the margins. See if your current thinking involves some of these misconceptions. Then, by exploring physics through experimentation throughout the course, develop your own understanding.

How did our present understanding of the universe begin? What was the progress over the centuries before present time? The thinking that we know about started with Artistotle.

Two Models from Aristotle

Over 2300 years ago, two related models were used as the basis for explaining why objects fall and move as they do. Aristotle (384–328 B.C.E.) used one model to account for the movement of objects on Earth, and a second model (see the diagram opposite) for the movement of stars and planets in the sky. We do not accept these models today as the best interpretation of movement of objects on Earth and in space. However, at the time they were very intelligent ways to explain these phenomena as Aristotle observed them.

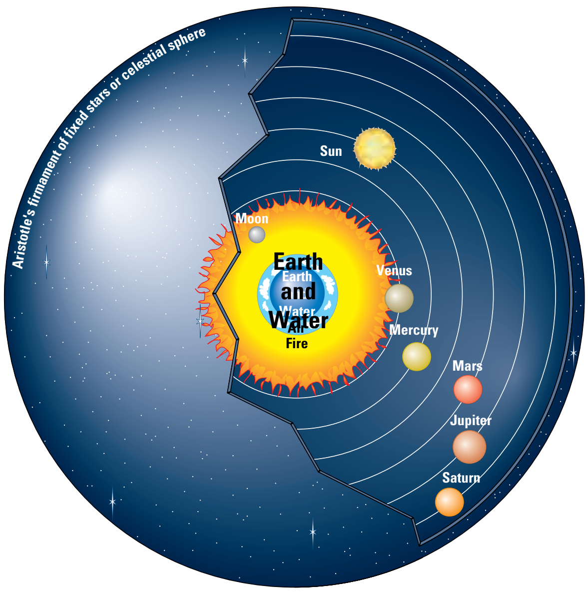

Figure 1.1 In Aristotle's cosmology, Earth is at the centre of the universe.

Aristotle and Motion

The model for explaining movement on Earth was based on a view advanced by the Greeks, following Aristotle's thinking. Aristotle accepted the view of Empedocles (492–435 B.C.E.) that everything is made of only four elements or essences — earth, water, air, and fire. All objects were assumed to obey the same basic rules depending on the essences of which they were composed. Each essence had a natural place in the cosmic order. Earth's position is at the bottom, above that is water, then air and fire. According to this model, every object in the cosmos is composed of varous amounts of these four elements. A stone is obviously earth. When it is dropped, a stone falls in an attempt to return to its rightful place in the order of things. Fire is the uppermost of the essences. When a log burns, the fire it trapped from the sun while it was growing is released and rises back to its proper place. Everything floats, falls, or rises in order to return to its proper place in the world, according to Aristotle. These actions were classified as natural motions. When an object experiences a force, it can move in directions other than the natural motions that return them to their natural position. A stone can be made to move horizontally or upward by exerting a force in the desired direction. When the force stops so does the motion.

The model for explaining movement in the sky was somewhat different. Greek astronomers knew that there were two types of "stars," the fixed stars and the planets (or wanderers), as well as the Sun and the Moon. These objects seemed not to be bound by the same rules as objects formed of the other essences. They

PHYSICS FILE

Richard Feynman (1918–1988), a Nobel Prize winner and the father of nanotechnology, was one of the most renowned physicists of the twentieth century. In 1959, while presenting a paper entitled "There's Plenty of Room at the Bottom" on the then little-known characteristics of the submicroscopic world, Feynman remarked: "There is nothing besides our clumsy size that keeps us from using [that] space." When he spoke those words, nanotechnology was still a distant dream. That dream now appears to be verging on reality. Indeed, twenty-first century medicine and computer science could well see the first applications of nanotechnology, as both disciplines race to develop tools that will one day allow them to manipulate individual atoms.

TRY THIS...

Physics in the News

Using print and electronic resources, research a current or historical article that discusses some aspect of physics. Summarize the article in two or three paragraphs, highlighting why you think the topic is significant. Provide as much information about the source of the article as possible.

Language Link

Even today the term quintessence (fifth essence) has come to mean on the highest plane of existence. Use the term, quintessence, or its adjectival form, quintessential, to describe an important event or person in your own life.

moved horizontally across the sky without forces acting on them. The Greeks placed them in a fifth essence of their own. All objects in this fifth essence were considered to be perfect. The Moon, for example, was assumed to be a perfect sphere. Aristotle's model assumes that perfect crystal, invisible spheres existed, supporting the celestial bodies.

Later, when Ptolemy (87–150 C.E.) developed his Earth-centred universe model, he used this idea as a base and expanded upon it to include wheels within wheels in order to explain why planets often underwent retrograde (backward) motion. A single spherical motion could explain only the motions of the Sun and the Moon.

To European cultures, Aristotle's two models were so successful that for almost 2000 years people accepted them without question. They remained acceptable until challenged by the revolutionary model of Copernicus (1473–1543) and the discoveries of Galileo Galilei (1564–1642).

Figure 1.2 The telescope through which Galileo first observed Jupiter's moons and other celestial bodies in our solar system.

Galileo and Scientific Inquiry

In 1609, using a primitive telescope (Figure 1.2), Galileo observed that the Moon's surface was dotted with mountains, craters, and valleys; that Jupiter had four moons of its own; that Saturn had rings; that our galaxy (the Milky Way) comprised many more stars than anyone had previously imagined; and that Venus, like the Moon, had phases. Based on his observations, Galileo felt he was able to validate a revolutionary hypothesis — one advanced previously by Polish astronomer Nicolaus Copernicus — which held that Earth, along with the other planets in the Solar System, actually orbited the Sun.

What the Greeks had failed to do was test the explanations based on their models. When Galileo observed falling bodies he noted that they didn't seem to fall at significantly different rates. Galileo built an apparatus to measure the rate at which objects fell, did the experiments, and analyzed the results. What he found was that all objects fell essentially at the same rate. Why had the Greeks not found this? Quite simply, the concept of testing their models by experim entation was not an idea they found valuable, or perhaps it did not occur to them.

Since Galileo's time, scientists the world over have studied problems in an organized way, through observation, systematic experimentation, and careful analysis of results. From these analyses, scientists draw conclusions, which they then subject to additional scrutiny in order to ensure their validity.

As you progress through this course, keep the following ideas about theories, models, and observations in mind. Use them to stimulate your own thinking, and questioning about current ideas.

Think It Through

- A log floats partially submerged on the surface of a lake. The log is obviously wood, a material which clearly grows out of the essence "earth" and is a fairly dense solid like other earth objects. If you were an ancient Greek who believed in the Aristotelian Cosmology, how could you explain why the log floats rather than sinking like rocks or other earth materials?

Thinking about Science, Technology, Society and the Environment

In the middle of the twentieth century, scientific progress seemed to go forward in leaps and bounds. The presence of figures like Albert Einstein gave science in general, and physics in particular, an almost mystical aura. Too often physics was seen as a pure study isolated from the "real" world. Contrary to that image, science is now viewed as part of the world and has the same responsibilities, perhaps even greater, to the world as any other form of endeavour. Everything science does has a lasting impact on the world. Part of this course is to explore the symbiotic relationship that exists between science, technology, society and the environment (STSE).

To many people, science and technology are almost one and the same thing. There is no doubt that they are very closely related. New discoveries in science are very quickly picked up by technology and vice versa. For example, once thought of as a neat but rather impractical discovery of physics, the laser is a classic example of how science, technology, society, and the environment are inseparable. The laser's involvement in our lives is almost a daily occurrence. Technology has very quickly refined and improved its operation. Today, laser use is widespread. Supermarket scanners, surveying, communications, holography, metal cutters, surgery, and the simple laser pointer are just a few examples of the innovations that technology has found for the laser. Clearly it would be impossible to separate the importance of science and technology to society. Figure 1.3 on the following page shows just a sfew of the many applications of physics in today's world.

Often the same developments have both positive and negative impacts. Our society's ever increasing demand for energy has strained our environment to its limits. Society, while demanding more and more energy, has also demanded that science and technology find alternate sources of energy. This has led to the technological development of nuclear, solar, wind, hydro, geothermal, and fossil fuel as energy sources. Society's and the environment's relationship with science and technology seems to be a two-edged sword.

TRY THIS...

Was Aristotle Right?

Do heavy objects fall faster than lighter ones? Drop an eraser and a sheet of paper simultaneously from about eye level to the floor. Which gets there first? Is there anything about the motion of the paper that makes you think that this was not a good test? Now crumple the paper up into a small ball and repeat the experiment. Is there a significant difference in the time they take to reach the floor? Describe the variables that you attempted to test.

PHYSICS FILE

Aristotle's models had been used to explain the nature of falling for centuries. According to Aristotle, since a large rock has more of the essence "earth" in it than a small one it has a greater tendency to return to the ground. This causes the big rock to weigh more and thus it must fall faster than a small rock. This is a classic application of a model to explain a phenomenon. However, it should not surprise you to find that since the model is in error so is the explanation based on the model.

Web Link

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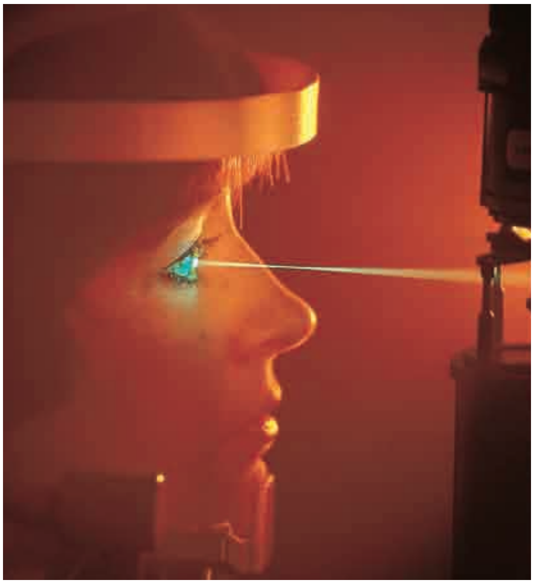
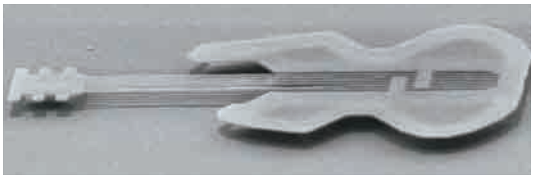
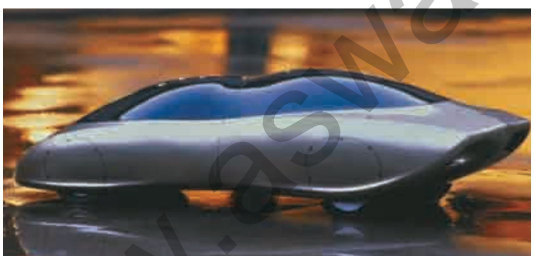
Figure 1.3 Some applications of physics discoveries



Laser eye surgery is one of many applications that technology has found for lasers.



This tiny "guitar" (about the size of a red blood cell) was built using nanotechnology. This technology will help scientists explore the processes by which atoms and molecules can be used individually as sub-microscopic building blocks.



Hybrid autos that run on both electricity and gasoline can greatly reduce pollution. Cars built of carbon composite materials are lighter and stronger than cars made of traditional materials. Computer-controlled ignition and fuel systems increase motor efficiency. All these factors can assist in protecting the environment.

Physics research into thermal properties of materials and technological advances in structural design have combined to produce energy efficient houses that greatly reduce our demand for heating fuels.

Innovations in technology have resulted in the ability to put more and more powerful computers into smaller and smaller spaces.

Technology reaches into the most mundane aspects of our lives. Micro-layers of Teflon™ on razor blades make them slide more smoothly over the skin.

Thinking Scientifically

Knowledge begins with observations and curiosity. Scientists organize their thinking by using observations, models, and theories, as summarized below.

Theory

A **theory** is a collection of ideas, validated by many scientists, that fit together to explain and predict a particular natural phenomenon. New theories often grow out of old ones, providing fresh, sometimes radical ways of looking at the universe. One such example, still in the process of development, is the GUT, or Grand Unified Theory, being sought by researchers across the different fields of physics. Through the GUT, physicists hope one day to be able describe all physical phenomena in the universe by using the same set of laws.

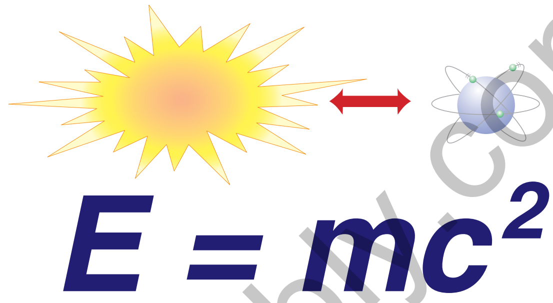


Figure 1.4 You have undoubtedly heard of Einstein's theory of special relativity. One part of the theory states that the speed of light, c, is the only thing in the universe that is constant. All other measurements are relative, depending on the observer's frame of reference. The famous formula (model) associated with the theory is $E = mc^2$.

Model

A **model** is a representation of phenomena and can come in a variety of forms, including a list of rules, pencil lines on a piece of paper, an object that can be manipulated, or a mathematical formula. An observation may be explained using more than one model; however, in most cases, one model type is more effective than others.

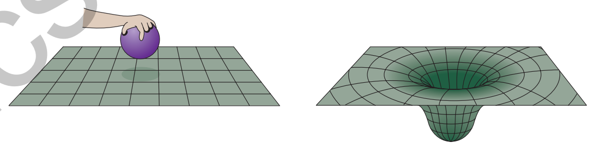


Figure 1.5 This "rubber sheet model" is often used to simulate Albert Einstein's idea of curved space. The model shows that a central mass can cause the space around the mass to curve.

Observations

An **observation** is information gathered by using one or more of the five senses. Observations may yield a variety of explanations, as participants in the same event often report different things. It takes hundreds of observations of a single phenomenon to develop a theory. There are two kinds of observations that can be made. The first are **qualitative**, which describe something using words: "A feather is falling slowly to the ground." The second are **quantitative**, which describe something using numbers and units: "The rock fell at 2 m/s."

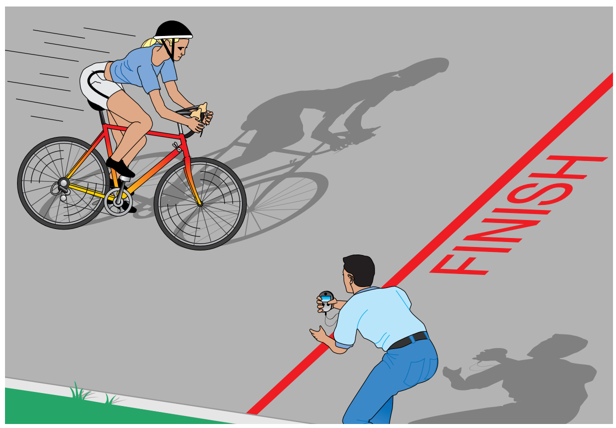
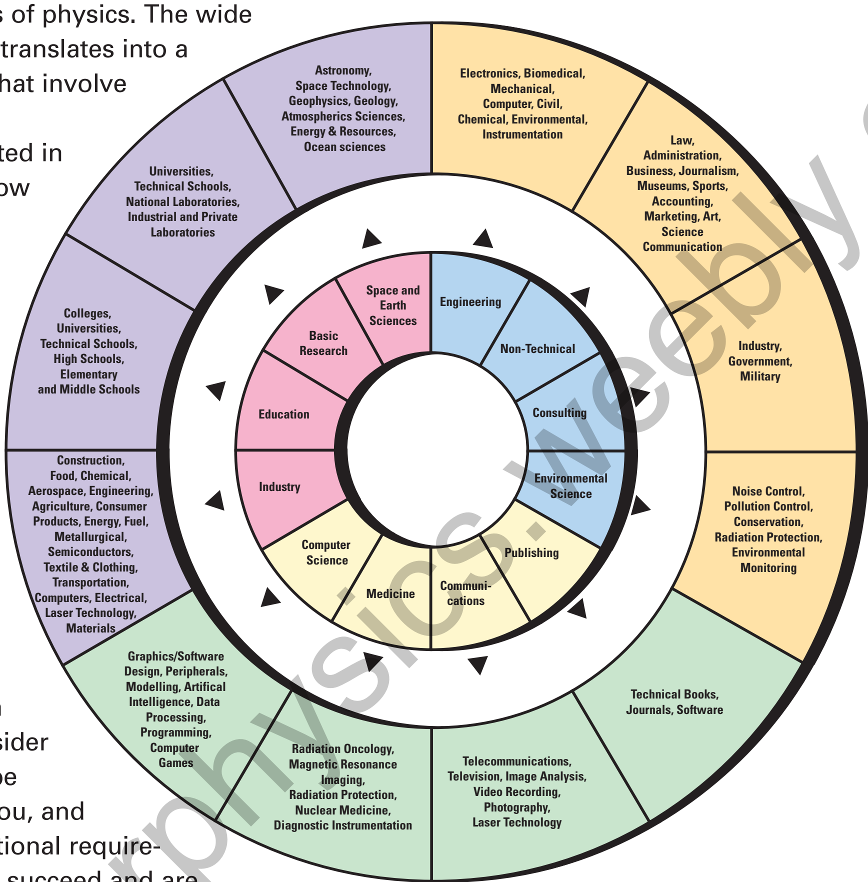


Figure 1.6 Observations can be quantitative or qualitative. The cyclist can determine her speed by applying the mathematical model, $v = \Delta d/\Delta t$, to her observable data of distance and time.

CAREERS IN PHYSICS

TARGET SKILLS
- Initiating and planning
- Conducting research

As you have read in this introductory section to the chapter, your world, from the natural cycles of weather to the high-tech gadgets of communication, relies on basic principles of physics. The wide scope of what physics is translates into a very long list of careers that involve the study of physics. For example, are you interested in theatre? Knowledge of how light acts is crucial to the intricate lighting techniques used in theatres today. Are you a musician? You will be able to achieve better musical effects by understanding more about the nature of sound. Study the diagram shown here to note career opportunities in physics that use much of the knowledge and skills you will gain in this physics course. Consider one or more that might be especially appealing to you, and begin research on educational requirements to attain it. People succeed and are happiest when in a career that really interests them, not just one they are good at, so keep that in mind as you explore opportunities.



1.1 Section Review

1. MC What is nanotechnology? Cite specific examples of how this technology could affect our lives.
2. C How would you define physics?
3. K/U Why do scientists employ scientific inquiry to investigate problems?
4. K/U What is the difference between a theory, a model, and an observation? What is the significance of each?
5. C Describe the difference between qualitative and quantitative observations, and provide an example of each.

1.2 Strategies for Problem-Solving Success

Problem-solving skills are important in everyday life, in school, and in the workplace. Some problems, like deciding whether to walk or ride your bike, are easier to solve than others. In each case, however, you develop a process to help you make up your mind. In physics, understanding a concept is more important than simply doing the math; hence, the need for creativity and adaptability. As you apply the problem-solving strategies contained in this textbook, remember that your answer to any one question is less important than the reasoning you use.

SECTION EXPECTATIONS

- Select and use appropriate numeric, symbolic, graphical, and linguistic modes of representation to communicate science.
- Analyze and synthesize information in the process of developing problem-solving skills.

KEY TERMS

- framing a problem

Figure 1.7 Chess is a game of intricate strategy. Victory belongs to the player who can visualize how the game will progress several moves into the future.

Framing A Problem

Framing a problem is a way to set parameters (important boundaries) and organize them in a way best suited to a particular problem. There is rarely only one way to frame a problem, and how you do so depends on each situation; you must determine which methods work best for you, and for each problem. Often, simply framing a problem will help the solution to become apparent to you.

Framing a problem, whether it is a physics question or a typical household problem, is a creative and systematic process designed to clarify what is known, what restrictions exist, and what the ultimate goal is. Most people have a preferred method of organizing information. Often the method used to organize information is topic specific rather than personal preference.

Figure 1.9 Framing a problem and developing solution strategies is applicable to all types of problems.

Figure 1.8 Recognizing the modes of organization that you prefer will help you develop your problem-solving strategies.

Example 1: Organizing Data Using Text

You can represent your thinking process in the form of questions.

In this way, you have framed the problem by posing key questions about your available time. Your solution must fit within these parameters.

A Typical Problem

A friend calls you on a Tuesday evening at 6:00 p.m. and asks if you want to join two other friends for two-and-a-half hours of "down time," to play an ongoing game you have all been enjoying. Your friends plan to begin at 7:30 p.m. You know that you have two homework assignments that must be completed before tomorrow. Before you are able to answer, you need to decide if you have enough time to complete your homework and to take time out to play the game. You also need to prioritize your feelings about the benefits of taking time out to play the game.

This scenario has been framed graphically using different strategies. As you examine them, consider their effectiveness. Develop your own strategies for framing problems, and for setting parameters that work best for you.

(a) Written Text

I feel like playing the game. It would be an enjoyable break, but I also have two homework assignments due in the morning. How long do my friends intend to play the game? Two-and-a-half hours. How much time do my assignments require? Physics: thirty minutes. Math: no homework tonight. English: thirty minutes. I should be home by 11:00.

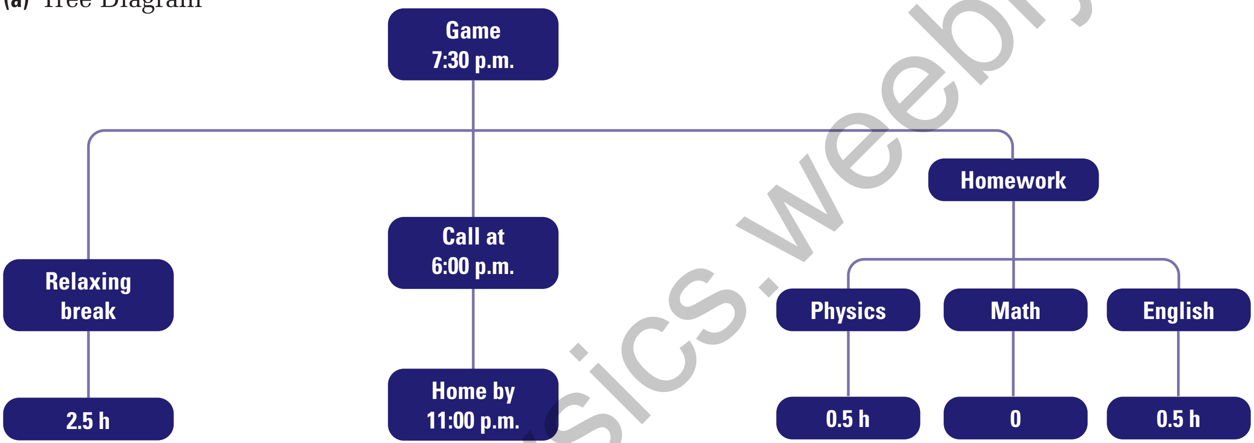
(b) Bulleted List

- Ongoing game
- Fun, and provides a break
- Homework to do
- Thirty minutes of Physics homework
- Thirty minutes of English
- Two-and-a-half hours
- Home by 11:00

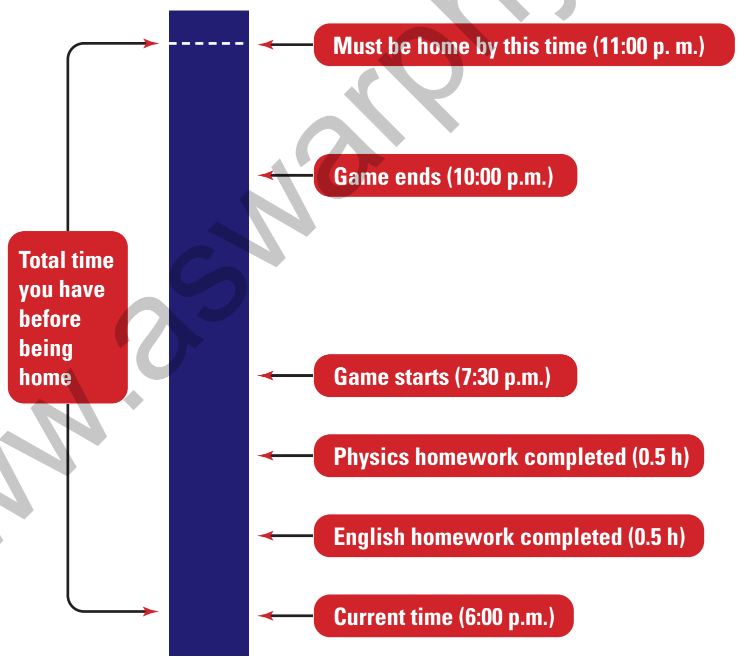
Example 2: Organizing Data Using Diagrams

You have framed the problem by generating diagrams (a) and (b) which outline the parameters. Your solution must fit within these parameters.

(a) Tree Diagram



(b) Temporal Diagram



Model Problems

Throughout this resource, you will find a feature called Model Problem. Each one presents a specific physics problem and its solution. Model Problems follow a step-by-step approach, identical to the one below. Become familiar with these steps, and integrate them into your own bank of problem-solving strategies. Throughout the book, the Model Problems are followed by Practice Problems to help you develop your skills. Answers to these are placed at the end of the Chapter Review.

MODEL PROBLEM

A problem is posed.

Frame the Problem

This section describes the problem and defines the parameters of the solution. Consider statements made in this section very carefully.

PROBLEM TIP

Often you will find problem tips embedded in model problems. The problem tips are designed to highlight strategies to help you successfully navigate a specific type of problem.

Identify the Goal

Narrow your focus and determine the precise goal.

Variables

Involved in the problem
Lists each variable that was mentioned in Frame the Problem.

Known
Lists variables about which information is known or implied.

Unknown
Lists variables that are unknown and must be determined in the solution.

Strategy

A step-by-step description of the mathematical operations involved.

Calculations

Use the data you have accumulated to complete the solution. Simplify the units required in your final answer.

A concluding statement verifies that the goal hasbeen accomplished. The number of significant digits in the solution statement must match those in the question statement.

Validate

This provides an opportunity to clarify the steps used in calculating the solution. Validating the solution helps catch numerical and conceptual errors.

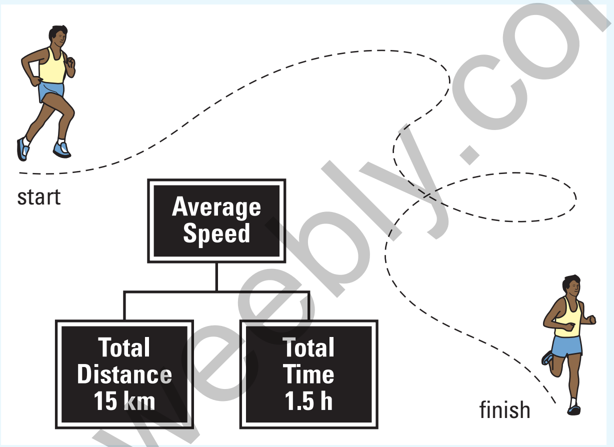
MODEL PROBLEM

Average Speed

A student runs 15 km in 1.5 h. What was the student's average speed?

Frame the Problem

- The student may or may not have stopped for a rest, but the term average implies that only total time and total distance are to be considered.
- Speed has units of distance/time.
- Use the distance/time information to help build a formula for speed (or verify that the one you have memorized is correct).
- Total distance/total time will provide the average speed.



Identify the Goal

The average speed, v_{ave}

Variables and Constants

Involved in the Problem	Known	Unknown
Δd	$\Delta d = 15$ km	v_{ave}
v_{ave}	$\Delta t = 1.5$ h	
Δt		

PROBLEM TIP

Be sure to identify the number of *significant figures* provided in the question as they will vary from one question to the next. Carry excess significant figures through during calculations, and then round your final answer to the correct number of significant figures. See Skill Set 2 at the back of this textbook for significant digits and rounding information.

Strategy	Calculations
Use the average speed formula	$v_{ave} = \dfrac{\Delta d_{Total}}{\Delta t_{Total}}$
Substitute in the known values, and solve	$v_{ave} = \dfrac{(15\text{ km})}{(1.5\text{ h})}$ $= \dfrac{10\text{ km}}{\text{h}}$

Therefore, the student ran at an average speed of 10 km/h.

Validate

The value for speed is given in distance (km) per time (h) which is correct.

Web Link

This feature directs you to conduct research on the Internet. To help you save time, the **Physics 11** Web page contains links to many useful Web sites.

PROBEWARE

This logo indicates where electronic probes could be used as part of the procedure, or as a separate lab.

Achieving in Physics

The following Achievement Chart identifies the four categories of knowledge and skills in science that will be used in all science courses to assess and evaluate your achievement. The chart is provided to help you in assessing your own learning, and in planning strategies for improvement, with the help of your teacher.

You will find that all written text, problems, investigations, activities, and questions throughout this textbook have been developed to encompass the curriculum expectations of your course. The expectations are encompassed by these general categories: Knowledge/Understanding K/U, Inquiry I, Communication C, and Making Connections MC. You will find, for example, that questions in the textbook have been designated under one of these categories to enable you to determine if you are able to achieve well in each category (some questions could easily fall under a different category; we have selected, for each question, one of the categories with which it best complies). Keep a copy of this chart in your notebook as a reminder of the expectations of you as you proceed through the course. (In addition, problems that involve calculation have been designated either Practice Problems or, in Chapter and Unit Reviews, Problems for Understanding.)

Table 1.1 Achievement Chart

Knowledge and Understanding	Inquiry	Communication	Making Connections
▪ Understanding of concepts, principles, laws, and theories ▪ Knowledge of facts and terms ▪ Transfer of concepts to new contexts ▪ Understanding of relationships between concepts	▪ Application of the skills and strategies of scientific inquiry ▪ Application of technical skills and procedures ▪ Use of tools, equipment, and materials	▪ Communication of information and ideas ▪ Use of scientific terminology, symbols, conventions, and standard (SI) units ▪ Communication for different audiences and purposes ▪ Use of various forms of communication ▪ Use of information technology for scientific purposes	▪ Understanding of connections among science, technology, society, and the environment ▪ Analysis of social and economic issues involving science and technology ▪ Assessment of impacts of science and technology on the environment ▪ Proposing courses of practical action in relation to science- and technology-based problems

At the end of each unit, you will have the opportunity to tie together the concepts and skills you have learned through the completion of either an investigation, an issue, or a project. Throughout each unit, one of the logos below will remind you of the end-of-unit performance task for that unit. Ideas are provided under each logo to help you prepare and plan for the task. Assessment of your work for each of the end-of-unit tasks, like all assessment in the course, will be based on the Achievement Chart shown in Table 1.1.

UNIT ISSUE PREP

UNIT PROJECT PREP

UNIT INVESTIGATION PREP

The Physics Course Challenge will allow you to incorporate concepts and skills learned from every unit of this course. This culminating assessment task will be developed during the year, but completed at or near the end of the course. Course Challenge logos exist throughout the text, cueing you to relate specific concepts and skills to your end-of-course task. The units in this course may seem to be largely unrelated. By investigating Space-Based Power in the Course Challenge, however, you will find some intriguing interactions among many concepts. Again, use the Achievement Chart in Table 1.1 as your guide to how your work will be assessed.

COURSE CHALLENGE

ELECTRONIC LEARNING PARTNER

The Electronic Learning Partner contains simulations, animations, and video clips to enhance your learning.

1.2 Section Review

1. C Explain why problem solving is a creative process. State the importance of framing a problem.
2. K/U Reflect on the game scenario. Which framing method most closely matches the thought process you would use to solve the same problem?
3. I Develop a different framing technique for the game problem. Share your model with the class.
4. I You have been offered a part-time job at the mall on weekends. However, you are determined to pursue a post-secondary education and have been devoting extra time to your studies. Should you accept the job? Frame the problem to help you decide.
5. I A friend asks you if warm water freezes faster than cold water. Frame the problem.
6. I Another friend tells you that astronauts are weightless when they orbit Earth. You know this to be inaccurate. Frame the problem to help dispel the misconception.

1.3 Inquiry, Experimentation, and Measurements

SECTION EXPECTATIONS

- Select and use appropriate equipment to accurately collect scientific data.
- Design and conduct experiments that control major variables.
- Hypothesize, predict, and test phenomena based on scientific models.

KEY TERMS

- period
- frequency
- percent difference
- percent deviation

Analyzing "real" world phenomena, as you will be doing throughout this course, requires the ability to take measurements — from very small to very large. It also requires that you be able to visualize the data in various ways, and to determine how accurately current models can predict actual events. In this section you will do two experiments that give you an opportunity to start having experience at measuring actual events, and analyzing the data generated in the experiments.

In the first investigation, you will design your own experiment to investigate the variables that determine the rate of the swing of a pendulum. In the second investigation, you will compare your experimental results from the first investigation to an existing model that predicts how the swing rate of a pendulum is controlled. You will then have the opportunity to practise using some of the mathematical tools of a physicist, comparing your data with the predictions of a mathematical model.

Before you conduct the investigations on the next two pages, think about the motion of a swing, like the one shown in Figure 1.10. See if you can apply the terms that follow the photograph to the child's motion.

Figure 1.10 A swing is an excellent example of periodic motion.

The time required for one complete oscillation is called the **period**.

Period = time interval / 1 cycle

The SI unit for period, T, is seconds (s).

The number of oscillations in a specific time interval is called the **frequency**.

f = number of oscillations / time interval

The SI unit for frequency, f, is 1/s or Hertz (Hz)

INVESTIGATION 1-A

Analyzing a Pendulum

TARGET SKILLS

- Hypothesizing
- Predicting
- Identifying variables
- Performing and recording
- Analyzing and interpreting
- Communicating results

Grandfather clocks are not merely timepieces, they are also works of art. A key feature of a grandfather clock is the ornate pendulum that swings back and forth.

Problem

Part 1: What factors affect the period of oscillation of a pendulum?

Part 2: Compare your results with your predictions.

Hypothesis

Formulate a hypothesis listing variables that will affect the period of oscillation of a pendulum. Predict how each variable will affect the period of oscillation.

Equipment

- various masses (50 g to 100 g)
- string (1 m)
- stopwatch
- retort stand

Procedure

1. With a partner, design an experiment to determine variables that will affect the period of oscillation of a pendulum. Investigate a minimum of three variables.
2. Provide step-by-step procedures.
3. Predict and record the effect of each variable, and have your teacher initial each prediction.
4. Following your school's safety rules, carry out the experiment and record your observations.

Analyze and Conclude

1. How many oscillations did you use to determine the period of the pendulum?
2. How many trials did you run before changing variables? Was this enough? Explain.
3. Did your hypothesis include length as a variable? If so, why? If not, why not? Explain your choice of variables.
4. Determine the uncertainty *within* your data by calculating the **percent difference** between your maximum and minimum values for the period of oscillation for each controlled variable. Refer to Skill Set 1 for an explanation of percent difference.
5. According to your results, what variables affect the period of oscillation of a pendulum? Explain, providing as much detail as possible.

INVESTIGATION 1-B

Analyzing Pendulum Data

TARGET SKILLS

- Hypothesizing
- Performing and recording
- Analyzing and interpreting
- Communicating results

Physicists and clock designers have used results from experiments like the previous one to develop a relationship between the period of oscillation of a pendulum and its length. The mathematical model for this relationship is approximated by the following equation:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where: T = period of oscillation
l = pendulum length
$g = 9.8\ \text{m/s}^2$ (acceleration due to gravity near Earth's surface)

Problem

How should experimental data be analyzed to test for (a) error within the data set and (b) accuracy when compared to a theoretical value?

Hypothesis

Formulate a hypothesis predicting how closely your experimental results from Investigation 1A will match the mathematical model shown above.

Procedure

1. Set up a table identical to the one shown.
2. Use the theoretical equation and the data you collected in the previous investigation to complete the table. Refer to Skill Set 1 for an explanation of **percent deviation**.
3. If length was not one of the variables that you and your partner tested, borrow data from tests carried out by your classmates.

Analyze and Conclude

1. Generate the following graphs on one set of axes:
   (a) $T_{\text{Experimental}}$ vs. l
   (b) $T_{\text{Theoretical}}$ vs. l
2. Analyze the graph. Is it possible to qualitatively determine whether your experimental data were similar to the results predicted by the theory?
3. Do the percent deviation values allow you to quantitatively determine whether your experimental data were similar to the results predicted by the theory? Again, refer to Appendix B for an explanation of percent deviation.
4. Suggest a method of determining whether the experimental deviation of your data is within acceptable parameters.
5. Suggest techniques to reduce the experimental deviation between your data and the theoretical period values.
6. Explain the difference between percent deviation and percent difference. When should each one be used?

Trial	Length (m)	Experimental results		Theoretical results $\left(T = 2\pi\sqrt{\frac{l}{g}}\right)$	Percent deviation
		Time 5 cycles (s)	Time 1 cycle (s)		
Sample 1	0.80 m	1.0×10^1 s	2.0 s	$T = 2\pi\sqrt{\frac{0.80\ \text{m}}{9.81\ \text{m/s}^2}} = 1.8\ \text{s}$	11 %
Sample 2					

Physics: an Active Endeavour

Understanding physics concepts requires making good observations and analyses. Thus, this book provides numerous active investigations, less formal Quick Labs that require few materials to carry them out, and marginal Try This activities that are just that — actions that won't take much time to do, but will help make concepts clearer. Watch for the following designations throughout the text:

INVESTIGATION 1-B
Analyzing Pendulum Data

TARGET SKILLS
- Hypothesizing
- Performing and recording
- Analyzing and interpreting
- Communicating results

QUICK LAB
Concave Lens Images

TARGET SKILLS
- Modelling concepts
- Communicating Results

TRY THIS...

1.3 Section Review

1. K/U When should percent deviation be used to analyze experimental data?
2. K/U When should percent difference be used to analyze experimental data?
3. I A group of science students hypothesize that the ratio of red jellybeans to green jellybeans is the same in packages with the same brand name, regardless of size. Their results are provided in Table 3.

Table 3 Jellybean data

Package	1	2	3	4	5
Red	23	18	50	62	19
Green	35	24	2	81	23

(a) Compute a red-to-green jellybean ratio for each package.

(b) Is there a general trend in the data?

(c) Is there a data set that, while properly recorded, should not be considered when looking for a trend? Explain.

CHAPTER 1 Review

REFLECTING ON CHAPTER 1

- Physics is the study of the relationships between matter and energy. As a scientific process, physics helps us provide explanations for things we observe. Physicists investigate phenomena ranging from subatomic particles, to everyday occurrences, to astronomical events.
- Like all science, physics is:
  1. a search for understanding through inquiry;
  2. a process of crafting that understanding into laws applicable to a wide range of phenomena; and
  3. a vehicle for testing those laws through experimentation.
- Aspects of physics are found in a wide range of careers. Engineering and academic research positions may be the first to come to mind, but medical and technological professions, science journalism, and computer science, are other fields that may require a physics background.
- A theory is a collection of ideas that fits together to describe and predict a particular natural phenomenon. New theories often grow out of old ones, providing fresh, sometimes radical ways of looking at the universe. A theory's value is determined by its ability to accurately predict the widest range of phenomena.
- A model is the representation of a theory. Models may take different forms, including mathematical formulas, sketches, and physical or computer simulations.
- An observation is information gathered by using one or more of the five senses. Models and theories attempt to predict observations.
- Changes in science and technology can have huge impacts on our society and on the global environment. An understanding of physics can help you assess some of the risks associated with those changes, and thus help guide your decision-making process. Since most real-world problems involve economic, political, and social components, applying scientific knowledge to the issues may help you separate fact from fiction.
- A learned skill, problem solving is a thought process specific to each of us and to each problem. Several problem-solving techniques are modelled in this chapter, each illustrating the conceptual thinking involved in framing the parameters within which the solution must fit.
- Experimental design requires a clear understanding of the hypothesis that is to be tested. Whenever you are designing your own experiments, your challenge will be to ensure that only one variable at a time is being tested. The number of trials that you run depends on the results. Enough trials have been run when there is a clear trend in the data. If, during your analyses, a clear trend is not evident, more data must be collected. Refer to the Skill Sets at the back of this textbook to help you with data analysis.

Knowledge and Understanding

1. Describe how nanotechnology is the product of both scientific inquiry and technology.
2. In general terms, describe the factors involved in the study of physics.
3. Describe how the Black Box activity can be used to explain the process of scientific inquiry.
4. State one definition of scientific inquiry.
5. Who first discussed the concept of nanotechnology?
6. What observation caused Aristotle to assume that the planets and the Moon were made of material different than Earth?
7. Why was Galileo able to observe the mountains and craters on the Moon, and four moons orbiting Jupiter?

Inquiry

8. While stargazing with friends, you observe a strange light in the sky. The following list of observations details information collected by you and your friends.

- The light moved from that distant hilltop in the east to the TV tower over there to the west.
- As the light moved, it seemed to be hovering just above the ground.
- As it moved from east to west, it got really bright and then faded again.
- It took about 3.0 s for it to move from the hilltop to the TV tower.
- The hilltop is about 15 km from the TV tower.
- It moved at a constant speed from point to point, and then stopped instantaneously.

What was the source of this light? Frame the problem using two different methods; incorporate the data provided and include any other parameters that you feel are relevant. You do not need to reach a solution.

Communication

9. Define scientific inquiry.

10. Generate two specific questions that you would like to have answered during this Physics course. Flip through the text to determine which unit(s) might contain the answers.

11. Briefly describe the purpose of a theory, a model, and an observation.

12. Describe how physics has evolved and continues to evolve.

13. Refer to Table 1.1. Provide one type of activity (for example, test, lab, presentation, debate) that would best allow you to demonstrate your strengths in each category (Knowledge and Understanding; Inquiry; Communication; and Making Connections).

Making Connections

14. Are there any scientific theories or models that you believe will eventually be proven false? Explain.

15. Read the Course Culminating Challenge on page 756. Generate a list of topics that you believe would be suitable as an independent study for this activity.

Problems for Understanding

16. A student conducts an experiment to determine the density of an unknown material. Use the data collected from both trials to calculate the percent difference in the density measurements.

Trial 1 19.6 g/mL

Trial 2 19.1 g/mL

17. A student decides to compare the theoretical acceleration due to gravity at her location ($g = 9.808\ m/s^2$) to experimental data that she collects using very sensitive equipment. She runs 15 trials and then averages her results to find $g = 9.811 m/s^2$.

(a) Calculate the percent deviation in her calculation.

(b) Is the percent deviation reasonable? Explain.

18. The following data are collected during an experiment.

Trial #	1	2	3	4	5	6	7	8	9	10	11
Frequency (Hz)	12	11	13	9	12	11	11	14	13	11	10

Refer to Skill Set 4 for reference on the following calculations:

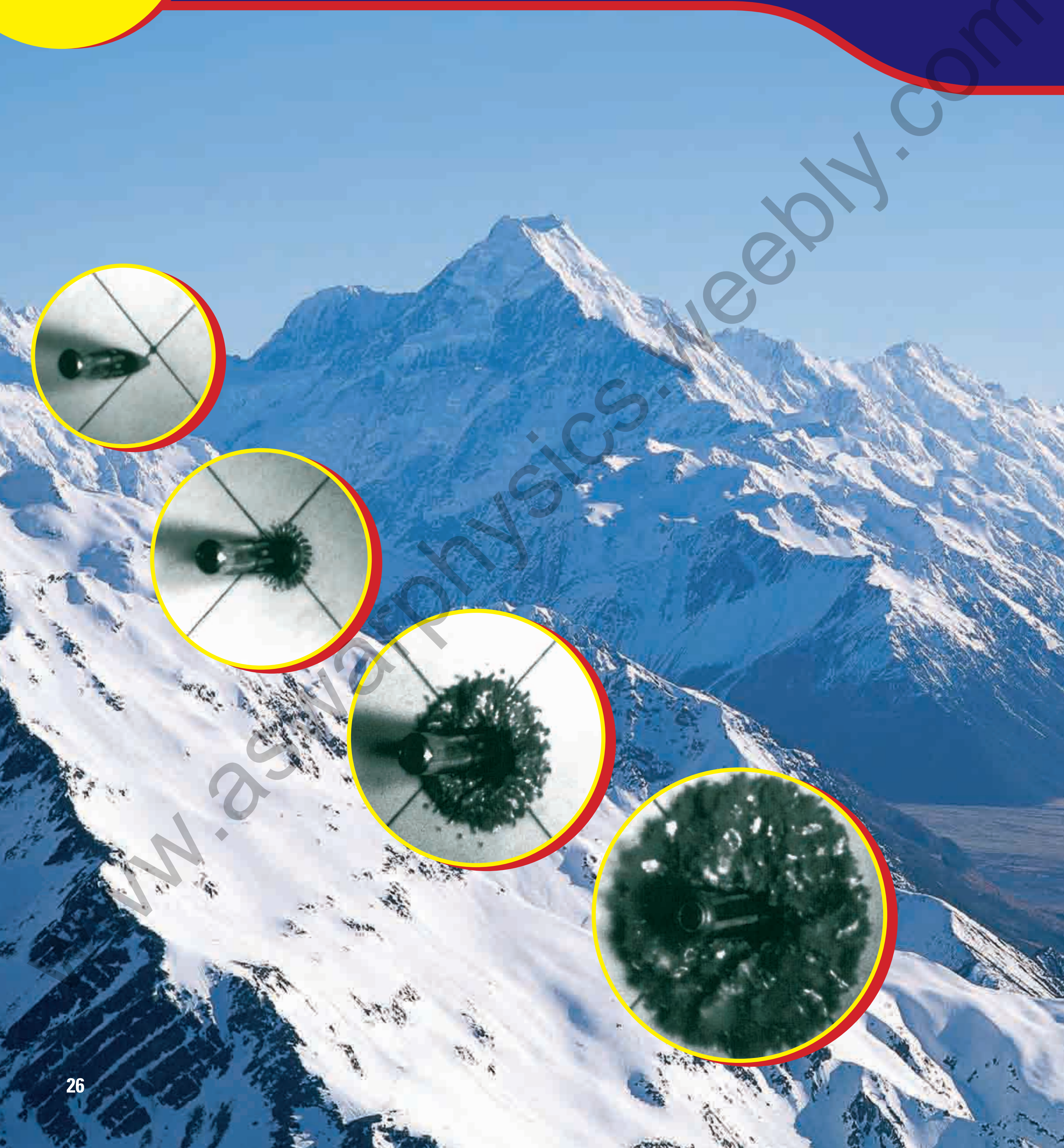
(a) Find the mean of the data.

(b) Find the median of the data.

(c) Find the mode of the data.

UNIT 1

Forces and Motion



OVERALL EXPECTATIONS

DEMONSTRATE an understanding of the relationship between forces and acceleration of an object.

INVESTIGATE and analyze force and motion using free-body diagrams and vector diagrams.

DESCRIBE contributions made to our understanding of force and motion, and identify current safety issues.

UNIT CONTENTS

A blink of an eye is a lifetime compared to the time that has elapsed between the first and last image in the inset photos of a bullet impacting on body armour. This sequence of motion was captured by a device composed of eight digital cameras, ingeniously wired together, that produces the fastest frame-by-frame images to date. Such technology is allowing scientists to examine an object's motion in the kind of minute detail that previously could only be hypothesized by using computer modelling.

Not all motion is quite this fast. Scientists have discovered, for example, that the continents of the world are adrift. What are now rugged mountain ranges were once buried deep beneath the sea. These very mountains might one day become rolling hills or farmland. The movements of the continents escaped the notice of scientists until recently, because the rate of the motion of continents is extremely slow.

This unit examines how physicists describe motion and how they provide explanations for the forces that cause it. The unit ends by giving you an opportunity to consider motion from the director's chair. Based on your expanded knowledge, you will be challenged to create your own realities by either speeding up imperceptibly slow motion through animation, or slowing down events that normally escape vision because they happen in the blink of an eye.

UNIT PROJECT PREP

Refer to pages 186–187 before beginning this unit. In this unit project, you will create a cartoon, video, or special effects show.

- How can you manipulate frames of reference to create the illusion of motion?
- What ideas can you get from amusement parks to simulate natural forces?

Photo insets courtesy of Professor Arun Shukla, University of Rhode Island

CHAPTER 2 Describing Motion

CHAPTER CONTENTS

The world of entertainment thrives on our passion for thrill and adventure. Many movies provide experiences that make you feel as though you are part of the action. Why do you get that sick feeling in your stomach when a car in a movie races up to the edge of a cliff, giving you a sudden panoramic view over the edge? How do live theatre productions such as the one in the photograph create the impression that an actor is travelling in relation to the other actors and audience? How are cartoons created to look like free-flowing action, when they are simply a series of individual pictures? How do cartoonists design a series of pictures so that they will simulate someone speeding up, slowing down, or travelling at a steady pace?

In this chapter, you will begin a detailed analysis of motion, which will lead you to the answers to some of the questions above. You will learn to apply models developed by physicists for understanding different types of motion.

MULTI LAB

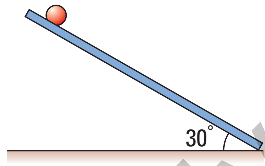
Winning the Race

TARGET SKILLS

- Identifying variables
- Performing and recording
- Analyzing and interpreting

The Tortoise and the Hare

Assemble a 1 m long ramp that has a groove to guide a marble that will roll down the ramp. For example, you may use a curtain track or tape two metre sticks together in a "V." Stabilize the ramp so it is at an angle of 30˚ with the horizontal. Hold one marble (the hare) at the top of the ramp. Roll another marble (the tortoise) along the bench beside the ramp. Start the "tortoise" rolling from behind the ramp. Release the "hare" when the "tortoise" is rolling along beside the ramp. Change the angle of the ramp in an attempt to find an angle at which the "hare" will beat the "tortoise" and win the race.



Analyze and Conclude

1. How is the motion of the "hare" different from the motion of the "tortoise?"
2. Did the "hare" ever win the race?
3. Give a possible explanation for the outcome of all of the races.

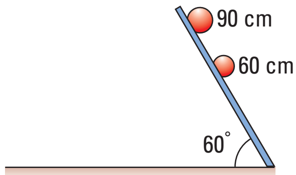
Caught in a Rut

Use the same ramp as above. Mark points on the ramp that are 60 cm and 90 cm from the base of the ramp as shown in the figure. Stabilize the ramp at an angle of 60˚ with the horizontal. Hold one marble at the 90 cm mark and another at the 60 cm mark. Observe the motion of the marbles under the following conditions.

CAUTION Do not drop the marbles from a greater height.

- use marbles of same mass; release at same time
- use marbles of same mass; release marble at 90 cm first; release 60 cm marble when first marble has rolled 10 cm
- use larger marble at 90 cm than at 60 cm; release both marbles at same time
- use larger marble at 90 cm than at 60 cm; release 90 cm marble first; release 60 cm marble when first marble has rolled 10 cm

Choose another angle for the ramp and repeat the procedure.



Analyze and Conclude

1. Describe any effect that the starting position of the marbles had on the rate at which their speed increased.
2. Was there any case in which the 90 cm marble caught up with the 60 cm marble? Give a possible reason for these results.
3. Describe any way in which the mass of the marble affected the outcome of the race.
4. Describe any way in which the angle of the ramp influenced the outcome of the race.
5. Write a summary statement that describes the general motion of marbles rolling, from rest, down a ramp.

2.1 Picturing Motion

SECTION EXPECTATIONS

- Describe motion with reference to the importance of a frame of reference.
- Draw diagrams to show how the position of an object changes over a number of time intervals in a particular frame of reference.
- Analyze position and time data to determine the speed of an object.

KEY TERMS

- frame of reference
- at rest

In the introductory investigations, you observed marbles moving in different ways. Some were moving at a constant rate or speed. Some were starting at rest and speeding up, while others were slowing down. How easy or difficult did you find it to describe the relative motion of the marbles and the pattern of their motion?

Although you might think you can readily identify and describe motion based on everyday experiences, when you begin to carefully examine the physical world around you, motion can be deceiving. A few examples were discussed in the chapter introduction. To describe motion in a meaningful way, you must first answer the question, "When are objects considered to be moving?" To answer this seemingly obvious question, you need to establish a **frame of reference**.

Frames of Reference

Figure 2.1 For more than 50 years, movie producers have used cameras that move to give you, the viewer, the sense that you are moving around the set of the movie and interacting with the actors.

Movie producers use a variety of reference clues to create images that fool your senses into believing that you are experiencing different kinds of motion. In the early years of moving making, film crews such as those in Figure 2.1, could drive motorized carts carrying huge cameras around a stage. To create the sense that the actors were in a moving car, the crew would place a large screen behind a stationary car and project a moving street scene on the screen so the viewer would see it through the car windows. Today, the movie crew might ride on a moving dolly that is pulling the car down an active street. In this case, the crew and the viewer would be **at rest** relative to the car in which the actors are riding. The buildings and street would be moving relative to the stationary actors.

COURSE CHALLENGE

Getting into Orbit

Research the current types of orbits given to satellites. Investigate which type of orbit would best meet the needs of a satellite that was to be used for a space based power system. Should the satellite be in motion relative to Earth?

Begin your research at the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and go to the *Physics 11 Course Challenge*.

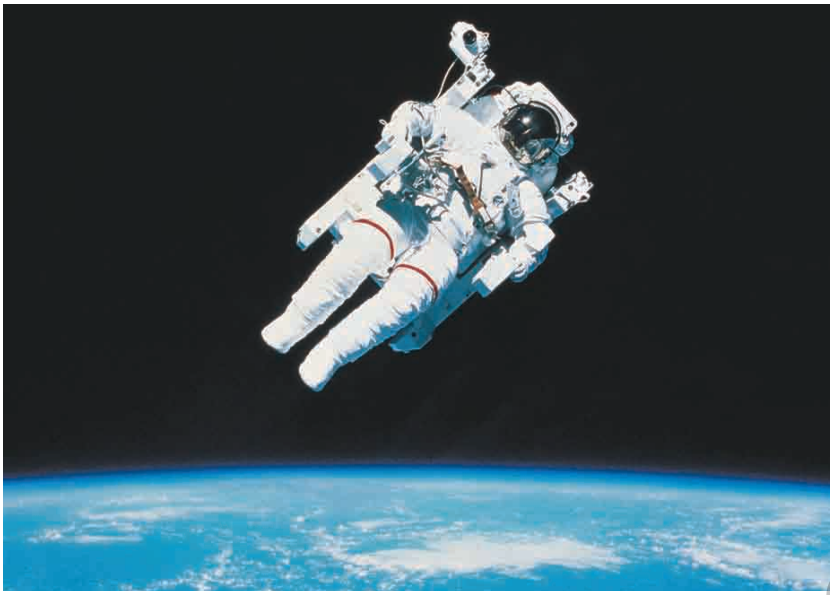


Figure 2.2 Does this astronaut appear to be hurtling through space at 28 000 km/h?

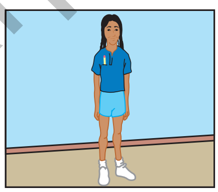
In everyday life, Earth's surface seems to provide an adequate frame of reference from which to consider the motion of all objects. However, Earth's reference frame is limited when you consider present-day scientific endeavours such as the flight of aircraft and space shuttles. As you examine the meanings of terms such as "position," "velocity," and "acceleration," you will need to consider the frame of reference within which objects are considered to be moving.

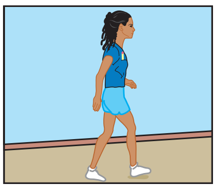
Think It Through

- For each picture shown here, describe a frame of reference in which the pencil

  (a) is moving

  (b) is not moving





Illustrating Motion

Because you need to establish a frame of reference to study motion, diagrams and sketches are critical tools. Diagrams show how the object's position is changing in relation to a stationary frame, during a particular time interval or over several time intervals. When comparing the object's position in each of a series of pictures, you can determine whether the object is at rest, speeding up, slowing down, or travelling at a constant speed.

PHYSICS FILE

Kinesiologists often record the motion of an athlete using a camcorder that takes 30 frames per second. By attaching reflective tags to different parts of the athlete's body, the kinesiologist can study, in detail, the motion of each part of the athlete's body while running, rowing, swinging a tennis racquet, or high-jumping. The kinesiologist might be able to help the athlete escape injury by avoiding movements that are likely to damage a joint or pull a muscle. The kinesiologist might also be able to help the athlete improve his or her performance by eliminating energy-wasting motions. The human body is an amazing instrument when properly trained.

Your diagrams could be as elaborate as pictures taken by a camcorder (see the Physics File on page 31), as simple as stick-people, or even just dots. In any case, you would superimpose (place one on top of the other) each image, ensuring that something visible in the background is in the same place in each frame. This point provides your frame of reference. Knowing the time that passed between the recording of each image, you can analyze the composite picture or diagram and determine the details of the motion.

The four stick diagrams in Figure 2.3 illustrate four different kinds of motion. Each diagram shows the position of a sprinter after five equal time intervals. In diagram A, the sprinter has not changed position, and is therefore at rest. In diagram B, she changes her position by an equal amount during each time period, and therefore she is travelling at a constant speed. In diagram C, she is changing her position by an increasing amount in each time interval, and therefore she is speeding up. In diagram D, she is changing her position by a decreasing amount, and therefore is slowing down.

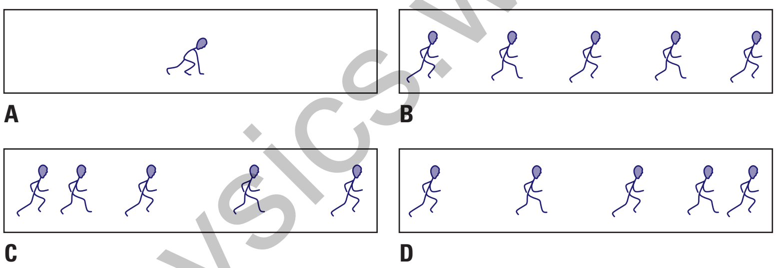


Figure 2.3 Stick diagrams illustrating the position of a sprinter after five equal time intervals

A diagram of the composite picture of the sprinter in motion can be made even simpler by considering a single point on her waist. This point is approximately her centre of mass. In other words, this point moves as though the sprinter's entire mass was concentrated there. You can measure the distance between points, and the analysis of her motion then becomes straightforward. The diagrams in Figure 2.4 show how a picture can be drawn simply as a set of dots to show how the position of an object changes over a number of time intervals in a particular frame of reference.

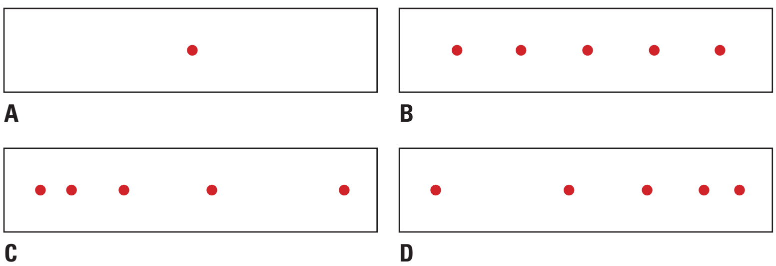


Figure 2.4 Dots can be used to show how the position of an object changes over a number of time intervals in a particular frame of reference.

The Importance of Relative Motion

Assume that you have selected a frame of reference in which you are at rest. For example, when you are dozing off in the back seat of a car that is traveling smoothly along a super highway, you may be unaware of your motion relative to the ground. The sensation is even more striking when you are in a large, commercial airliner. You are often entirely unaware of any motion at all relative to the ground. You become aware of it only when the motion of your frame of reference changes. If the car or airplane speeds up, slows down, or turns, you become very aware of the change in the motion of your reference frame. Physicists and engineers need to understand these relative motions and their effects on objects that were at rest in that reference frame. As you solve motion problems and move on into a study of forces, always keep the reference frame and its motion in mind.

PHYSICS & SOCIETY

TARGET SKILLS

- Analyzing and interpreting
- Hypothesizing

The Physics of Car Safety

When a car stops suddenly, you keep going. This example of Newton's first law of motion has been responsible for many traffic injuries. Countless drivers and passengers have survived horrible crashes because they were wearing seat belts, and air bags have also played a major role.

To understand the physics behind the design of air bags, imagine that the car you are driving is suddenly involved in a head-on collision. At the instant of impact, the car begins to decelerate. Your head and shoulders jerk forward, and the air bag pops out of its compartment. The bag must inflate rapidly, before your head reaches the wheel, and then start to deflate as your head hits it. This causes your head to decelerate at a slower rate. In addition, the force of your impact with the air bag is exerted over a wider area of your body, instead of being concentrated at the impact site of your head with something small, such as the top of the steering wheel.

Physics is also involved in the design of car tires. The key consideration is the amount of tire area that stays in contact with the road during braking and turning; the more tire contact, the better your control of the car. Also important is having tires that resist "hydroplaning" on wet roads — at slow speeds, water skiers sink; at high speeds, they glide over the surface of the water. That's just what you do not want your car tires to do in the rain. Engineers used various physics principles to design tires with a centre groove that pumps water away from the surface as the tires roll over wet pavement.

Analyze

1. Air bags have come under increased scrutiny. Research the reasons for this debate.
2. To keep more rubber in contact with the road, tires could be made wider. The ultimate would be a single tire as wide as the car. What would be the disadvantage of this type of tire? What might limit the maximum width of a tire?

2.1 Section Review

1. K/U Draw dot diagrams, such as those illustrated in Figure 2.4 on page 32, of the motion described in the following situations.
   (a) A sprinter running at a constant speed.
   (b) A marble starting from rest and rolling down a ramp.
   (c) A car starting from rest, speeding up, and then travelling at a constant speed. Finally, the car slows down and stops.

2. K/U Alex is sitting at a bus stop facing north. Darcy walks by heading west. Jennifer jogs by going east. Draw dot diagrams of the motion of each person from:
   (a) Alex' frame of reference,
   (b) Darcy's frame of reference, and
   (c) Jennifer's frame of reference.

3. I Draw dot diagrams according to the following directions then write two scenarios for each diagram that would fit the motion.
   (a) Draw seven, evenly spaced dots going horizontally. Above the fourth dot, draw five vertical dots that are evenly spaced.
   (b) Draw a square. Make a diagonal line of dots starting at the upper left corner to the lower right corner. Make the dots closer together at the upper left and getting farther apart as they progress to the lower right.
   (c) Draw a horizontal line of dots starting with wide spacings. The spacing becomes smaller, then, once again gets wider on the right end.
   (d) Start at the lower left with widely spaced dots. The dots start going upward to the right and get closer together. They then go horizontally and become evenly spaced.

4. C Sketch two frames of reference for each of the following:
   (a) a ferry boat crossing a river.
   (b) a subway car moving through a station.
   (c) a roller coaster cart at Canada's Wonderland.

5. C Use single points (centre of mass) to sketch the motion in the following situations: (The distance between dots should represent equal time intervals.)
   (a) a person on a white water rafting trip jumps off a cliff.
   (b) a person hops across the length of a trampoline.
   (c) an Olympic diver jumps off a high dive board, hits the water and comes back to the surface.

6. MC Explain how the frequency of frames affects the quality of a Disney cartoon.

7. I A marble rolls down a 1.0 m ramp that is at an angle of 30˚ with a horizontal bench. The marble then rolls along the bench for 2.0 m. Finally, it rolls up a second 1.0 m ramp that is at an angle of 40˚ with the bench.
   (a) Draw a scale diagram of this situation and use dots to illustrate your predictions of the marble's motion. Use at least four position dots on each ramp.
   (b) Design and conduct a brief investigation to determine the accuracy of your predictions.
   (c) Describe your observations and explain any discrepancies with your predictions.

2.2 Displacement and Velocity

In the last section, you saw how diagrams allow you to describe motion qualitatively. It is not at all difficult to determine whether an object or person is at rest, speeding up, slowing down, or moving at a constant speed. Physicists, however, describe motion quantitatively by taking measurements.

From the diagrams you have analyzed, you can see that the two fundamental measurements involved in motion are distance and time. You can measure the distance from a reference point to the object in each frame. Since a known amount of time elapsed between each frame, you can determine the total time that passed, in relation to a reference time, when the object reached a certain location. From these fundamental data, you can calculate an object's position, speed, and rate of change of speed at any particular time during the motion.

SECTION EXPECTATIONS

- Differentiate between vector and scalar quantities.
- Describe and provide examples of how the position and displacement of an object are vector quantities.
- Analyze problems with variables of time, position, displacement, and velocity.

KEY TERMS

- scalar
- vector
- position
- displacement
- velocity
- acceleration
- time interval
- speed

Vectors and Scalars

Most measurements that you use in everyday life are called scalar quantities, or **scalars**. These quantities have only a magnitude, or size. Mass, time, and energy are scalars. You can also describe motion in terms of scalar quantities. The distance an object travels and also the speed at which it travels are scalar quantities.

In physics, however, you will usually describe motion in terms of vector quantities, or **vectors**. In addition to magnitude, vectors have *direction*. Whereas distance and speed are scalars, the **position**, **displacement**, **velocity**, and **acceleration** of an object are vector quantities. Table 2.1 lists some examples of vector and scalar quantities. A vector quantity is represented by an arrow drawn in a frame of reference. The length of the arrow represents the magnitude of the quantity and the arrow points in the direction of the quantity within that reference frame.

Table 2.1 Examples of Scalar and Vector Quantities

Scalar quantities		Vector quantities	
Quantity	**Example**	**Quantity**	**Example**
distance	15 km	displacement	15 km[N45°E]
speed	30 m/s	velocity	30 m/s [S]
		acceleration	9.81 m/s^2 [down]
time interval	10 s		
mass	6 kg		

Note: There is no scalar equivalent of acceleration.

Position Vectors

A position vector locates an object within a frame of reference. You will notice in Figure 2.5 that an *x*-*y* coordinate system has been added to the diagram of the sprinting stick figures. The coordinate system allows you to designate the zero point for the variables under study and the direction in which the vectors are pointing. It establishes the *origin* from which the position of an object can be measured. The position arrow starts at the origin and ends at the location of the object at a particular instant in time. In this case, the sprinter is the object.

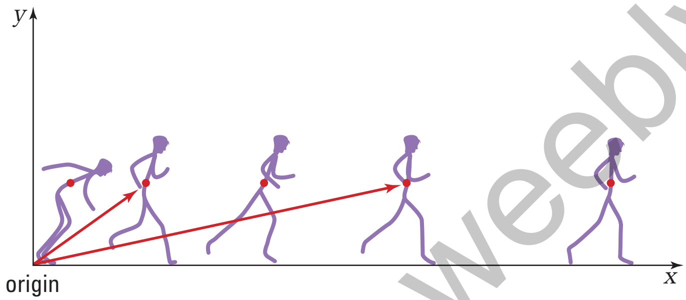


Figure 2.5 Stick diagram with coordinate system and position vectors added

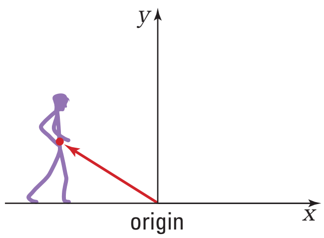


Figure 2.6 As the sprinter walks toward the origin, the sprinter's position is negative in this coordinate system.

POSITION VECTOR

A position vector, $\vec{d}$, points from the origin of a coordinate system to the location of an object at a particular instant in time.

As you can see in Figure 2.5, vectors locate the sprinter's position for two of the five different points in time. Time zero is selected as the instant at which the sprint started. However, as shown in Figure 2.6, you can show the sprinter several seconds before the race. Her position is to the left of the origin as she is walking up to the starting position. Thus, it is possible to have negative values for positions and times in a particular frame of reference.

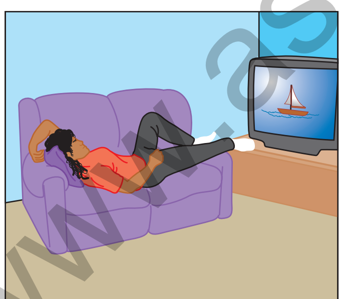


Figure 2.7 Could this be an example of displacement?

Displacement

Although you might think you know when an object is moving or has moved, you can be fooled! Pay close attention to the scientific definition of displacement and you will have a ready denial for the next time you are accused of lying around all day.

The **displacement** of an object, $\Delta\vec{d}$, is a vector that points from an initial position, $\vec{d}_1$, from which an object moves *to* a second position, $\vec{d}_2$, in a particular frame of reference. The vector's magnitude is equal to the straight-line distance between the two positions.

DISPLACEMENT

Displacement is the vector difference of the final position and the initial position of an object.

$$\Delta\vec{d} = \vec{d}_2 - \vec{d}_1$$

Quantity	Symbol	SI unit
displacement	$\Delta\vec{d}$	m (metre)
final position	$\vec{d}_2$	m (metre)
initial position	$\vec{d}_1$	m (metre)

Notice in the boxed definition that displacement depends only on the initial and final positions of the object or person. It is like taking snapshots of a person at various points during the day and not knowing or caring about anything that happened in between.

To see how the definition of displacement affects your perception of motion, follow a typical student, Freda, through a normal day. Figure 2.8 is a map of Townsville, where Freda lives. The map is framed by a coordinate system with its origin at Freda's home, position $\vec{d}_0$. In Table 2.2, you are given her position at six times during the day. What can you learn about her displacement from these data?

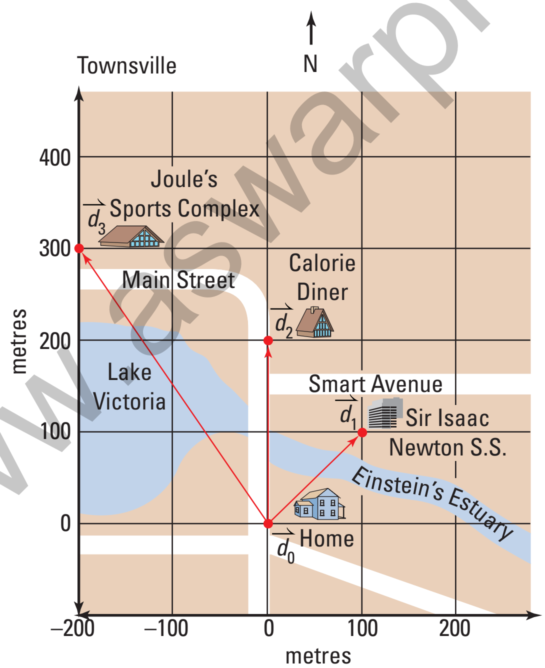


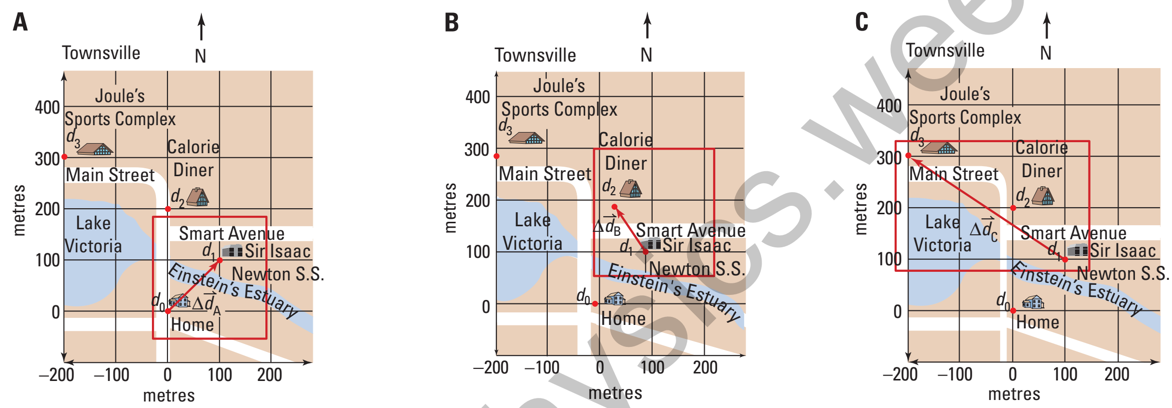
Figure 2.8 Freda's town

Table 2.2 Freda's Typical Daily Schedule

Time	Location	Position	Activity
6:30 a.m.	home	$\vec{d}_0$	sleeping
9:00 a.m.	school	$\vec{d}_1$	studying physics
12:00 noon	diner	$\vec{d}_2$	eating lunch
2:00 p.m.	school	$\vec{d}_1$	studying physics
5:00 p.m.	sports complex	$\vec{d}_3$	playing squash
10:00 p.m.	home	$\vec{d}_0$	sleeping

You can determine Freda's displacement for any pair of position vectors. To develop a qualitative understanding of displacement, consider the following examples.

Figure 2.9 Freda's displacement from **(A)** home to school, **(B)** school to diner, and **(C)** school to sports complex



Home to School

6:30 a.m. to 9:00 a.m.

$\vec{d}_0$ to $\vec{d}_1$

$\Delta\vec{d}_A = \vec{d}_1 - \vec{d}_0$

Since $\vec{d}_0 = 0$, $\Delta\vec{d}_A = \vec{d}_1$

Scale measurement would show that $\Delta\vec{d}_A$ = 140 m and points northeast.

School to Lunch

9:00 a.m. to 12:00 noon

$\vec{d}_1$ to $\vec{d}_2$

$\Delta\vec{d}_B = \vec{d}_2 - \vec{d}_1$

Scale measurement would show that $\Delta\vec{d}_B$ = 140 m, but points northwest.

School to Sports Complex

9:00 a.m. to 5:00 p.m.

$\vec{d}_1$ to $\vec{d}_3$

$\Delta\vec{d}_C = \vec{d}_3 - \vec{d}_1$

Scale measurement would show that $\Delta\vec{d}_C$ = 360 m, and points a little west of northwest.

By now, you have probably discovered the important difference between measuring the *distance* a person travels and determining the person's *displacement* between two points in time. You know that Freda covered a much greater distance during the day than these displacements indicate. Suppose that someone observed Freda only at 6:30 a.m. and at 10:00 p.m. Her position at both of those times was the same — she was in bed. Despite the fact that she had a very energetic day, her displacement for this time interval is zero. Imagine what her reaction would be if she was accused of lying around all day.

Think It Through

- Use the scale map of Townsville in Figure 2.8 to estimate the minimum distance that Freda would walk while following her daily schedule. Compare this value to her displacement for the day.
- Determine Freda's displacement when she walks from the sports complex to her home.
- On a piece of graph paper, draw a scale map of your home and school area. Mark on it the major locations that you would visit on a typical school day. Frame the map with a coordinate system that places your home at the origin, the positive *x*-axis pointing east and the positive *y*-axis pointing north. Label your home position $\vec{d}_0$ and designate the other locations $\vec{d}_1$, $\vec{d}_2$, and so on. Determine your displacement and estimate the distance you travel
  (a) from home to school
  (b) from school to home
  (c) from school to a location that you visit after school
  (d) from a location that you visit after school to home
  (e) from the time you get out of bed to the time you get back into bed
- In the following situation, choose the correct answer and explain your choice. A basketball player runs down the court and shoots at the basket. After she arrives at the end of the court, her displacement is
  (a) either greater than or equal to the distance she travelled
  (b) always greater than the distance she travelled
  (c) always equal to the distance she travelled
  (d) either smaller than or equal to the distance she travelled
  (e) always smaller than the distance she travelled
  (f) either smaller or larger than, but not equal to, the distance she travelled

Time and Time Intervals

The second fundamental measurement you will use to describe motion is *time*. In the example of Freda's schedule, you used clock time. However, in physics, clock time is very inconvenient, even if you use the 24 h clock. In physics, the time at which an event begins is usually designated as time zero. You might symbolize this as $t_0 = 0$ s. Other instants in time are measured in reference to t_0 and designated as t_n. The subscript "n" indicates the time at which a certain incident occurred during the event.

The elapsed time between two instants of time is called a **time interval**, Δt. Notice the difference between t_n and Δt: t_n is an instant of time and Δt is the time that elapses between two incidents.

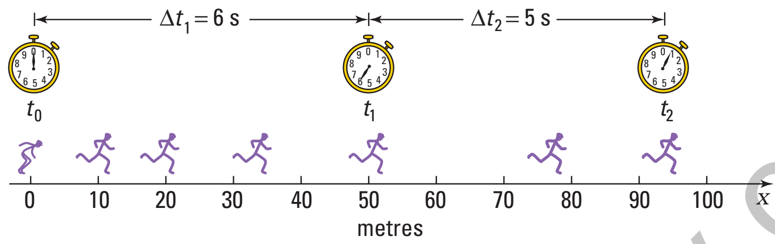


Figure 2.10 A time interval is symbolized as Δt. The symbol t with a subscript indicates an instant in time related to a specific event.

Think It Through

- Write an equation to show the mathematical relationship between the time interval Δt that elapsed while you were travelling to school this morning and the instants in time at which you left home and at which you arrived at school.
- Draw a sketch, similar to Figure 2.10, of a sprinter running a 100 m race and label it with the following information. (Remember, if you are not a good artist, you can use dots to show the sprinter at the specified positions.)

Time (s)	Position (m)
0	0
3.6	10
5.7	25
10.0	50
12.8	80
14.0	100

(a) Determine the time interval that elapsed between the runner passing the following positions.
  - the beginning of the race and the 10 m point
  - the 10 m point and the 80 m point
  - the 80 m point and the 100 m point

(b) Compare the time interval taken for the first 50 m and the second 50 m of the sprint. Explain why they are different.

Velocity

You have probably known the meaning of "speed" since you were very young. Speed is a scalar quantity that is simply defined as the distance travelled divided by the time spent travelling. For example, a car that travels 250 m in 10 s has an average speed of 25 m/s.

In physics, you will use the vector quantity *velocity* much more frequently than *speed*. Velocity not only describes how fast an object moves from one position to another, but also indicates the direction in which the object is moving. Physicists define velocity as the *rate of change of position*.

As you have discovered, when you determine the displacement (change of position) of an object (or person), you do not consider anything that has occurred between the initial and final positions. Consequently, you do not know whether the velocity has been changing during that time. Therefore, when you calculate velocity by dividing displacement by time, you are, in reality, finding the *average* velocity and ignoring any changes that might have occurred during the time interval.

VELOCITY

Velocity is the quotient of displacement and the time interval.

$$\vec{v}_{\text{ave}} = \frac{\Delta\vec{d}}{\Delta t} \quad \text{or} \quad \vec{v}_{\text{ave}} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

Quantity	Symbol	SI unit
average velocity	$\vec{v}_{\text{ave}}$	$\frac{\text{m}}{\text{s}}$ (metres per second)
displacement	$\Delta\vec{d}$	m (metres)
time interval	Δt	s (seconds)

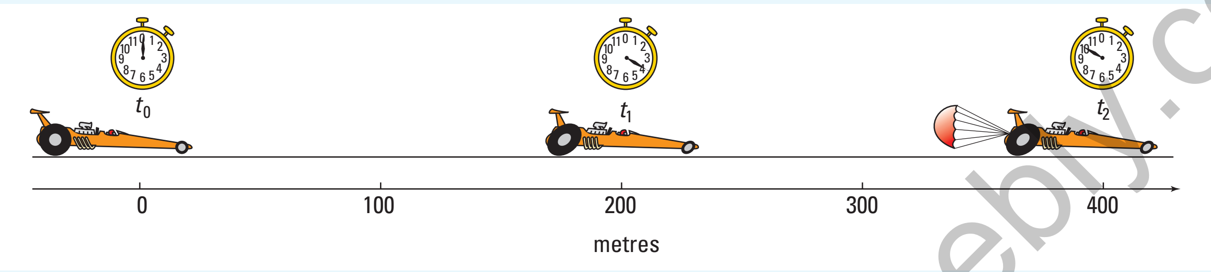
Think It Through

- Consider the speedometer of a car. Does it provide information about speed or velocity?
- A student runs around a 400 m oval track in 80 s. Would the average velocity and average speed be the same? Explain this result using both the definition of average velocity and a distinction between scalars and vectors.
- Consider the definition of average velocity. Describe the effect of reducing the time interval over which average velocity is calculated from a very large value such as several hours compared to a very short interval such as a fraction of a second.

MODEL PROBLEM

Calculating Average Velocity

1. A dragster in a race is timed at the 200.0 m and 400.0 m points. The times are shown on the stopwatches in the diagram. Calculate the average velocity for (a) the first 200.0 m, (b) the second 200.0 m, and (c) the entire race.



Frame the Problem

- The dragster undergoes a *change in position*.
- The stopwatch shows a reading at *three instants in time*.
- Since you have data for only three instants, you can determine only the *average* velocity.
- The equation for average velocity applies to this problem.

Identify the Goal

(a) The average velocity, $\vec{v}_{\text{ave}}$, for the displacement from 0.0 m to 200.0 m

(b) The average velocity, $\vec{v}_{\text{ave}}$, for the displacement from 200.0 m to 400.0 m

(c) The average velocity, $\vec{v}_{\text{ave}}$, for the displacement from 0.0 m to 400.0 m

Variables and Constants

Involved in the problem

$\vec{d}_0$	t_0	$\vec{v}_{\text{ave}(0\to1)}$
$\vec{d}_1$	t_1	$\vec{v}_{\text{ave}(1\to2)}$
$\vec{d}_2$	t_2	$\vec{v}_{\text{ave}(0\to2)}$
$\Delta\vec{d}_{0\to1}$	$\Delta t_{0\to1}$	
$\Delta\vec{d}_{1\to2}$	$\Delta t_{1\to2}$	
$\Delta\vec{d}_{0\to2}$	$\Delta t_{0\to2}$	

Known

$\vec{d}_0 = 0.0$ m[E]	$t_0 = 0.0$ s
$\vec{d}_1 = 200.0$ m[E]	$t_1 = 4.3$ s
$\vec{d}_2 = 400.0$ m[E]	$t_2 = 11$ s

Unknown

$\Delta\vec{d}_{0\to1}$	$\Delta t_{0\to1}$	$\vec{v}_{\text{ave}(0\to1)}$
$\Delta\vec{d}_{1\to2}$	$\Delta t_{1\to2}$	$\vec{v}_{\text{ave}(1\to2)}$
$\Delta\vec{d}_{0\to2}$	$\Delta t_{0\to2}$	$\vec{v}_{\text{ave}(0\to2)}$

Strategy

Find the displacement for the first 200.0 m, using the definition of displacement.

Calculations

$$\Delta d_{0\to1} = \vec{d}_1 - \vec{d}_0$$
$$\Delta d_{0\to1} = 200.0\text{ m[E]} - 0.0\text{ m[E]}$$
$$\Delta d_{0\to1} = 200.0\text{ m[E]}$$

Find the time interval for the first 200.0 m, using the definition of time interval.

$$\Delta t = t_1 - t_0$$
$$\Delta t = 4.3\ \text{s} - 0.0\ \text{s}$$
$$\Delta t = 4.3\ \text{s}$$

Find the average velocity for the first 200.0 m, using the definition of average velocity.

$$\vec{v}_{\text{ave}(0\rightarrow 1)} = \frac{\Delta \vec{d}_{0\rightarrow 1}}{\Delta t_{0\rightarrow 1}}$$
$$\vec{v}_{\text{ave}(0\rightarrow 1)} = \frac{200.0\ \text{m[E]}}{4.3\ \text{s}}$$
$$\vec{v}_{\text{ave}(0\rightarrow 1)} = 46.51\ \frac{\text{m}}{\text{s}}\text{[E]}$$

(a) The average velocity for the first 200.0 m was 47 m/s[E].

Find the displacement for the second 200.0 m, using the definition of displacement.

$$\Delta d_{1\rightarrow 2} = \vec{d}_2 - \vec{d}_1$$
$$\Delta d_{1\rightarrow 2} = 400.0\ \text{m[E]} - 200.0\ \text{m[E]}$$
$$\Delta d_{1\rightarrow 2} = 200.0\ \text{m[E]}$$

Find the time interval for the second 200.0 m, using the definition of time interval.

$$\Delta t = t_2 - t_1$$
$$\Delta t = 11\ \text{s} - 4.3\ \text{s}$$
$$\Delta t = 6.7\ \text{s}$$

Find the average velocity for the second 200.0 m, using the definition of average velocity.

$$\vec{v}_{\text{ave}(1\rightarrow 2)} = \frac{\Delta \vec{d}_{1\rightarrow 2}}{\Delta t_{1\rightarrow 2}}$$
$$\vec{v}_{\text{ave}(1\rightarrow 2)} = \frac{200.0\ \text{m[E]}}{6.7\ \text{s}}$$
$$\vec{v}_{\text{ave}(1\rightarrow 2)} = 29.85\ \frac{\text{m}}{\text{s}}\text{[E]}$$

(b) The average velocity for the second 200.0 m was 30 m/s[E].

Find the displacement for the entire race.

$$\Delta d_{0\rightarrow 2} = \vec{d}_2 - \vec{d}_0$$
$$\Delta d_{0\rightarrow 2} = 400.0\ \text{m[E]} - 0.0\ \text{m[E]}$$
$$\Delta d_{0\rightarrow 2} = 400.0\ \text{m[E]}$$

Find the time interval for the entire race.

$$\Delta t = t_2 - t_0$$
$$\Delta t = 11\ \text{s} - 0.0\ \text{s}$$
$$\Delta t = 11\ \text{s}$$

Find the average velocity for the entire race.

$$\vec{v}_{\text{ave}(0\rightarrow 2)} = \frac{\Delta \vec{d}_{0\rightarrow 2}}{\Delta t_{0\rightarrow 2}}$$
$$\vec{v}_{\text{ave}(0\rightarrow 2)} = \frac{400.0\ \text{m[E]}}{11\ \text{s}}$$
$$\vec{v}_{\text{ave}(0\rightarrow 2)} = 36.36\ \frac{\text{m}}{\text{s}}\text{[E]}$$

(c) The average velocity for the entire race was 36 m/s[E].

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Validate

Velocities with magnitudes between 30 m/s and 47 m/s are very large (108 km/h to 169 km/h), which you would expect for dragsters. As well, the units gave m/s, which is correct for velocity.

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2. **A basketball player gains the ball in the face-off at centre court. He then dribbles down to the opponents' basket and scores 6.0 s later. After scoring, he runs back to guard his own team's basket, taking 9.0 s to run down the court. Using centre court as his reference position, calculate his average velocity (a) while he is dribbling up to the opponents' net, and (b) while he is running down from the opponents' net to his own team's net. (A basketball court is 3.0×10^{1} m long.)**

Frame the Problem

- The basketball player's *starting position* is at *centre court*.
- Two additional *positions* are identified, one up-court and one down-court from his starting position.
- Two *time intervals* are given in the description of his play.
- *Average velocity* is a calculation of his *displacement* for particular *time intervals*.
- Centre court is the *origin* of the coordinate system.
- Since *directions* are required in order to determine *velocities*, define the direction of the opponents' net as *positive* and the direction of the player's own net as *negative*.

Identify the Goal

(a) The average velocity, $\vec{v}_{\text{ave}}$, for the first event

(b) The average velocity, $\vec{v}_{\text{ave}}$, for the second event

Variables and Constants

Involved in the problem			Known	Implied	Unknown
$\vec{d}_0$	t_0	$\vec{v}_{\text{ave}(0\to1)}$	$\vec{d}_0 = 0.0$ m	$\vec{d}_1 = +15$ m	$\vec{v}_{\text{ave}(0\to1)}$
$\vec{d}_1$	t_1	$\vec{v}_{\text{ave}(1\to2)}$	$\Delta t_1 = 6.0$ s	$\vec{d}_2 = -15$ m	$\vec{v}_{\text{ave}(1\to2)}$
$\vec{d}_2$	t_2		$\Delta t_2 = 9.0$ s		$\Delta\vec{d}_{0\to1}$
$\Delta\vec{d}_{0\to1}$	$\Delta t_{0\to1}$		**Note:** Since the court is 30 m long and the position zero is defined as centre court, each basket must be half of 30 m, or 15 m, from position zero.		$\Delta\vec{d}_{1\to2}$
$\Delta\vec{d}_{1\to2}$	$\Delta t_{1\to2}$				t_0
					t_1
					t_2

Strategy

Find the displacement for the first event, using the definition of displacement.

Calculations

$$\Delta\vec{d}_{0\to1} = \vec{d}_1 - \vec{d}_0$$
$$\Delta\vec{d}_{0\to1} = +15\text{ m} - 0.0\text{ m}$$
$$\Delta\vec{d}_{0\to1} = +15\text{ m}$$

The time interval is given, so calculate the average velocity of the first event by using the definition of average velocity.

$$\vec{v}_{0\to1} = \frac{\Delta\vec{d}_{0\to1}}{\Delta t_{0\to1}}$$
$$\vec{v}_{0\to1} = \frac{+15\text{ m}}{6.0\text{ s}}$$
$$\vec{v}_{0\to1} = +2.5\ \frac{\text{m}}{\text{s}}$$

(a) The average velocity for the first event was +2.5 m/s. The positive sign indicates that the direction of the player's velocity was toward the opponents' net.

Find the displacement for the second event by using the definition of displacement.

$$\Delta\vec{d}_{1\to2} = \vec{d}_2 - \vec{d}_1$$
$$\Delta\vec{d}_{1\to2} = -15\text{ m} - (+15\text{ m})$$
$$\Delta\vec{d}_{1\to2} = -30\text{ m}$$

The time interval is given, so calculate the average velocity of the second event by using the definition of average velocity.

$$\vec{v}_{1\to2} = \frac{\Delta\vec{d}_{1\to2}}{\Delta t_{1\to2}}$$
$$\vec{v}_{1\to2} = \frac{-30\text{ m}}{9.0\text{ s}}$$
$$\vec{v}_{1\to2} = -3.33\ \frac{\text{m}}{\text{s}}$$

(b) The average velocity for the second event was −3.3 m/s. The negative sign indicates that the direction of the player's velocity was toward the player's own net.

Validate

The units in the answer were m/s, which is correct for velocity. The player's velocity was faster when he was going to guard his own net than when he was dribbling toward his opponents' net to make a shot. This is logical because, when planning a shot, a player would take more time. When guarding, it is critical to get to the net quickly.

PRACTICE PROBLEMS

1. Calculate the basketball player's average velocity for the entire time period described in Model Problem 2.

2. Freda usually goes to the sports complex every night after school. The displacement for that walk is 360 m[N57°W]. What is her average velocity if the walk takes her 5.0 min?

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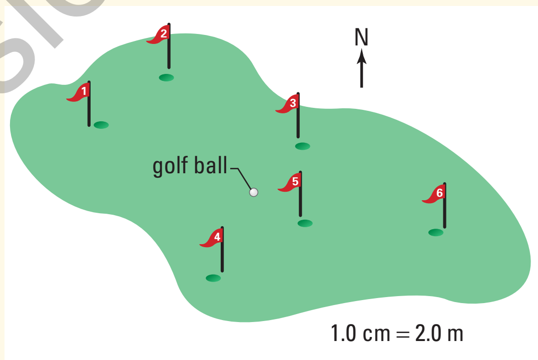
3. Imagine that you are in the bleachers watching a swim meet in which your friend is competing in the freestyle event. At the instant the starting gun fires, the lights go out! When the lights come back on, the timer on the scoreboard reads 86 s. You observe that your friend is now about halfway along the length of the pool, swimming in a direction opposite to that in which he started. The pool is 5.0×10^1 m in length.
   (a) Determine his average velocity during the time the lights were out.
   (b) What are two possible distances that you might infer your friend swam while the lights were out?
   (c) Given that the record for the 100 m freestyle race is approximately 50 s, which is the most likely distance that your friend swam while the lights were out? Explain your reasoning.
   (d) Based on your conclusions in (c), calculate your friend's average speed while the lights were out.

2.2 Section Review

1. K/U List four scalar quantities and five vector quantities.
2. K/U Describe the similarities and difference between:
   (a) time and time interval.
   (b) position, displacement, and distance.
   (c) speed and velocity.
3. K/U What is the displacement of Earth after a time interval of 365 $\frac{1}{4}$ days?
4. MC Create a scale diagram of your route to school. What is the displacement of your house from the school?
5. C Draw a displacement **and** a velocity scale diagram for the following:
   (a) a farmer drives 3 km[N43˚W] at 60 km/h.
   (b) a swimmer crosses a still river, heading [S56˚W] at 3 m/s, in 75 s.
   (c) an easterly wind blows a plastic bag at 6 km/h over a distance of 100 m.
6. K/U The following diagram represents a putting green at a 9 hole golf course.
   (a) What is the displacement from the furthest hole to the ball?
   (b) What is the displacement from the ball to furthest hole?
   (c) What is the displacement from the closest hole to the ball?
   (d) What is the displacement from the ball to the closest hole?



UNIT ISSUE PREP

Displacement, velocity, and the time interval are important features of any motion picture.

- How do film-makers manipulate these quantities to simulate motion?
- Have you ever been in a vehicle that was stopped but seemed like it was moving?
- What situations and effects can you create by lengthening or decreasing the time interval?

2.3 Constant, Average, and Instantaneous Velocity

How is the motion of a tortoise similar to the motion of a jet aircraft? How does the motion of a jet cruising at 10 000 m differ from that of a space shuttle lifting off?

Physicists have classified different patterns of motion and developed sets of equations to describe these patterns. For example, **uniform motion** means that the velocity (or rate of change of position) of an object remains constant. A tortoise and a cruising jet might be travelling with extremely different velocities, yet they move for long periods without *changing* their velocities. Therefore, both tortoises and jet airplanes often travel with uniform motion.

Non-uniform motion means that the velocity *is* changing, either in magnitude or in direction. A cruising jet is travelling at a constant velocity, or with uniform motion, while a space shuttle changes velocity dramatically during lift-off. The shuttle travels with non-uniform motion.

In the last section, you studied motion by looking at "snapshots" in time. You had no way of knowing what was happening between the data points. The only way you could report velocity was as an *average* velocity. Clearly, you need more data points to infer that an object is moving with uniform motion, or at a constant velocity. Graphing your data points provides an excellent tool for analyzing patterns of motion and determining whether the motion is uniform or non-uniform.

SECTION EXPECTATIONS

- Describe motion with reference to the importance of a frame of reference.
- Draw diagrams to show how the position of an object changes over a number of time intervals in a particular frame of reference.
- Analyze position and time data to determine the speed of an object.

KEY TERMS

- uniform motion
- non-uniform motion
- instantaneous velocity
- tangent

Constant Velocity

Is the motion of the skateboarder in Figure 2.11 uniform or non-uniform? To answer questions such as this, you should organize the data in a table (see Table 2.3) and then graph the data as shown in Figure 2.12. This plot is called a "position-time graph." When you plot the points for the skateboarder, you can immediately see that the plot is a straight line, with an upward slope.

Figure 2.11 Is a skateboarder's motion uniform or non-uniform?

Time (s)	Position (m[E])
0.0	0.0
1.3	12
2.6	24
3.9	36
5.2	48
6.5	60

Table 2.3 Position versus Time for a Skateboarder

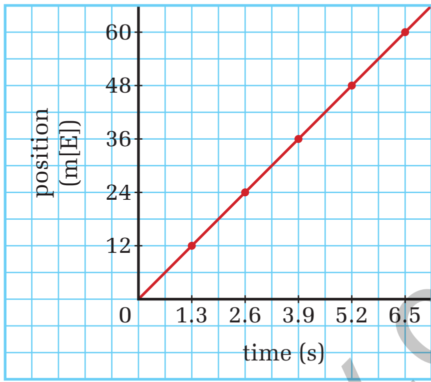


Figure 2.12 Position-time graph for a skateboarder's motion

To determine the significance of the straight line, consider the meaning of the slope. Start with the mathematical definition of slope.

- Slope is the rise over the run. $\text{slope} = \dfrac{\text{rise}}{\text{run}}$
- On a typical x-y plot, the slope is written as $\text{slope} = \dfrac{\Delta y}{\Delta x}$
- However, on a position-time plot, the slope is $\text{slope} = \dfrac{\Delta \vec{d}}{\Delta t}$
- The definition of velocity is $\vec{v} = \dfrac{\Delta \vec{d}}{\Delta t}$
- Since the slope and the velocity are equal to the same expression, the slope of the line on a position-time graph must be the velocity of the object. $\vec{v} = \text{slope}$

ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner to help you visualize the process of graphing motion.

Since you now know that the slope of a position-time graph is the velocity of the moving object, the straight line on the graph of the skateboarder's motion is very significant. The slope is the same everywhere on a straight line, so the skateboarder's velocity must be the same throughout the motion. Therefore, the skateboarder is moving with a constant velocity, or uniform motion. You could take any two points on the graph and calculate the velocity. For example, use the first and last points.

$$\text{slope} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\text{slope} = \frac{60\ \text{m[E]}}{6.5\ \text{s}}$$

$$\vec{v} = 9.2\ \frac{\text{m}}{\text{s}}\text{[E]}$$

$$\vec{v} = \text{slope}$$

$$\vec{v} = 9.2\frac{\text{m}}{\text{s}}[E]$$

Mathematically, this is the same way that you calculated average velocity. What, then, is the difference between *average velocity* and *constant velocity*? Think back to the snapshot analogy and the case of Freda's typical school day. Over several hours, you had only two points to consider — the beginning and the end of the motion.

In the case of the skateboarder, you have several points between the beginning and end of the motion and they are all consistent, giving the same velocity. Nevertheless, you still cannot know exactly what happened between each measured point. Although it is reasonable to think that the motion was uniform throughout, you cannot be sure. Strictly speaking, you can calculate only an average velocity for each small interval. Without continuous data, you cannot be certain that an object's velocity is constant.

To emphasize this point, use your imagination to fill in what could be happening between your observation points for a master skateboarder and for a novice struggling to stay on the board. Examine the graphs in Figures 2.13 and 2.14. What is the average velocity for each time interval on each graph? Is the rate of change of position between time intervals constant on each graph? Based on the data, is there a difference between the average velocities of each skateboarder?

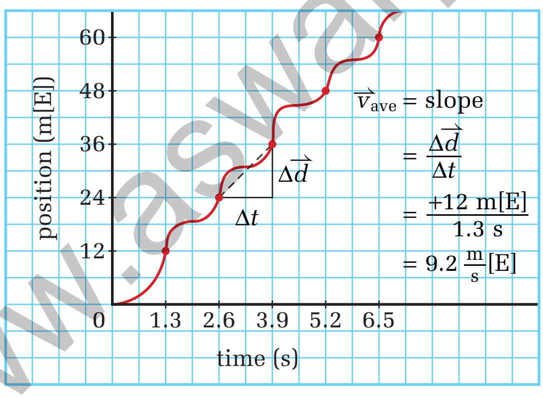


Figure 2.13 The sharp curves in the graph indicate that the skate boarder's velocity was constantly changing. You would expect this jerky motion from a novice skateboarder.

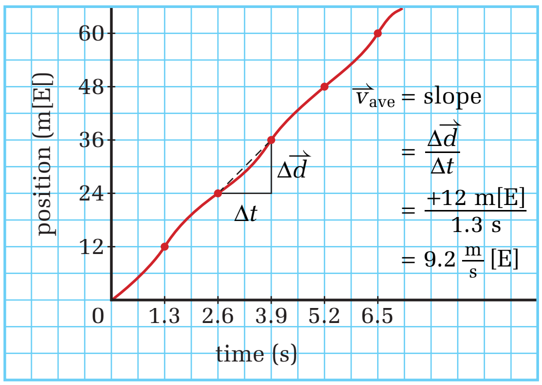


Figure 2.14 Since the line is nearly straight the velocity is almost constant. This motion is what you would expect from a master skateboarder.

QUICK LAB

Maintaining a Constant Pace

TARGET SKILLS
- Identifying variables
- Performing and recording
- Modelling concepts

Generate a position-time graph using Method A or Method B.

Method A: Motion Sensor

Use a motion sensor and computer interface to generate a position-time graph of your own motion as you walk toward the sensor, while trying to maintain a constant pace.

Method B: Spark Timer

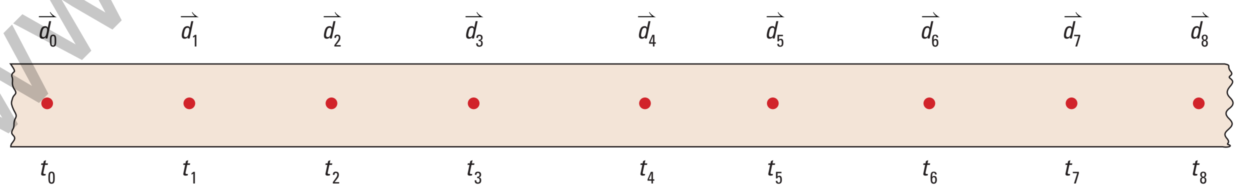
Pull a piece of recording tape, about 1 m long, through a spark timer, while trying to maintain a constant velocity. Examine the recording tape and locate a series of about 10 dots that seem to illustrate a period of constant velocity. On the recording tape, label the first dot in the series $\vec{d}_0$. Mark an arrow on your tape to show the direction of the motion. Make a data table to record the position and time of the 10 dots that immediately follow your labelled starting point, $\vec{d}_0$. Draw a position-time graph based on your data table.

Analyze and Conclude

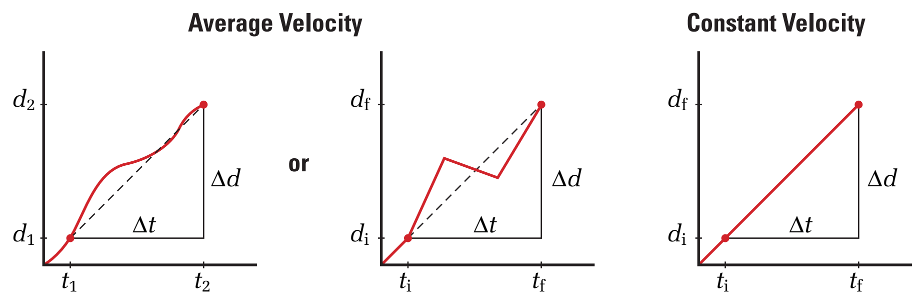
1. Explain, using the graph as evidence, whether you were successful in maintaining a constant velocity. If you were not successful for the entire timing, were you successful for at least parts of it?
2. Determine your average velocity for the entire timing period and your constant velocity for appropriate segments of your walk by calculating the relevant slopes of the graph.

Apply and Extend

3. Explain for each of the following situations whether you can determine if the person or object is maintaining a constant velocity.
   - **(a)** A student leaves home at 8:00 a.m. and arrives at school at 8:30 a.m.
   - **(b)** A dog was observed running down the street. As he ran by the meat store, the butcher noted that it was 10:00 a.m. When he ran by the bakery, it was 10:03 a.m. A woman in the supermarket saw him at 10:05 a.m. Finally, he reached home at 10:10 a.m.
   - **(c)** A swimmer competes in a 50 m backstroke race. Three judges, each with a stopwatch, timed her swim. Their stopwatches read 28.65 s, 28.67 s, and 28.65 s.
4. A spark timer generated the recording tape, shown here, as a small cart rolled across a lab bench.
   - **(a)** Set up a data chart to record the positions and times for the 8 dots after $\vec{d}_0$. The spark timer was set at a frequency of 60 Hz, thus making 60 dots per second.
   - **(b)** Draw a position-time graph.
   - **(c)** State whether the graph shows a constant velocity for the whole time period under observation or for only segments of it. Explain your reasoning.
   - **(d)** Calculate the value of a segment of constant velocity.
   - **(e)** Calculate the average velocity for the entire time period.



Concept Organizer



Notice that two different ways of writing subscripts are used for the position and time symbols. One graph uses $\vec{d}_1$, $\vec{d}_2$, t_1, and t_2, to designate consecutive positions and times. The other two graphs use $\vec{d}_i$, $\vec{d}_f$, t_i, and t_f, to designate initial and final positions and times. The use of subscripts to designate different positions and velocities varies in physics literature. The important point to remember is to use a system of subscripts that allows you to be clear about the meaning. For example, you might want to calculate the average velocity for several pairs of points, such as point 1 to point 2, and then from point 2 to point 3. Is point 2 the initial or final point? In the first case, point 2 is the final point, and in the second case, it is the initial point.

Figure 2.15 The numerical value of the velocities represented in the graphs are all the same but the concepts are quite different.

Average Velocity and Changing Directions

You have seen how a position-time graph helps you to determine whether motion is uniform or non-uniform. These graphs are even more helpful when doing a detailed analysis of non-uniform motion. Consider the situation illustrated in Figure 2.16. Adrienne drives her friend Jacques home from school. Jacques lives 800 m east of the school and Adrienne lives 675 m west. The diagram shows Adrienne's position at several specific times.

The data in Figure 2.16 are organized in Table 2.4 and graphed in Figure 2.17. Notice that Adrienne stops for 10 s to let Jacques out and then turns around and goes in the opposite direction.

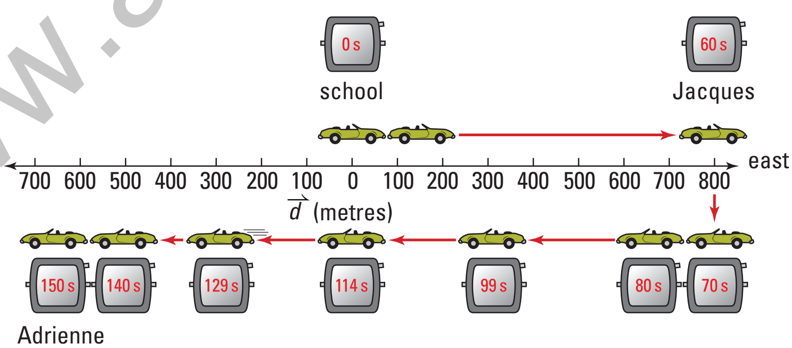


Figure 2.16 Motion diagram of Adrienne's car trip

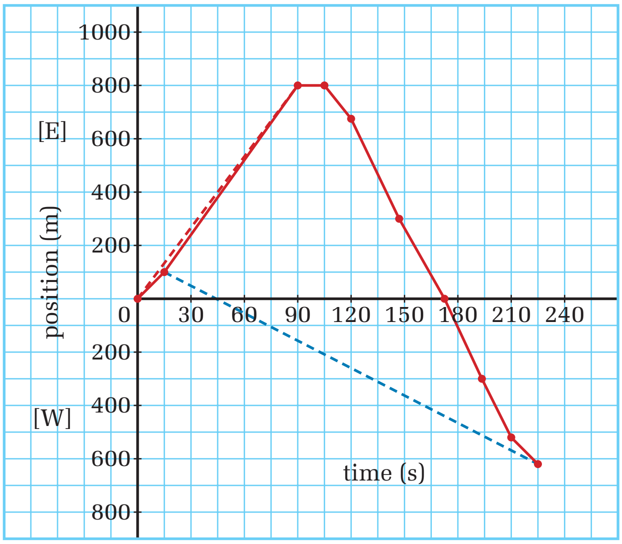


Figure 2.17 Position-time graph of Adrienne's car trip

Table 2.4 Data for Adrienne's Trip

Time (s)	Position (m)
0.0	0.0
15	100 [E]
90	800 [E]
105	800 [E]
120	675 [E]
148	300 [E]
171	0.0
194	300 [W]
210	525 [W]
225	625 [W]

Clearly, the position-time graph of Adrienne's journey shows that her velocity is not constant for her entire trip home. You can see from the changing slopes on the graph that not only is she speeding up and slowing down, she is also changing direction.

Note: In the calculations to the right, you will see that the choice of time intervals for determining average velocity can lead to unreasonable results.

Segment of Trip

From school to Jacques' home

From the 15 s mark to Adrienne's home

Initial and Final Times

$t = 0$ s to $t = 90$ s
(See dashed line on graph)

$t = 15$ s to $t = 225$ s
(See dashed line on graph)

Average Velocity

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$\text{slope} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\text{slope} = \frac{800\text{ m[E]} - 0.0\text{ m}}{90\text{ s} - 0.0\text{ s}}$$

$$\text{slope} = \frac{800\text{ m[E]}}{90\text{ s}}$$

$$\text{slope} = 8.88\ \frac{\text{m}}{\text{s}}\text{[E]}$$

$$\vec{v} \approx 9\ \frac{\text{m}}{\text{s}}\text{[E]}$$

$$\text{slope} = \frac{\text{rise}}{\text{run}}$$

$$\text{slope} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\text{slope} = \frac{625\text{ m[W]} - 100\text{ m[E]}}{225\text{ s} - 15\text{ s}}$$

$$\text{slope} = \frac{(-625\text{ m[E]}) - 100\text{ m[E]}}{210\text{ s}}$$

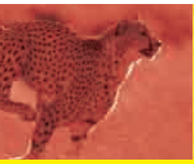
$$\text{slope} = \frac{-725\text{ m[E]}}{210\text{ s}}$$

$$\text{slope} = -3.45\ \frac{\text{m}}{\text{s}}\text{[E]}$$

$$\vec{v} \approx 3\ \frac{\text{m}}{\text{s}}\text{[W]}$$

Notice that, if you consider east to be positive, then west is equivalent to negative east.

You have probably concluded that the average velocity from the 15 s point to Adrienne's home does not seem reasonable. If you convert 3 m/s to km/h, the result is approximately 11 km/h. As well, the direction is west, but you know that Adrienne started the trip going east. The seemingly unreasonable average velocity is due to the *definition* of average velocity.

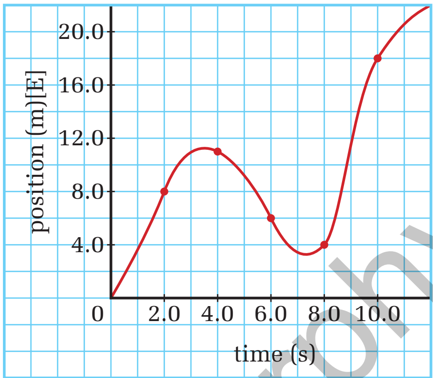


QUICK LAB

Velocity and Time Intervals

TARGET SKILLS
- **Analyzing and interpreting**
- **Communicating results**

The diagram records the flight of a hawk soaring in the air looking for prey. Using videotape footage, the observer recorded the position of the hawk at 2.0 s intervals. He plotted the points and connected them with a smooth curve.



To estimate the hawk's velocity at precisely $t = 8.0$ s, determine its average velocity at several intervals that include the 8.0 s mark. Observe any changes in the calculated values for average velocity as the interval becomes smaller. Then, draw conclusions based on the following steps.

1. Reconstruct the graph on a piece of graph paper.
2. Draw straight lines on the curve connecting the following pairs of points.
   (a) 5.0 s and 11.0 s
   (b) 6.0 s and 10.0 s
   (c) 7.0 s and 9.0 s
   (d) 7.5 s and 8.5 s
3. Determine the hawk's average velocity for each of the pairs of points in step 2.
4. Draw one more straight line between points on opposite sides of the 8.0 s point and as close as possible to the 8.0 s mark. Extend the straight line as far as possible on the graph. Determine the slope of the straight line by choosing any two points on the line and calculating $\frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$, for those points.

Analyze and Conclude

1. Why were the calculated average velocities different for the different pairs of points?
2. What do you think is the meaning of the slope that you calculated in step 4?
3. Describe the relationship among the five velocities that you calculated.
4. Evaluate, in detail, the process you just performed. From your evaluation, propose a method for determining the velocity of an object at one specific time, rather than an average between two time points.
5. Using your method, determine the velocity of the hawk at exactly 3.0 s and 5.0 s.

Think It Through

- Describe circumstances in which the average velocity of a segment of a trip is very close to the reading you would see on the speedometer of a car.
- Describe circumstances in which the average velocity of a segment of a trip appears to totally contradict reason. Explain why.

Instantaneous Velocity

When you apply the definition of average velocity to points on a graph that are far apart, sometimes the resulting value is extremely unreasonable as you discovered in the example of Adrienne's trip. When you bring the points on the graph closer and closer together, the calculated value of the velocity is nearly always very reasonable. In the Quick Lab, you brought the points so close together that they merged into one point. To perform a calculation of velocity, you had to draw a tangent line and use two points on that line. The value that you obtain in this way is called the **instantaneous velocity**. It might seem strange to define a velocity at one instant in time when velocity was originally defined as a *change* in position over a time *interval*. However, as you saw in the Quick Lab, you can make the time interval smaller and smaller, until the two points actually meet and become one point.

Think It Through

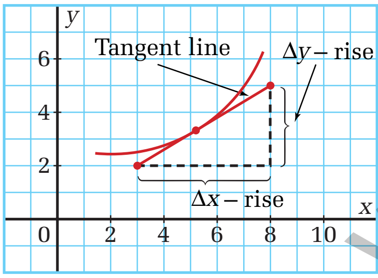
- A jet-ski is able to maintain a constant speed as it turns a corner. Describe how the instantaneous speed of the jet-ski will differ from its instantaneous velocity during the turning process?
- The concept organizer on page 50 illustrates how to calculate the average velocity from a position versus time graph.
  1. Sketch a position time graph with a smooth curve having increasing slope. Select and mark two points on the curve. Draw in a dotted line to represent the average velocity between those two points.
  2. Now mark a point directly between the first two points. How would the average velocity for the very small time interval represented by the single dot look? Sketch it.
- Draw a concept organizer to show how position, displacement, average velocity, instantaneous velocity, and time are related.

The straight lines that you drew between points on the curve are called *chords* of the curve. When the straight line finally touches only one point on the curve, it becomes a **tangent** line. The magnitude of the velocity of an object at the point where the tangent line touches the graph is the slope of the tangent. You now have the tools to do a detailed analysis of position-time data.

INSTANTANEOUS VELOCITY

The *instantaneous velocity* of an object, at a specific point in time, is the *slope of the tangent* to the curve of the position-time graph of the object's motion at that specific time.

Note: Although average velocity is symbolized as $\vec{v}_{ave}$, a subscript is not typically used to indicate instantaneous velocity. When a subscript is present, it usually refers to the time or circumstances represented by that specific instantaneous velocity.

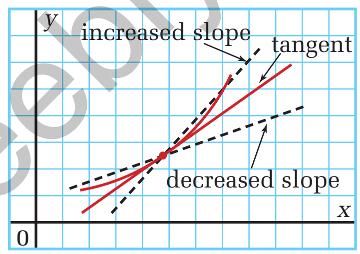


$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{5 - 2}{8 - 3} = \frac{3}{5}$$

The slope is $\frac{3}{5}$ or 0.60.

Math Link

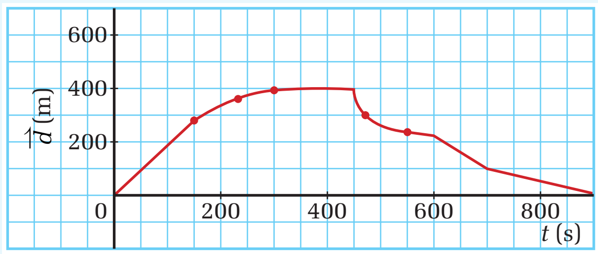
One, and only one, tangent line exists at any one point on a curve. Notice in the diagram that if the slope of the tangent line is changed, either increased or decreased, the line then cuts two points on the curve. It is no longer a tangent line but is now a *secant* line. A secant line intersects a curve at two points and continues beyond those points. How is the tangent line related to the trigonometric function named tangent?



MODEL PROBLEM

Determining Instantaneous Velocity

The plot shown here is a position-time graph of someone riding a bicycle. Assume that position zero is the cyclist's home. Find the instantaneous velocity for at least nine points on the curve. Use the calculated values of velocity to draw a velocity-time graph. In your own words, describe the bicycle ride.



Frame the Problem

- Between 0 s and 100 s, the graph is a straight line. Therefore, the velocity for that period of time is constant. Label the segment of the graph "A."
- Between 100 s and 350 s, the graph is curved, indicating that the velocity is changing. Label the segment of the graph "B."
- Between 350 s and 450 s, the graph is horizontal. There is no change in position, so the velocity is zero. Label the segment of the graph "C."
- At 450 s, the cyclist turns around and starts toward home. Up to 600 s, the graph is a curve, so the velocity is changing. Label the segment "D."

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- Between 600 s and 700 s and again between 700 s and 900 s, the graph forms straight lines. The velocity is constant during each period. Label those sections "E" and "F."
- At 900 s, the cyclist is back home.
- The motion is in one dimension so denote direction by positive and negative values.

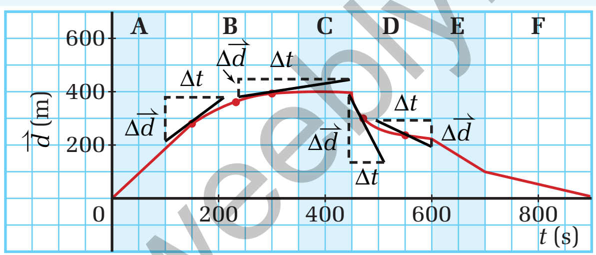
Identify the Goal

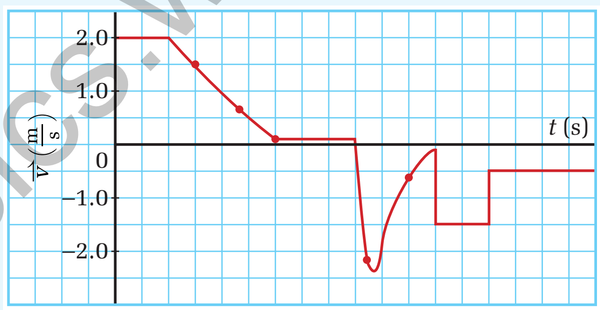
Find the value of the instantaneous velocity at nine points in time.

Draw a velocity-time graph.

Variables and Constants

Involved in the problem		Known	Unknown
$\vec{d}_n$	$\Delta\vec{d}_n$	$\vec{d}_n$	$\vec{v}_n$
t_n		t_n	
$\vec{v}_n$			
For all points (n) from $t = 0$ s to $t = 900$ s		For all points (n) from $t = 0$ s to $t = 900$ s	





Strategy

Redraw the graph with enough space below it to draw the velocity-time graph on the same time scale.

Identify the linear segments of the position-time graph. Select at least five points on the non-linear segments. Draw lines that are tangent to the graph at these points.

Calculate the velocity for each linear segment of the graph and the points at which you have drawn tangent lines. Record the velocities in a table.

Plot the points on the velocity-time graph. Connect the points with a smooth curve where the points do not form a straight line.

Time period or point	
	$\dfrac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1} = \vec{v}$
t_0 to t_{100}	$\dfrac{200\text{ m} - 0\text{ m}}{100\text{ s} - 0\text{ s}} = 2.0\ \dfrac{\text{m}}{\text{s}}$
t_{150}	$\dfrac{350\text{ m} - 200\text{ m}}{200\text{ s} - 100\text{ s}} = 1.5\ \dfrac{\text{m}}{\text{s}}$
t_{225}	(not shown) $= 0.80\ \dfrac{\text{m}}{\text{s}}$
t_{300}	$\dfrac{450\text{ m} - 360\text{ m}}{450\text{ s} - 250\text{ s}} = 0.45\ \dfrac{\text{m}}{\text{s}}$
t_{350} to t_{450}	slope is zero, $\vec{v} = 0.0\ \dfrac{\text{m}}{\text{s}}$
t_{475}	$\dfrac{210\text{ m} - 400\text{ m}}{530\text{ s} - 450\text{ s}} = -2.4\ \dfrac{\text{m}}{\text{s}}$

t_{550}	$\dfrac{180\text{ m} - 300\text{ m}}{700\text{ s} - 490\text{ s}} = -0.57\,\dfrac{\text{m}}{\text{s}}$
t_{600} to t_{700}	$\dfrac{100\text{ m} - 250\text{ m}}{700\text{ s} - 600\text{ s}} = -1.5\,\dfrac{\text{m}}{\text{s}}$
t_{700} to t_{900}	$\dfrac{0.0\text{ m} - 100\text{ m}}{900\text{ s} - 700\text{ s}} = -0.50\,\dfrac{\text{m}}{\text{s}}$

A: The cyclist is riding at a constant velocity, away from home.

B: The cyclist slows down and, at the end of the segment, stops.

C: The cyclist is not moving.

D: The cyclist starts toward home at a high velocity, then slows. The position vector is positive, because the cyclist is at a positive position in relation to home. However, the velocity is negative because the cyclist is moving in a negative direction, toward home.

E: The cyclist is still heading toward home, but at a constant velocity.

F: The cyclist slows even more but is still at a positive position and a negative velocity.

Validate

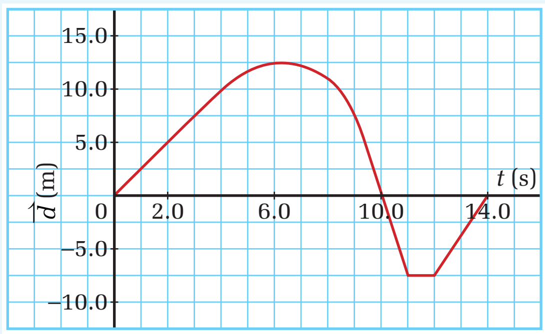
The slopes of the curve in A and B are positive (line and tangents go up to the right); therefore, the velocities should all be positive. They are.

The slope in C is zero so the velocity should be zero. It is.

The slopes of the curve in D, E, and F are all negative (lines and tangents go down to the right); therefore, the velocities should be negative. They are.

PRACTICE PROBLEMS

4. Redraw the position-time graph shown here. Determine the velocity in each of the linear segments and for at least three points along the curved section. Use the calculated velocities to draw a velocity-time graph of the motion. Explain the circumstances that make the position vector negative and the velocity vector positive.



continued from previous page

5. Using the data table, draw a position-time graph. For points that do not lie on a straight line, connect the points with a smooth curve. Calculate the velocity for a sufficient number of points so that you can draw a good velocity-time graph.

Time (s)	Position (m)	Time (s)	Position (m)
0.0	0.0	16.0	0.0
2.0	−10.0	17.0	10.0
4.0	−20.0	18.0	20.0
6.0	−30.0	20.0	25.0
8.0	−36.0	22.0	30.0
10.0	−38.0	24.0	26.6
12.0	−32.0	26.0	23.3
13.0	−27.0	28.0	20.0
14.0	−10.0	30.0	0.0

Concept Organizer

What type of velocity is the police officer measuring with the radar gun? A radar gun takes data points that are so close together, that it measures instantaneous velocity. If the car is moving with a constant velocity, the instantaneous velocity is the same as the constant velocity. If the car's velocity is changing, the radar gun will not measure average velocity. How would you measure a car's average velocity? To understand and report data correctly, you need to know how a measuring instrument works as well as knowing the precise meaning of specific terms.

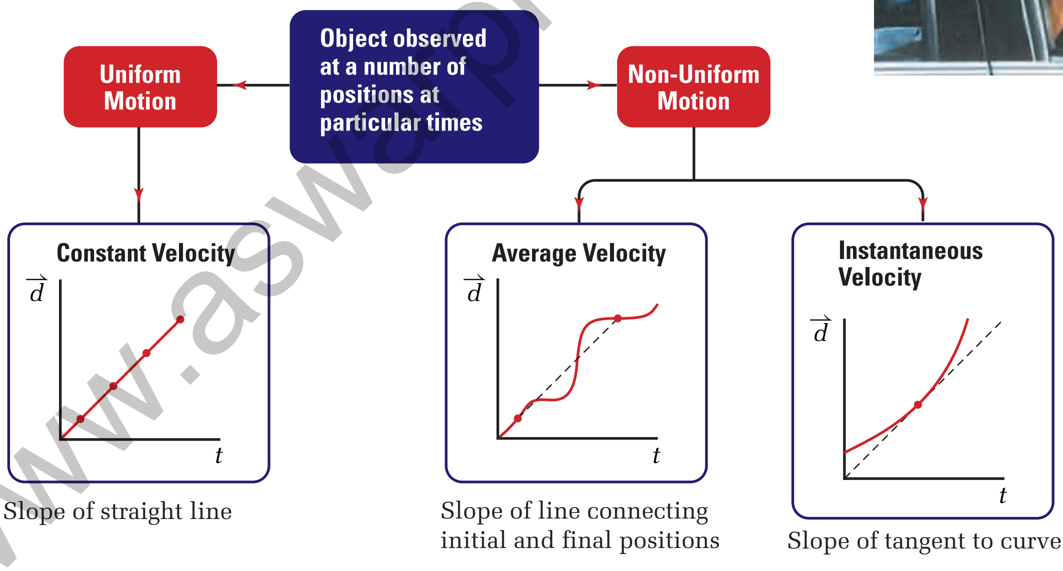
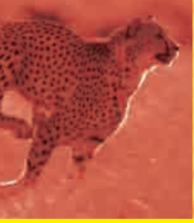


Figure 2.18 This concept organizer will help you understand and remember three ways in which you can describe velocity.

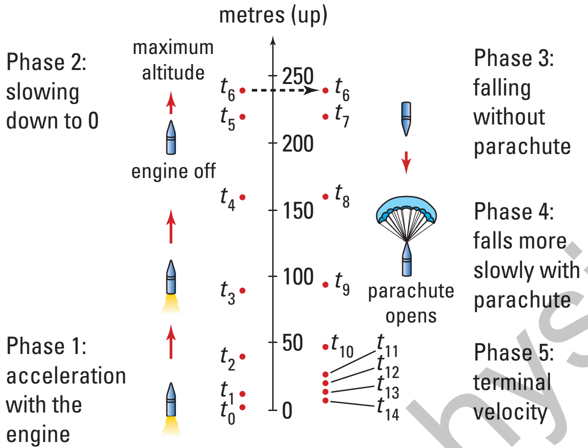


QUICK LAB

Rocket Motion

TARGET SKILLS
- Analyzing and interpreting
- Communicating results

Imagine that you fire a toy rocket straight up into the air. Its engine burns for 8.0 s before it runs out of fuel. The rocket continues to climb for 4.0 s, then stops and begins to fall back down. After falling freely for 4.0 s, a parachute opens and slows the descent. The rocket then reaches a terminal velocity of 6.0 m/s[down]. Using videotape footage, you determined the rocket's altitude, h, at 2 s intervals. Your data are shown in the table.



Phase	Time (seconds)	Position (metres[up])
1 engine on	0	0
	2	10
	4	40
	6	90
	8	160
2 engine off (rising)	10	220
	12	240
3 engine off (falling)	14	220
	16	160
4 parachute opens	18	92
	20	48
	22	28
5 terminal velocity	24	20
	26	12
	28	4
	30	0

Make a motion analysis table like the one shown here, but add three more columns and label them: Time interval, Displacement, and Average velocity. Perform the indicated calculations for all intervals between the points listed, then complete the table.

Plot an average velocity-time graph. Remember, when you plot *average* velocity, you plot the point that lies at the midpoint of the time interval. For example, when you plot the average velocity for the interval from 2 s to 4 s, you plot the point at 3 s. Draw a smooth curve through the points.

Determine the instantaneous velocity at $t = 7$ s, $t = 13$ s, $t = 21$ s, and $t = 25$ s.

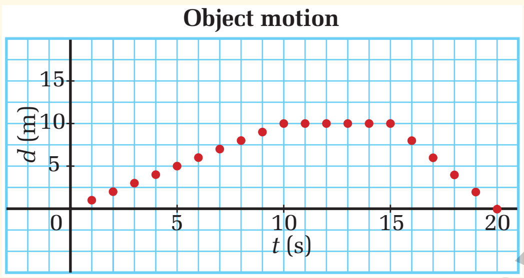
Analyze and Conclude

1. In your own words, describe the motion of the rocket during each of the five stages.
2. What is the condition of the position-time graph when the velocity-time graph passes through zero? Explain the meaning of this point.
3. Under what specific conditions is the velocity-time graph a straight, horizontal line?
4. Compare the instantaneous velocities that you calculated for times 7 s, 13 s, 21 s, and 25 s, with the average velocities for the intervals that included those times. In which cases are the instantaneous and average velocities nearly the same? Quite different? Explain why.
5. Explain why it is reasonable to draw the line connecting the points on the position-time graph as a smooth curve rather than connecting the dots with a straight line.

2.3 Section Review

1. C Explain why the following situations do not represent uniform motion.
   (a) driving through downtown at rush hour
   (b) start and stop sport drills that are executed at top speed
   (c) pendulum swinging with a constant frequency
   (d) a ball rolling down a ramp
   (e) standing on a merry go round that rotates at a constant number of revolutions per minute

2. I Analyze the following position time graph and sketch the velocity time graph of the same data.



3. C Explain the relationship between:
   (a) slope and position time graphs.
   (b) slope and velocity time graphs.
   (c) average velocity, constant velocity, and instantaneous velocity.
   (d) tangent line on a position time graph, and time interval.
   (e) negative time and a position time graph.
   (f) velocity, acceleration, and terminal velocity.
   (g) m/s and km/h.

4. MC Both physicists and mathematicians use observations from the physical world to create theories. Suggest criteria that separates physicists from mathematicians.

5. MC A boy and a girl are going to race twice around a track. The girl's strategy is to run each lap with the same speed. A boy is going to run the first lap slower so he can run the final lap faster. Suppose that the girl's speed is x m/s for both laps and the boy's speed for the first lap is $(x - 2)$ m/s, and for the second lap is $(x + 2)$ m/s. Decide who will win and justify your response. If you need help, try using real numbers for the speeds.

6. K/U By what factor does velocity change if the time interval is increased by a factor of 3 and the displacement is decreased by a factor of two?

2.4 Acceleration

Many times in the last section, you read that an object's velocity was increasing, decreasing, or that it was changing direction. Once again, physicists have a precise way of stating the changes in velocity. **Acceleration** is a vector quantity that describes the rate of change of velocity.

ACCELERATION

Acceleration is the quotient of the change in velocity and the time interval over which the change takes place.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$$

Quantity	Symbol	SI unit
acceleration	$\vec{a}$	$\frac{m}{s^2}$ (metres per second squared)
change in velocity	$\Delta\vec{v}$	$\frac{m}{s}$ (metres per second)
time interval	Δt	s (seconds)

Unit Analysis

$$\frac{\frac{\text{metres}}{\text{second}}}{\text{second}} = \frac{\frac{m}{s}}{s} = \frac{m}{s^2}$$

The units of acceleration — metres per second squared — do not have an obvious meaning. If you think about the basic definition of acceleration, however, the meaning becomes clear. The velocity of an object changes by a certain number of metres per second *every second*. For example, analyze the statement, "A truck is travelling at a constant velocity of 20 m/s[E], then accelerates at 1.5 m/s^2[E]." This acceleration means that the truck's velocity increases by 1.5 m/s[E] every second. One second after it starts accelerating, it will be travelling at 21.5 m/s[E]. One second later, it will be travelling at 23 m/s[E]. The truck's velocity increases by 1.5 m/s[E] *every second*, as long as it is accelerating.

Direction of Acceleration Vectors

The direction of the acceleration vector is the direction of the *change* in the velocity and not the direction of the velocity itself. To determine the direction of the acceleration vector, it is helpful to visualize the direction in which you would have to push on an object to *cause* a particular change in velocity.

SECTION EXPECTATIONS

- Define and describe the concept of acceleration.
- Design and conduct an experiment to determine variables that effect the acceleration due to gravity.
- Relate the direction of acceleration to the direction of a change in velocity.
- Interpret patterns and trends in motion data by hand or computer drawn graphs.

KEY TERMS

- acceleration
- constant (uniform) acceleration
- non-uniform acceleration
- average acceleration
- instantaneous acceleration

ELECTRONIC LEARNING PARTNER

To enhance your understanding of the language of acceleration go to the Electronic Learning Partner for an interactive activity.

Figure 2.19 shows the motion of a van that starts from rest, speeds up, travels at a constant velocity, slows down, and then stops. The frame of reference shows the origin at the left, with the *x*-axis pointing in a positive direction to the right. When the van is speeding up, the average velocity vectors and the average acceleration vector point in the same direction (+). When the van is travelling at a constant speed, the average acceleration is zero. When the van is slowing down, the average velocity vectors (+) and the average acceleration vector (–) are in opposite directions.

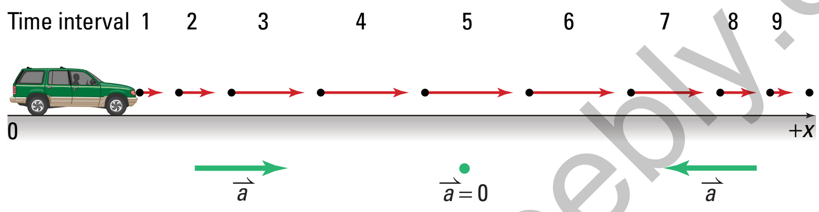


Figure 2.19 When the van is moving in a positive direction but slowing down, the direction of the acceleration is negative.

MISCONCEPTION

They *Don't* Mean the Same Thing!

Many people think that *negative acceleration* and *deceleration* mean the same thing — that an object is slowing down. "Deceleration" is not a scientific term but a common term that people use for slowing down. "Negative acceleration" is a scientific term meaning that the acceleration vector is pointing in the negative direction. However, an object with a negative acceleration might be speeding up.

Consider the directions that the average velocity and average acceleration vectors point if the van turns around and travels back to its starting point. As shown in Figure 2.20, when the van is speeding up in a negative direction, both the average velocity vectors and the acceleration vector point in the negative direction. While the van travels at constant velocity, the average velocity vectors are negative and the acceleration vector is zero. As the van slows down to stop, the average velocity vectors are pointing in the negative direction and the average acceleration vector is pointing in the positive direction.

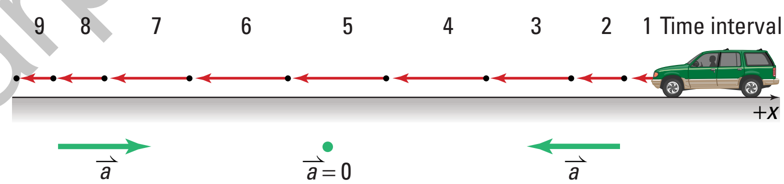


Figure 2.20 When the van is moving in a negative direction and slowing down, the direction of acceleration is positive.

An object can accelerate without either speeding up or slowing down. If the magnitude of the velocity does not change but the direction does change, the object is accelerating. To visualize the direction of the acceleration vector in such cases, study Figure 2.21. Imagine the direction that you would have to push on the tip of the initial velocity vector to make it overlap with the final velocity vector. The direction of the acceleration vector is from the tip of the initial velocity vector toward the tip of the final velocity vector.

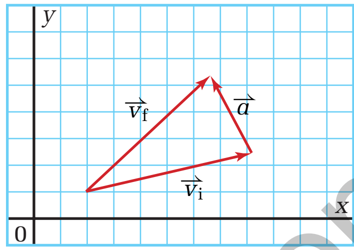


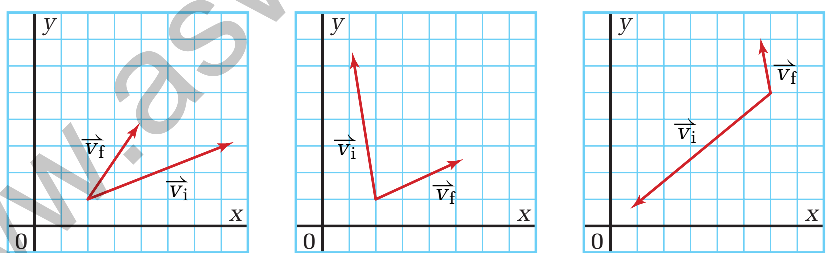
Figure 2.21 Envision pushing on the tip of $\vec{v}_1$, until it overlaps with $\vec{v}_2$.

Think It Through

- The following charts refer to the van's journeys in Figures 2.19 and 2.20. Redraw the charts below and, using as examples the two rows that have been completed, fill in the remaining rows.

Images in figure	Direction of velocity vector	Direction of acceleration vector	Description of motion
Figure 2.19 Van is moving in the positive direction.			
1-2-3	positive	positive	speeding up in positive direction
4-5-6			
7-8-9			
Figure 2.20 Van is moving in the negative direction			
1-2-3			
4-5-6			
7-8-9	negative	positive	slowing down in negative direction

- Sketch each of the combinations of initial and final velocity vectors, and add to your sketch another vector showing the direction of the acceleration vector.



Uniform and Non-Uniform Acceleration

Have you noticed the similarity in the mathematical expressions for velocity and acceleration?

$$\vec{v} = \frac{\Delta\vec{d}}{\Delta t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1} \qquad \vec{a} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

The mathematical operations you performed on position vectors to find velocity are nearly the same as those you will perform on velocity vectors to find acceleration. The similarity applies to both equations and graphs. For example, the slope of a velocity-time graph is the acceleration. If the velocity graph is curved, the slope of the tangent to the velocity-time graph at a specific time is the acceleration of the object at that time. The terms applied to velocity also apply to acceleration. **Constant** or **uniform acceleration** means that the acceleration does not change throughout specified time intervals. As well, **non-uniform acceleration** means that the acceleration is changing with time.

The terms, "average," "constant," and "instantaneous" apply to acceleration in the very same way that they apply to velocity. **Average acceleration** is an acceleration calculated from initial and final velocities and the time interval. Constant acceleration means that the acceleration is not changing over a certain interval of time. The velocity-time graph for the time interval is a straight line. **Instantaneous acceleration** is the acceleration found at one moment in time, and is equal to the slope of the tangent to velocity-time graph at that point in time.

To see the connections among time, position, velocity, and acceleration of a moving object, consider the example of a ball that is thrown straight up in the air with an initial velocity of 20.0 m/s. The position-time data are listed in Table 2.5 and the graphs of position, velocity, and acceleration are shown in Figure 2.22.

The data for the velocity-time graph were determined by the slope of the position-time graph. (Only four tangent lines are shown.) The velocity-time graph of data taken from the slopes of the position-time graph is a straight line with a negative slope that is the same everywhere. Since the slope of the velocity-time graph is the acceleration, the acceleration has the same negative value throughout the motion. (The value is –9.81 m/s².)

PHYSICS FILE

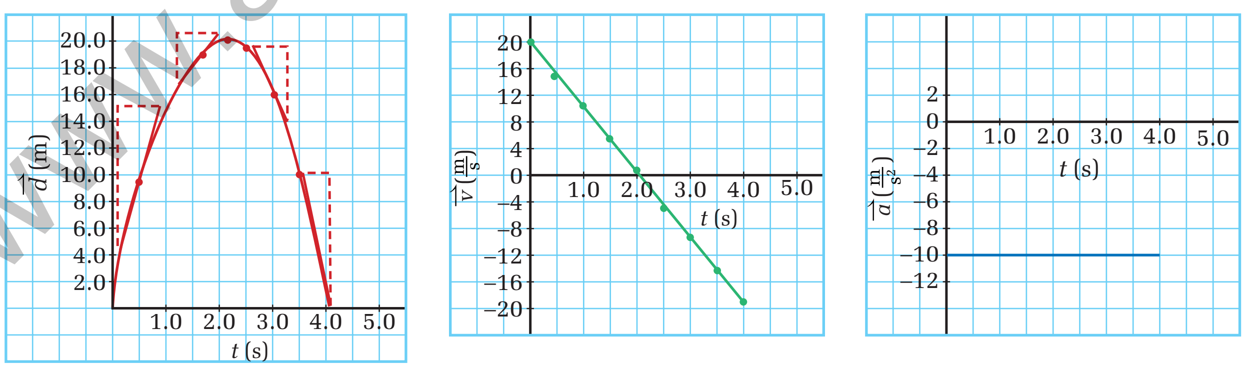
Physicists often use the term "uniform motion" to apply to motion with a constant velocity, and "uniformly accelerated motion" to apply to motion with a constant acceleration.

Table 2.5 Position-Time Data

t (s)	$\vec{d}$ (m)
0.0	0.0
0.5	8.8
1.0	15.1
1.5	19.0
2.0	20.4
2.5	19.4
3.0	15.9
3.5	10.0
4.0	1.6

Note: Since the motion is in one dimension, direction is indicated by plus (+) or minus (–).

Figure 2.22 Position, velocity, and acceleration graphs for Table 2.6



QUICK LAB

Graphing the Motion of a Vans

TARGET SKILLS
- Analyzing and interpreting
- Communicating results

You qualitatively analyzed the motion of a van earlier. Now, using the example of the ball thrown into the air, you can do a more detailed analysis of the van's motion. The table shown here includes the time and position data, with one worked example for finding acceleration.

Sample Calculation

Notice that the velocity that will be plotted at $t = 1.0$ s is the average velocity between $t = 0.0$ s and $t = 2.0$ s. The velocity that will be plotted at $t = 3.0$ s is the average velocity between $t = 2.0$ s and 4.0 s. The acceleration that will be plotted at t = 2.0 s is the average acceleration between $t = 1.0$ s and $t = 3.0$ s.

$$\vec{v}_1 = \frac{\Delta\vec{d}_{0\to 2}}{\Delta t_{0\to 2}} = \frac{\vec{d}_2 - \vec{d}_0}{t_2 - t_0} = \frac{12\text{ m} - 0.0\text{ m}}{2.0\text{ s} - 0.0\text{ s}} = \frac{12\text{ m}}{2.0\text{ s}} = 6.0\frac{\text{m}}{\text{s}}$$

$$\vec{v}_3 = \frac{\Delta\vec{d}_{2\to 4}}{\Delta t_{2\to 4}} = \frac{\vec{d}_4 - \vec{d}_2}{t_4 - t_2} = \frac{36\text{ m} - 12\text{ m}}{4.0\text{ s} - 2.0\text{ s}} = \frac{24\text{ m}}{2.0\text{ s}} = 12\frac{\text{m}}{\text{s}}$$

$$\vec{a}_2 = \frac{\Delta\vec{v}_{1\to 3}}{\Delta t_{1\to 3}} = \frac{\vec{v}_3 - \vec{v}_1}{t_3 - t_1} = \frac{12\frac{\text{m}}{\text{s}} - 6.0\frac{\text{m}}{\text{s}}}{3.0\text{ s} - 1.0\text{ s}} = \frac{6.0\frac{\text{m}}{\text{s}}}{2.0\text{ s}} = 3.0\frac{\text{m}}{\text{s}^2}$$

Complete the table for all average velocities and average accelerations. Then plot position-time, velocity-time, and acceleration-time graphs. On the position-time graph, select one point between 0 and 4 s and one point between 6 and 10 s. Draw tangents to the curve and determine their slopes.

Time t (s)	Position $\vec{d}$ (m)	Velocity $\frac{\Delta\vec{d}}{\Delta t}$ (m/s)	Acceleration $\frac{\Delta\vec{v}}{\Delta t}$ (m/s^2)
0.0	0.0	6.0	
2.0	12	12	+3.0
4.0	36		
6.0	48		
8.0	96		
10.0	142		
12.0	190		
14.0	226		
16.0	250		
18.0	262		

Analyze and Conclude

1. How well do the average and instantaneous velocities that you calculated agree with each other?
2. Separate the graphs into three sections: (a) 0 s to 8s, (b) 8 s to 12 s, and (c) 12 s to 20 s. For each of these three time periods, compare all three graphs in the following ways.
   (a) How do the shapes of the graphs (curved, straight, horizontal) relate to each other?
   (b) How do the signs of the values (positive, zero, or negative) relate to each other?
3. Under what circumstances can the van be moving but have a zero acceleration?
4. Under what circumstances is the sign of the velocity the same as the sign of the acceleration?
5. What general statement can you make about the motion of the van when the direction of the acceleration vector is opposite to the direction of the velocity vector?

Think It Through

- How do intervals of constant acceleration appear on an acceleration-time graph?
- How do intervals of constant acceleration appear on a velocity-time graph?
- What does a straight-line slope indicate on an acceleration-time graph?
- What would a curved line indicate on an acceleration-time graph?
- Explain circumstances in which an object would be accelerating but have an instantaneous velocity of zero?
- How does uniform acceleration differ from uniform motion?

Concept Organizer

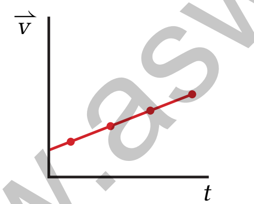
The acceleration of these sprinters will probably be very large at first and then level off to zero. Their instantaneous acceleration will not be measured and reported. You can only determine an average acceleration if the data taken are only the overall distance and time. What data would you need in order to calculate instantaneous acceleration?

Velocity of object determined during a number of time intervals

Uniform Acceleration

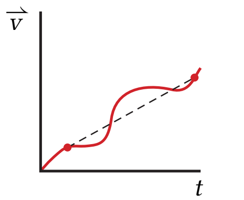
Non-Uniform Acceleration

Constant Acceleration



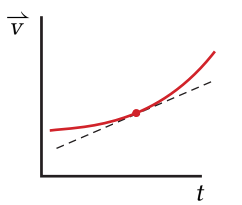
Slope of straight line

Average Acceleration



Slope of line connecting initial and final positions

Instantaneous Acceleration



Slope of tangent to curve

Figure 2.23 The three ways in which you can describe acceleration are very similar to the ways of describing velocity.

CANADIANS IN PHYSICS

Balancing Forces in Structural Engineering

Dr. Jane Thorburn knows about the importance of balancing forces. In her work as a structural engineer, she designed highway bridges for the New Brunswick Department of Transportation. Now a professor at Dalhousie University in Halifax, Nova Scotia, she teaches courses on structural engineering and conducts research on the behaviour of structural steel members.

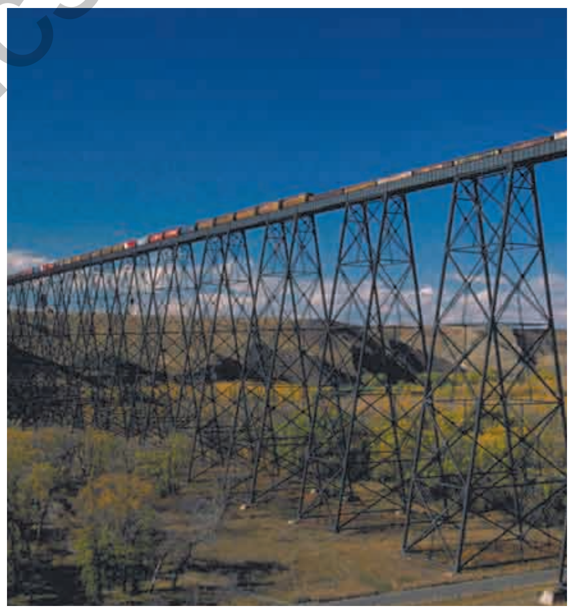
According to Newton's laws, any stable structure — such as a building, bridge, or tower — must produce internal reactions equal in magnitude and opposite in direction to all of the forces acting on it. Structures will be inadequate unless they can balance these external forces, also called "loads."

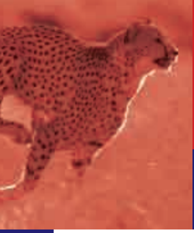
Structural engineers like Dr. Thorburn determine the right design and materials that will allow a structure to support all possible loads. For example, all structures must be able to support their own mass. They also might have to bear temporary loads related to their use, such as traffic, people, or furniture. At times, a structure might need to balance environmental forces caused by temperature changes, wind, snow accumulation, or earthquakes.

Dr. Thorburn worked on the Hammond River bridge in New Brunswick. When designing this bridge and choosing the materials for its construction, she took several factors into consideration. The bridge had to support the weight of two lanes of traffic. It also had to support its own weight, so the building materials had to be as light as possible. Dr. Thorburn also took environmental factors into account. For example, since the Hammond River is the site of an important salmon run, she wanted to minimize the number of concrete bridge supports, or piers, that were embedded in the riverbed, to reduce any effects that the piers might have on the salmon fishery. In her design, she was able to use only three piers.

Dr. Thorburn also had to determine how the bridge materials could be moved into the construction area, how they would connect together, and how to balance forces during the actual construction of the bridge.

Like most structural engineers, Dr. Thorburn uses special computer software that enables her to create mathematical models of her bridge designs and to determine the impact of external loads on these designs. Her calculation of forces and her understanding of building materials ensure the safety and stability of highway bridges and other structures.





INVESTIGATION 2-A

Acceleration Due to Gravity

TARGET SKILLS
- **Performing and recording**
- **Identifying variables**
- **Analyzing and interpreting**

One of the most famous stories of physics tells of how Galileo dropped cannonballs of various masses off the leaning Tower of Pisa to disprove the accepted theories of free-fall. Until Galileo's time, natural philosophers (the name for scientists of the time) thought that heavy objects fell "faster" than light objects. However, based on Galileo's thinking and experimentation, scientists now agree that acceleration due to gravity *in a vacuum* is

- uniform
- independent of the mass of the falling object

This investigation challenges you to verify Galileo's model experimentally and to determine the numerical value of the acceleration due to gravity. Since you will be working in air and not a vacuum, your results will provide some information about the effect of air resistance on the acceleration of falling objects.

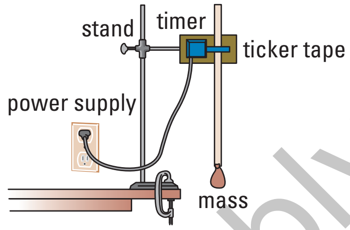
Problem

Verify that acceleration due to gravity is uniform and independent of mass.
Determine the numerical value of acceleration due to gravity.

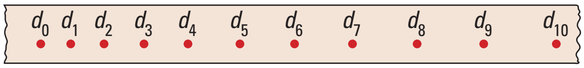
Equipment

- spark timer
- recording tape
- variety of small objects (rubber stoppers, steel balls, wooden beads, film canisters filled with different amounts of sand) (CAUTION Do not open canisters)
- cellophane tape
- retort stand
- clamp

Procedure



1. Set your spark timer at 10 Hz so the time between dots will be 0.10 s.
2. Clamp a spark timer to a retort stand. Secure the retort stand close to the edge of a desk or lab bench so that an object pulling the recording tape through the timer can fall to the floor.
3. Attach a small object to a piece of recording tape that is 1 m long.
4. Thread the recording tape through the timer.
5. Hold the object in place. Turn on the timer and release the object.
6. Repeat step 5 for at least three objects of different masses. Collect enough tapes so that each member of your lab group has one tape to analyze.
7. While the object is falling, the timer will record a series of dots on the tape that will look like the diagram. Locate the first clear dot that marks the beginning of a series of at least 10 time intervals. Label this dot "$\vec{d}_0$" to designate it as the origin of your frame of reference. Label the next 10 dots "$\vec{d}_1$," "$\vec{d}_2$," ..., "$\vec{d}_{10}$" to mark the position of the object at the end of each of 10 time intervals.
8. Make a table with the following headings: Position, Time, Time interval, Displacement, Average velocity, Change in velocity, Acceleration.



9. Use the label "t_0" for the instant in time at which the object is at position $\vec{d}_0$. Record the time and position of the object for the sequence of 10 positions following your designation of $\vec{d}_0$.
10. Complete the table by performing the indicated calculations.
11. Construct position-time, average velocity-time, and average acceleration-time graphs.

Analyze and Conclude

1. Using the slope of your average velocity-time graph, calculate the value of the acceleration.
2. Compare your value of acceleration calculated in the above step to the values in your table that you calculated for individual intervals. Do they agree or is there a significant difference among them? If they differ, which values do you think are more accurate?
3. Compare the average acceleration determined from your velocity-time graph with the values determined by (a) other members of your group and (b) other groups in your class. Do the masses of the objects appear to have any influence on the value calculated for acceleration? If so, what effect does mass appear to have?
4. Considering all of the comparisons you have just made, does your class data support the model that says that acceleration due to gravity is constant and independent of mass? If not, explain how your class data contradict the model. How might you account for any discrepancies?
5. The accepted value for acceleration due to gravity is 9.81 m/s^2. Calculate the percent deviation of your own calculated value from the accepted value. If you need to review the method for determining percent deviation, go to Skill Set 1.
6. Calculate an average of the class data for the acceleration due to gravity. Omit any data points that are extremely different from the majority of the values. Calculate the percent deviation of the class average value to the accepted value. How might you account for any discrepancies?
7. Discuss how well (or poorly) your class data support the accepted value of 9.81 m/s^2 for the acceleration due to gravity.
8. Describe any factors that might be affecting the free-fall of each object as it pulls the recording tape through the timer.
9. How might air friction affect your data?
10. Discuss any other possible reasons for a deviation from the accepted value for acceleration due to gravity in a vacuum.
11. Identify possible errors that could have arisen during your experiment and suggest refinements to your procedure to minimize these errors.
12. Identify and discuss any evidence that the shape of an object affects its free-fall acceleration.

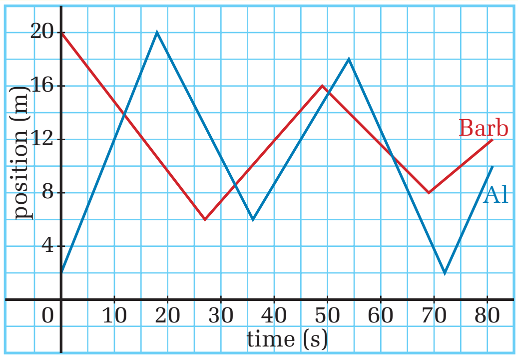
Apply and Extend

13. Design and conduct an investigation to determine how the shape of an object affects its acceleration due to gravity in air. Determine what shape is the most aerodynamic; that is, determine what shape allows the object to accelerate downward with an acceleration as close to 9.81 m/s^2 as possible? (**Note:** To correctly test for the effect of shape, each object must have the same mass.)

CAUTION Get your teachers approval.

2.4 Section Review

1. **I** The following graphs represent the motion of two students, Al and Barb, walking back and forth in front of the school, waiting to meet friends.



   (a) During what periods of time are Al and Barb walking in the same direction?

   (b) At what points do Al and Barb meet?

   (c) During what periods of time are Al and Barb facing each other?

   (d) Which student is, on the average, walking faster than the other? Explain your reasoning.

2. **K/U** Describe the similarities and differences between:

   (a) constant acceleration and non-uniform acceleration.

   (b) average acceleration and instantaneous acceleration.

3. **C** Explain the relationship between:

   (a) tangent line on a velocity time graph, time interval, and acceleration.

   (b) negative acceleration and deceleration.

   (c) m/s and m/s^2

4. **K/U** How is the direction of an acceleration vector determined?

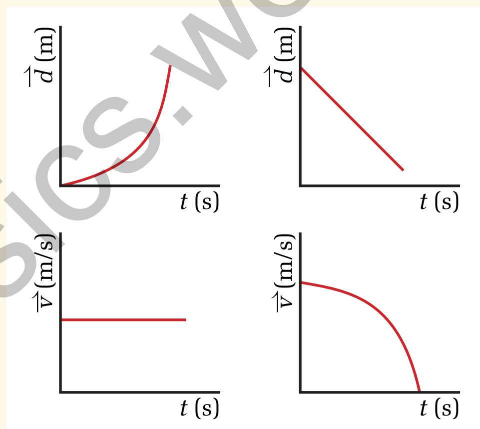
5. **K/U** Describe a motion when:

   (a) velocity and acceleration vectors are in the same direction.

   (b) velocity and acceleration vectors are in opposite directions.

6. **I** Throw a ball up into the air (from rest) and catch it. Sketch the path of the ball. Label points where the vertical velocity is zero. Label points where the acceleration is zero.

7. **I** Draw conclusions about the acceleration of the motion represented by the following graphs.



8. **I** Design a simulation on interactive physics software to verify that acceleration due to gravity is uniform and independent of mass.

UNIT PROJECT PREP

Vehicles and objects are commonly seen speeding up, slowing down, and changing direction in motion pictures.

- What do you feel when a vehicle starts or stops suddenly? How can you use this in your "virtual reality"?
- An object accelerating towards the ground can be a dramatic situation. What effects can you use to simulate this?

2.5 Mathematical Models of Motion

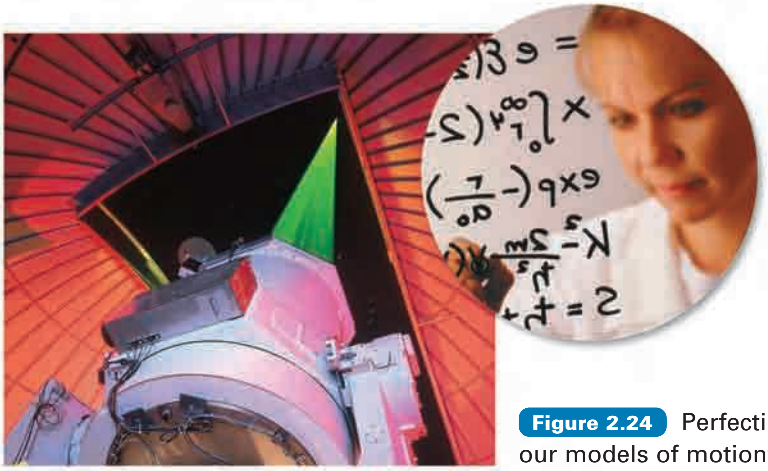


Figure 2.24 Perfecting our models of motion

SECTION EXPECTATIONS

- Identify the variables and equations used to mathematically model the motion of an object.
- Apply quantitative relationships among displacement, velocity, and acceleration.
- Develop problem-solving skills and strategies through the analysis and synthesis of information.

KEY TERMS

- equations of motion

Throughout this chapter, you have been developing models of motion. Your models have taken the form of stick figures, mathematical definitions of displacement, velocity, and acceleration, and graphs. In this section, you will call on all of those models to build a set of mathematical equations called the **equations of motion** (or of kinematics) for uniform acceleration. As the name implies, these equations apply *only* to situations in which the *acceleration is constant*.

A very important feature of the equations of motion is that they apply independently to each dimension, so you will use them to analyze motion in one direction at a time. For example, you will analyze only north-south motion or only vertical (up and down) motion. Consequently, the variables in the equations represent only the parts, or components, of the vector quantities, position, displacement, velocity, and acceleration.

Figure 2.25 shows a position and displacement vector separated into components. Since components of vectors apply to only one dimension, they are not vectors themselves. Therefore, vector notations will not be used in the equations of motion.

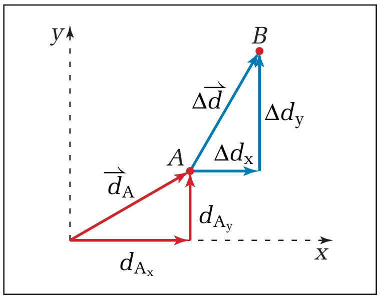


Figure 2.25 The displacement of an object that moved from point A to point B is represented by the vector $\Delta\vec{d}$. The object moved a distance, Δd_x, in the x direction and a distance, Δd_y in the y direction. Therefore, Δd_x is called the x-component of the displacement vector and Δd_y is the y-component. Any vector can be divided into components. The x- and y-components of position vector $\vec{d}_A$ are also shown, and are labelled as "d_{Ax}" and "d_{Ay}".

Deriving the Kinematic Equations

The fundamental definitions of displacement, velocity, and acceleration form the basis of the set of equations you will develop and apply. Start with the definition of acceleration in one dimension.

$$a = \frac{\Delta v}{\Delta t}$$

In some cases, you will know the initial and final velocities for a certain time interval and want to determine the acceleration. So, you will use the expanded form of the mathematical definition for the change in velocity: $\Delta v = v_f - v_i$. Substituting this expression into the original equation for acceleration, you obtain a useful equation.

$$a = \frac{v_f - v_i}{\Delta t}$$

In many cases, you will know the initial velocity and acceleration and want to find the final velocity for a time interval. Algebraically rearranging the above equation will give you another useful form.

- Mulitply both sides of the equation by Δt and simplify.

$$a\Delta t = \left(\frac{v_f - v_i}{\cancel{\Delta t}}\right)\cancel{\Delta t}$$
$$v_f - v_i = a\Delta t$$

- Add v_i to both sides of the equation and simplify.

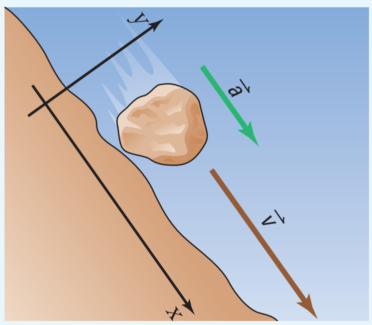
$$v_f - v_i + v_i = a\Delta t + v_i$$
$$v_f = v_i + a\Delta t$$

MODEL PROBLEMS

Changing Velocities

1. A slight earth tremor causes a large boulder to break free and start rolling down the mountainside with a constant acceleration of 5.2 m/s^2. What was the boulder's velocity after 8.5 s?

Frame the Problem



- Sketch and label a diagram of the motion.
- Choose the *direction of the motion* of the boulder as the *positive x* direction so the displacement will be positive.
- The boulder was *stationary* before the tremor, so its *initial velocity* was zero.
- The boulder's *acceleration* was constant, so the *equations of motion* apply to the problem.

Identify the Goal

The velocity (in one dimension), v, of the boulder 8.5 s after it started rolling

Variables and Constants

Involved in the problem		Known	Implied	Unknown
v_i	a	$a = 5.2$ m/s^2	$v_i = 0$ m/s	v_f
v_f	Δt	$\Delta t = 8.5$ s		

Strategy

Select the equation that relates the final velocity to the initial velocity, acceleration and time interval.

All of the needed quantities are known so substitute them into the equation.

Simplify.

The final velocity of the boulder was 43 m/s.

Calculations

$$v_f = v_i + a\Delta t$$

$$v_f = 0.0\ \frac{m}{s} + \left(5.2\ \frac{m}{s^{\cancel{2}}}\right)(8.3\ \cancel{s})$$

$$v_f = 43.16\ \frac{m}{s}$$

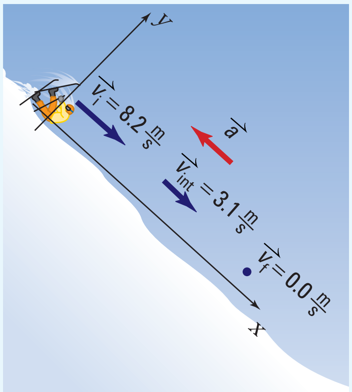
Validate

The units cancel to give metres per second, which is correct for velocity. The product of 5 x 8 is 40, so you would expect the answer to be slightly larger than 40 m/s.

2. A skier is going 8.2 m/s when she falls and starts sliding down the ski run. After 3.0 s, her velocity is 3.1 m/s. How long after she fell did she finally come to a stop? (Assume that her acceleration was constant.)

Frame the Problem

- Sketch and label the situation.
- Choose a coordinate system that places the skier at the origin when she falls and places her motion in the positive *x* direction.
- When the skier falls and begins to slide, her *initial velocity* is the same as her skiing velocity.
- Friction begins to *slow* her down and, eventually, she will come to a *stop*.
- Her *final velocity* will be *zero*.
- Since her *acceleration is constant*, the *equation of motion* relating initial and final velocities to acceleration and time applies to this problem.



Identify the Goal

The total time, Δt, it takes for the skier to stop sliding

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Variables and Constants

Involved in the problem		Known	Implied	Unknown
v_i	a	$v_i = 8.2\ \frac{\text{m}}{\text{s}}$	$v_f = 0.0\ \frac{\text{m}}{\text{s}}$	a
$v_{intermediate}$	Δt	$v_{int} = 3.1\ \frac{\text{m}}{\text{s}}$		Δt
v_f				

Strategy

You know the initial and final velocities but you need to find the acceleration in order to solve for the time interval. In this case, it is best to use the definition for acceleration.

Use the information about the intermediate velocity to find the acceleration. At the intermediate time, the "final" velocity is 3.1 m/s. Substitute values into the equation.

Knowing the acceleration, you can use it to find the length of the entire time interval from the initial fall to the time the skier stopped. Use the same form of the equation, but use the calculated acceleration. Also, in this part of the problem, the final velocity is zero.

It took 4.8 s for the skier to come to a stop.

Calculations

$$a = \frac{v_f - v_i}{\Delta t}$$

$$a = \frac{3.1\ \frac{\text{m}}{\text{s}} - 8.2\ \frac{\text{m}}{\text{s}}}{3.0\ \text{s}}$$

$$a = \frac{-5.1\ \frac{\text{m}}{\text{s}}}{3.0\ \text{s}}$$

$$a = -1.7\ \frac{\text{m}}{\text{s}^2}$$

Substitute first

$$a = \frac{v_f - v_i}{\Delta t}$$

$$-1.7\ \frac{\text{m}}{\text{s}^2} = \frac{0.0\ \frac{\text{m}}{\text{s}} - 8.2\ \frac{\text{m}}{\text{s}}}{\Delta t}$$

$$\left(-1.7\ \frac{\text{m}}{\text{s}^2}\right)\Delta t = \frac{0.0\ \frac{\text{m}}{\text{s}} - 8.2\ \frac{\text{m}}{\text{s}}}{\cancel{\Delta t}}\cancel{\Delta t}$$

$$\frac{\cancel{\left(-1.7\ \frac{\text{m}}{\text{s}^2}\right)}\Delta t}{\cancel{\left(-1.7\ \frac{\text{m}}{\text{s}^2}\right)}} = \frac{-8.2\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{\left(-1.7\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)}$$

$$\Delta t = 4.823\ \text{s}$$

Solve for Δt first

$$a = \frac{v_f - v_i}{\Delta t}$$

$$a\Delta t = \frac{v_f - v_i}{\cancel{\Delta t}}\cancel{\Delta t}$$

$$\frac{\cancel{a}\Delta t}{\cancel{a}} = \frac{v_f - v_i}{a}$$

$$\Delta t = \frac{0.0\ \frac{\text{m}}{\text{s}} - 8.2\ \frac{\text{m}}{\text{s}}}{-1.7\ \frac{\text{m}}{\text{s}^2}}$$

$$\Delta t = \frac{-8.2\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{-1.7\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}}$$

$$\Delta t = 4.823\ \text{s}$$

Validate

The units cancelled to give seconds, which is correct for a time interval. Eight seconds is a reasonable time period for a skier to slide to a stop.

PRACTICE PROBLEMS

6. An Indy 500 race car's velocity increases from +6.0 m/s to +38 m/s over a 4.0 s time interval. What is its average acceleration?
7. A stalled car starts to roll backward down a hill. At the instant that it has a velocity of 4.0 m/s down the hill, the driver is able to start the car and start accelerating back up. After accelerating for 3.0 s, the car is travelling uphill at 3.5 m/s. Determine the car's acceleration once the driver got it started. (Assume that the acceleration was constant.)
8. A bus is travelling along a street at a constant velocity when the driver steps on the brakes and brings the bus to a stop in 3.0 s. If the brakes cause the bus to accelerate at $-8.0\ \text{m/s}^2$, at what velocity was the bus travelling when the brakes were applied?

Building Equations

The next logical step in building a set of equations would be to rearrange the equation that defines velocity. However, a problem arises when you try to use the equation. Can you see why?

$$v = \frac{\Delta d}{\Delta t}$$

$$v\Delta t = \left(\frac{\Delta d}{\cancel{\Delta t}}\right)\cancel{\Delta t}$$

$$\Delta d = v\Delta t$$

This equation is valid *only if the velocity is constant*, that is, if the motion is uniform. The equations of motions are developed for *constant acceleration*. So, unless that constant acceleration is zero, the velocity will be changing.

To find a relationship between displacement and velocity for a changing velocity, turn, once again, to graphs. First, consider an object moving at a constant velocity. The velocity-time graph is simply a horizontal line, as shown in Figure 2.26. As well, displacement is the product of the constant velocity and the time interval. Notice on the graph that velocity and time interval form the sides of a rectangle. Since the area of a rectangle is the product of its sides, velocity times time must be the same as the area of the rectangle.

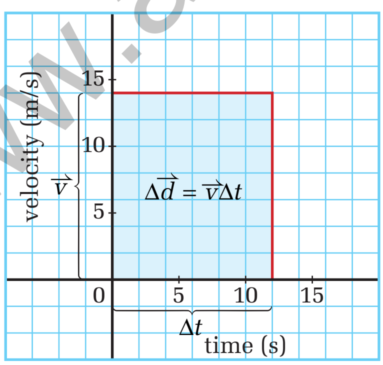


Figure 2.26 The area under the curve of a velocity-time graph is the displacement.

In fact, the displacement of an object is always the same as the area under the velocity-time graph. When the graph is a curve, you can approximate displacement by estimating the area under the curve. In Figure 2.27 (A), the area of each of the small squares is 5.0 m/s times 1.0 s or 5.0 m. Counting the number of squares and multiplying by 5.0 m gives a good estimate of displacement. You can make your estimate more accurate by dividing up the area into small rectangles as shown in Figure 2.27 (B). Notice that the corner of each rectangle above the curve on the left is nearly the same area as the space between the rectangle and the curve on the right. So the area of the rectangle is very nearly the same as the area under the curve. When you add the areas of all of the rectangles, you have a very close approximation of the displacement.

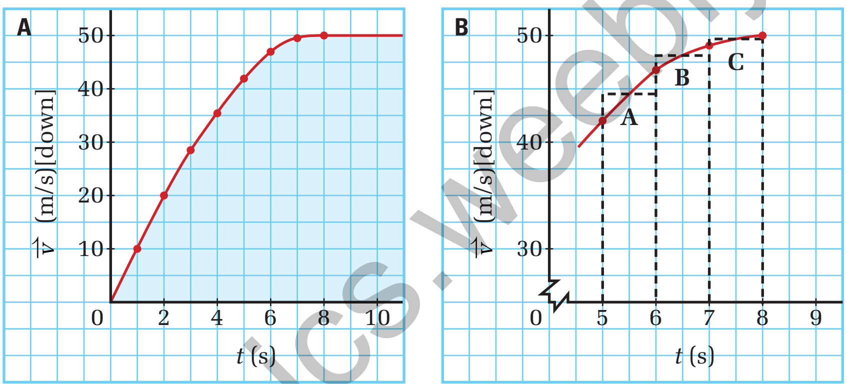


Figure 2.27 **(A)** The area under the curve is the displacement. **(B)** You can increase the accuracy of the area determination by making the columns narrower. (Why?)

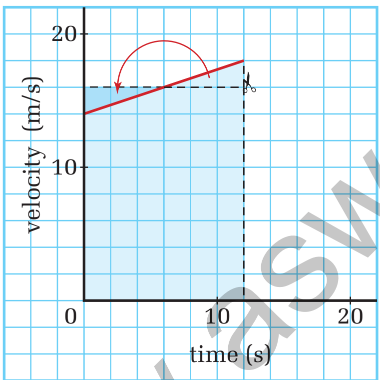


Figure 2.28 Confirm the results of the analysis by using the formula for the area of a trapazoid. $A = \frac{(\text{side 1} + \text{side 2})}{2}(\text{width})$

How does the knowledge that the area under the curve is the same as the displacement help you to develop precise equations for displacement under constant acceleration? Consider the shape of the velocity-time graph for an object travelling with uniform acceleration. The graph is a straight line, as shown in Figure 2.28. If you draw a rectangle so that the line forming the top is precisely at the midpoint between the initial velocity and the final velocity, you will find that the line intersects the velocity curve exactly at the midpoint of the time interval. The top of the rectangle and the velocity line create a congruent triangle. If you cut out the triangle on the right (below the graph), it would fit perfectly into the triangle on the left (above the graph). The area of the rectangle is *exactly* the same as the displacement. The height of the rectangle is the average of the initial and final velocities for the time interval or $v_{ave} = \frac{v_i + v_f}{2}$. You can now use this expression for velocity in the equation developed for displacement, above.

$$\Delta d = v\Delta t$$

$$\Delta d = \frac{v_i + v_f}{2}\Delta t$$

You have just developed another useful equation of motion for uniform acceleration.

Often, you know the initial velocity of an object and its acceleration but not the final velocity. You can develop an expression for displacement that does not include final velocity.

- Start with the equation above. $\Delta d = \frac{v_i + v_f}{2}\Delta t$
- Recall the expression you developed for final velocity. $v_f = v_i + a\Delta t$
- Substitute this value into the first equation. $\Delta d = \left(\frac{v_i + (v_i + a\Delta t)}{2}\right)\Delta t$
- Combine like terms. $\Delta d = \left(\frac{2v_i + a\Delta t}{2}\right)\Delta t$
- Multiply through by Δt. $\Delta d = \frac{\cancel{2}v_i\Delta t}{\cancel{2}} + \frac{a\Delta t^2}{2}$
- Simplify. $\Delta d = v_i\Delta t + \frac{1}{2}a\Delta t^2$

Table 2.6 summarizes the equations of motion and indicates the variables that are related by each equation. Notice that, in every case, the equation relates four of the five variables. Therefore, if you know three of the variables, you can find the other two. First, use an equation that relates the three known variables to a fourth. Then, find an equation that relates any three of the four you now know to the fifth.

Table 2.6 Equations of Motion under Uniform Acceleration

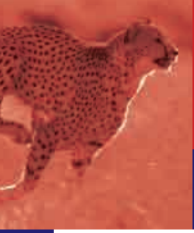
Equation	Variables				
	Δd	v_i	v_f	a	Δt
$a = \frac{v_f - v_i}{\Delta t}$		x	x	x	x
$v_f = v_i + a\Delta t$		x	x	x	x
$\Delta d = \frac{v_i + v_f}{2}\Delta t$	x	x	x		x
$\Delta d = v_i\Delta t + \frac{1}{2}a\Delta t^2$	x	x		x	x

Think It Through

- Derive an equation that relates v_i, v_f, Δd, and a. (Hint: Notice that Δt is not involved.) Solve for Δt in the first equation. Substitute that value into Δt in the third equation. Solve for v_f^2. Can you prove that $v_f^2 = v_i^2 + 2ad$?

History Link

Research how Galileo Galilei used the equation $\Delta d = v_i\Delta t + \frac{1}{2}a\Delta t^2$ to calculate the acceleration due to gravity. Given the fact that he could not use a stopwatch to measure time, how close was his value for a?



INVESTIGATION 2-B

Stop on a Dime

TARGET SKILLS
- Initiate and planning
- Hypothesizing
- Analyzing and interpreting

In this investigation, you will be challenged to build a vehicle that, when launched from a ramp, will travel a horizontal distance of 3.0 m and come to rest on a dime!

Problem

Design, build, and test a vehicle. Enter it into a competition.

Equipment

- flat 1.0 m ramp
- dime
- materials of your choice for building a vehicle

Procedure

Designing and Building

1. With a partner or a small group, discuss potential designs for your vehicle, according to the following criteria.
   (a) Prefabricated kit and prefabricated wheels are not allowed.
   (b) Propulsion may come only from the energy gained by rolling the vehicle down a 1.0 m ramp.
   (c) You may adjust the angle of the ramp.
   (d) The vehicle must be self-contained. No external guidance systems, such as tracks, guide wires, or strings, are permitted.

   Be creative. Do not limit your thinking to a traditional four-wheeled vehicle.
2. Collect materials and build your vehicle according to your design. Get your teacher's approval before testing.
3. Test your vehicle and make adjustments until you are satisfied with its performance. Collect data on at least three trial runs.

Entering the Competition

4. As a class, establish criteria for being allowed to enter the competition. For example, the vehicle must stop within 10 cm of the dime in at least one test run.
5. Submit a written application for entry into the competition. The application must include the following.
   (a) Description of design features
   (b) Outline of any major problems encountered in testing the vehicle, accompanied by a discussion of the solutions you discovered
   (b) Data from trial runs, including position-time, velocity-time, and acceleration-time graphs. Data must include at least three time intervals while accelerating down the ramp and five time intervals after the vehicle begins its horizontal motion.

The Competition

6. As a class, decide on the scoring system for the competition. Decide how many points will be given for such results as coming within 6.0 cm of the dime. Decide on other possible criteria for points. For example, points could be given for sturdiness, creative use of materials, originality, or aesthetic appeal.
7. Hold the competition.

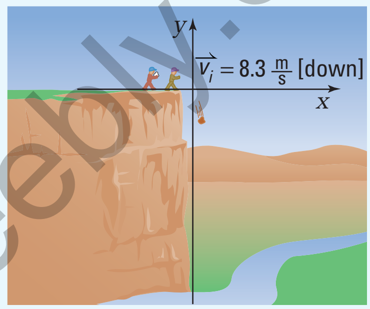
Analyze and Conclude

1. Analyze the performance of your own vehicle in comparison with your own criteria.
2. Analyze your vehicle in comparison with the vehicle that won the competition.
3. Considering what you learned from the competition, how would you design your vehicle differently if you were to begin again?
4. Summarize what you have learned about motion from this challenge.

Applying the Equations of Motion

1. You throw a rock off a cliff, giving it a velocity of 8.3 m/s, straight down. At the instant you released the rock, your hiking buddy started a stopwatch. You heard the splash when the rock hit the river below, exactly 6.9 s after you threw the rock. How high is the cliff above the river?

Frame the Problem



- Make a sketch of the problem and assign a coordinate system.
- The rock had an *initial velocity downward*. Since you chose downward as negative, the initial velocity is *negative*.
- The rock is *accelerating* due to gravity.
- The acceleration due to gravity is *constant*. Therefore, the equations of motion for uniform acceleration apply to the problem.

Identify the Goal

The displacement, Δd, from the top of the cliff to the river below

Variables and Constants

Involved in the problem		Known	Implied	Unknown
v_i	Δt	$v_i = -8.3$ m/s	$a = -9.81$ m/s^2	Δd
a	Δd	$\Delta t = 6.9$ s		

Strategy

Calculations

Use the equation of motion that relates the unknown variable, Δd, to the three known variables, v_i, a, and Δt.

$$\Delta d = v_i \Delta t + \frac{1}{2} a \Delta t^2$$

Substitute the known variables.

$$\Delta d = \left(-8.3\ \frac{\text{m}}{\cancel{\text{s}}}\right)(6.9\ \cancel{\text{s}}) + \frac{1}{2}\left(-9.81\ \frac{\text{m}}{\text{s}^2}\right)(6.9\ \text{s})^2$$

Simplify.

$$\Delta d = -57.27\ \text{m} + \left(-4.905\ \frac{\text{m}}{\cancel{\text{s}^2}}\right)(47.61\ \cancel{\text{s}^2})$$

$$\Delta d = -57.27\ \text{m} - 233.53\ \text{m}$$

$$\Delta d = -290.8\ \text{m}$$

The cliff was 2.9×10^2 m above the river. The negative sign indicates that the distance is in the negative direction, or down, from the origin, the point from which you threw the rock.

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Validate

All of the units cancel to give metres, which is the correct unit. The sign is negative, which you would expect for a rock going down. The rock fell a long distance (more than a quarter of a kilometre), so 6.9 s is a reasonable length of time for the rock's fall to have taken.

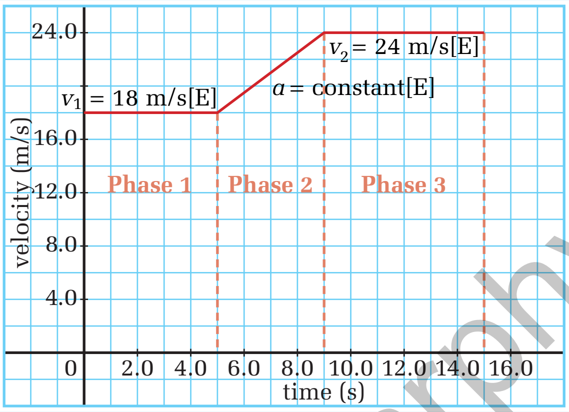
2. A car travels east along a straight road at a constant velocity of 18 m/s. After 5.0 s, it accelerates uniformly for 4.0 s. When it reaches a velocity of 24 m/s, the car proceeds with uniform motion for 6.0 s. Determine the car's total displacement during the trip.

PROBLEM TIP

When the type of motion of an object changes, the problem must be split into phases. Each phase is treated as a separate problem. The "final" conditions of one phase become the "initial" conditions of the next phase.

Frame the Problem

- Make a diagram of the motion of the car that includes the known variables during each phase of the car's motion.



- During phase 1, the car is moving with *uniform motion*. Since the *acceleration* is *zero*, the equations of motion with uniform acceleration are not needed. The equation *defining velocity* applies to this phase.
- During phase 2 of the motion, the car is *accelerating*. Therefore, use the equation of motion with *uniform acceleration* that relates time, initial velocity, and final velocity to displacement.
- During phase 3, the car is again moving with *uniform motion*.
- The *total displacement* of the car is the *sum* of the displacements for all three phases.

Identify the Goal

The total displacement, Δd, of the car for the duration of the motion

Variables and Constants

Involved in the problem		**Known**		**Unknown**
v_1	Δt_3	$v_1 = 18$ m/s	$\Delta t_2 = 4.0$ s	Δd_{total}
v_2	Δd_1	$v_2 = 24$ m/s	$\Delta t_3 = 6.0$ s	Δd_1
Δt_1	Δd_2	$\Delta t_1 = 5.0$ s		Δd_2
Δt_2	Δd_3			Δd_3

Strategy

Calculations

Use the equation that defines velocity.

$$\Delta d = v\Delta t$$

Substitute values.

$$\Delta d_1 = v_1\Delta t_1$$

Simplify.

$$\Delta d_1 = \left(18\ \frac{\text{m}}{\cancel{\text{s}}}[\text{E}]\right)(5\ \cancel{\text{s}})$$

$$\Delta d_1 = 90\ \text{m}[\text{E}]$$

The displacement for phase 1 was 90 m east.

Use the equation of motion that relates time, initial velocity, and final velocity to displacement.

$$\Delta d = \frac{v_\text{i} + v_\text{f}}{2}\Delta t$$

$$\Delta d_2 = \frac{v_1 + v_2}{2}\Delta t_2$$

Substitute values.

$$\Delta d_2 = \frac{18\ \frac{\text{m}}{\text{s}}[\text{E}] + 24\ \frac{\text{m}}{\text{s}}[\text{E}]}{2}(4\ \text{s})$$

Simplify.

$$\Delta d_2 = 21\ \frac{\text{m}}{\cancel{\text{s}}}[\text{E}]\ 4\ \cancel{\text{s}}$$

$$\Delta d_2 = 84\ \text{m}[\text{E}]$$

The displacement during phase 2 was 84 m east.

Use the equation that defines velocity.

$$\Delta d = v\Delta t$$

$$\Delta d_3 = v_2\Delta t_3$$

Substitute values.

$$\Delta d_3 = \left(24\ \frac{\text{m}}{\cancel{\text{s}}}[\text{E}]\right)6\ (\cancel{\text{s}})$$

Simplify.

$$\Delta d_3 = 144\ \text{m}[\text{E}]$$

The displacement during phase 3 was 144 m east.

Find the sum of the displacements for all three phases.

$$\Delta d_\text{total} = \Delta d_1 + \Delta d_2 + \Delta d_3$$

$$\Delta d_\text{total} = 90\ \text{m}[\text{E}] + 84\ \text{m}[\text{E}] + 144\ \text{m}[\text{E}]$$

$$\Delta d_\text{total} = 318\ \text{m}[\text{E}]$$

The total displacement for the trip was 3.2×10^2 m east.

Validate

In every case, the units cancelled to give metres, which is the correct unit for displacement. The duration of the trip was short (15 s), so the displacement cannot be expected to be very long. The answer of 318 m[E] is very reasonable.

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3. A truck is travelling at a constant velocity of 22 m/s north. The driver sees a traffic light turn from red to green soon enough, so he does not have to alter his speed. Meanwhile, a woman in a sports car is stopped at the red light. At the moment the light turns green and the truck passes her, she begins to accelerate at 4.8 m/s². How far have both vehicles travelled when the sports car catches up with the truck? How long did it take for the sports car to catch up with the truck?

Frame the Problem

- The truck and the sports car leave the traffic signal at the *same time*. Define this time as $t = 0.0$ s.
- The truck passes the sports car at the traffic light. Let this point be $d = 0.0$ m.
- The truck travels with *uniform motion*, which means *constant velocity*. The truck's motion can therefore be described using the *equation that defines velocity*.
- The car's *initial velocity is zero*. Then, the car travels with *uniform acceleration*. The *equation of motion* that relates displacement, initial velocity, acceleration, and time interval describes the car's motion.
- When the sports car catches up with the truck, both vehicles have travelled for the *same length of time* and the *same distance*.

Identify the Goal

The displacement, Δd, that the sports car and truck travel from the traffic light to the point where the sports car catches up with the truck

The time interval, Δt, that it takes for the sports car to catch up with the truck

Variables and Constants

Involved in the problem		Known	Implied	Unknown	
a_{car}	v_{truck}	$v_{truck} = 22$ m/s	$v_{i(car)} = 0.0$ m/s	Δd_{car}	Δt_{car}
$v_{i(car)}$	Δt_{truck}	$a_{car} = 4.8$ m/s^2		Δd_{truck}	Δt_{truck}
Δt_{car}	Δd_{truck}				
Δd_{car}					

Strategy / Calculations

Write the equation that defines velocity for the motion of the truck.

$$\Delta d = v\Delta t$$

$$\Delta d_{truck} = 22\ \frac{m}{s}\Delta t_{truck}$$

Write the equation of motion for the sports car.

$$\Delta d = v_i\Delta t + \frac{1}{2}a\Delta t^2$$

$$\Delta d_{car} = 0.0\ \frac{m}{s}\Delta t_{car} + \frac{1}{2}4.8\ \frac{m}{s^2}\Delta t_{car}^2$$

$$\Delta d_{car} = 2.4\ \frac{m}{s^2}\Delta t_{car}^2$$

Strategy

Calculations

The displacement for the sports car and the truck are the same. Call them both Δd.

$$\Delta d_{\text{car}} = \Delta d_{\text{truck}} = \Delta d$$

The time interval is the same for the sports car and the truck. Call them both Δt.

$$\Delta t_{\text{car}} = \Delta t_{\text{truck}} = \Delta t$$

You now have two equations and two unknowns. Solve for Δt in the equation for the sports car. Then substitute that expression into Δt for the truck. This will give you one equation with only one unknown, Δd.

$$\Delta d = 22\ \frac{\text{m}}{\text{s}}\Delta t$$

$$\frac{\Delta d}{22\ \frac{\text{m}}{\text{s}}} = \frac{\cancel{22\ \frac{\text{m}}{\text{s}}}}{\cancel{22\ \frac{\text{m}}{\text{s}}}}\Delta t$$

$$\Delta t = \frac{\Delta d}{22\ \frac{\text{m}}{\text{s}}}$$

$$\Delta d = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta t^2$$

$$\Delta d = 2.4\ \frac{\text{m}}{\text{s}^2}\left(\frac{\Delta d}{22\ \frac{\text{m}}{\text{s}}}\right)^2$$

Solve for displacement.

$$\Delta d\left(22^2\ \frac{\text{m}^2}{\text{s}^2}\right) = 2.4\ \frac{\text{m}}{\text{s}^2}\frac{\Delta d^2}{\cancel{22\ \frac{\text{m}^2}{\text{s}^2}}}\cancel{22^2\ \frac{\text{m}^2}{\text{s}^2}}$$

$$484\ \frac{\text{m}^2}{\text{s}^2}\Delta d = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta d^2$$

Subtract $484\ \frac{\text{m}^2}{\text{s}^2}\Delta d$ from both sides of the equation.

$$484\ \frac{\text{m}^2}{\text{s}^2}\Delta d - 484\ \frac{\text{m}^2}{\text{s}^2}\Delta d = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta d^2 - 484\ \frac{\text{m}^2}{\text{s}^2}\Delta d$$

$$0.0 = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta d^2 - 484\ \frac{\text{m}^2}{\text{s}^2}\Delta d$$

Factor out the Δd.

$$0.0 = \left(2.4\ \frac{\text{m}}{\text{s}^2}\Delta d - 484\ \frac{\text{m}^2}{\text{s}^2}\right)\Delta d$$

Set each of the factors equal to 0.

$$2.4\ \frac{\text{m}}{\text{s}^2}\Delta d - 484\ \frac{\text{m}^2}{\text{s}^2} = 0 \quad \text{or} \quad \Delta d = 0.0\ \frac{\text{m}}{\text{s}}$$

Solve for Δd.

$$2.4\ \frac{\text{m}}{\text{s}^2}\Delta d = 484\ \frac{\text{m}^2}{\text{s}^2}$$

$$\frac{\cancel{2.4\ \frac{\text{m}}{\text{s}^2}}\Delta d}{\cancel{2.4\ \frac{\text{m}}{\text{s}^2}}} = \frac{484\ \frac{\text{m}^{\cancel{2}}}{\cancel{\text{s}^2}}}{2.4\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}}$$

$$\Delta d = 201.67\ \text{m}$$

You found two solutions for displacement of the sports car and truck when setting the time intervals and displacements of the two vehicles equal to each other. The value of zero for displacement simply means that they had the same displacement (zero) at time zero. The displacement of the sports car and truck was 2.0×10^2 m when the sports car caught up with the truck.

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Strategy

To find the time it took for the sports car to catch up with the truck, substitute the displacement into the equation relating displacement of the truck and time interval.

Calculations

$$\Delta t = \frac{\Delta d}{22\frac{\text{m}}{\text{s}}}$$

$$\Delta t = \frac{201.66\ \cancel{\text{m}}}{22\frac{\cancel{\text{m}}}{\text{s}}}$$

$$\Delta t = 9.167\ \text{s}$$

It took 9.2 s for the sports car to catch up with the truck.

Validate

The units cancelled to give metres for displacement and seconds for time interval, which is correct. A second equation exists for calculating time interval from displacement. Substitute the displacement into the equation relating time and displacement for the truck, and solve for time interval. It should give the same value, 9.167 s.

$$\Delta d_{\text{car}} = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta t_{\text{car}}^2$$

$$201.67\ \text{m} = 2.4\ \frac{\text{m}}{\text{s}^2}\Delta t_{\text{car}}^2$$

$$\frac{201.67\ \cancel{\text{m}}}{2.4\ \frac{\cancel{\text{m}}}{\text{s}^2}} = \frac{\cancel{2.4\ \frac{\text{m}}{\text{s}^2}}}{\cancel{2.4\ \frac{\text{m}}{\text{s}^2}}}\Delta t_{\text{car}}^2$$

$$\Delta t_{\text{car}}^2 = 84.027\ \text{s}^2$$

$$\Delta t = 9.167\ \text{s}$$

The values are in agreement.

PRACTICE PROBLEMS

9. A field hockey player starts from rest and accelerates uniformly to a speed of 4.0 m/s in 2.5 s

(a) Determine the distance she travelled.

(b) What is her acceleration?

10. In a long distance race, Michael is running at 3.8 m/s and is 75 m behind Robert, who is running at a constant velocity of 4.2 m/s. If Michael accelerates at 0.15 m/s^2, how long will it take him to catch Robert?

11. A race car accelerates at 5.0 m/s^2. If its initial velocity is 200 km/h, how far has it travelled after 8.0 s?

12. A motorist is travelling at 20 m/s when she observes that a traffic light 150 m ahead of her turns red. The traffic light is timed to stay red for 10 seconds. If the motorist wishes to pass the light without stopping just as it turns green again, what will be the speed of her car just as it passes the light?

2.5 Section Review

1. K/U Define kinematics.

2. MC Refer to model problem #1 on page 77. Given the explanation of timing, is 6.9 s likely to be exact? Explain the types of errors that could lead to an over measurement of the time interval. How might the hiking buddies minimize their error?

3. C Develop an appropriate problem for each of the following formulas.

(a) $a = \frac{(v_{\text{f}} - v_{\text{i}})}{\Delta t}$

(b) $\Delta d = \frac{(v_{\text{i}} + v_{\text{f}})}{2}\Delta t$

(c) $\Delta d = v_{\text{i}}\Delta t + \frac{1}{2}a\Delta t^2$

CHAPTER 2 Review

REFLECTING ON CHAPTER 2

- An object is in motion if it changes position in a particular frame of reference or coordinate system.
- A motion diagram documents an object's position in a frame of reference at particular instants in time.
- Vector quantities are described in terms of their magnitude and direction.
- A position vector locates an object with a magnitude and direction from the origin of a frame of reference.
- A displacement vector designates the change in position of an object.
  $\Delta\vec{d} = \vec{d}_f - \vec{d}_i$
- A time interval t is the time elapsed between two instants in time.
  $\Delta t = t_f - t_i$
- Velocity is the rate of change of position or the displacement of an object over a time interval.
  $\vec{v}_{ave} = \dfrac{\Delta\vec{d}}{\Delta t}$
- Position-time graphs reveal patterns of uniform and non-uniform motion. Uniform motion or constant velocity appears as a straight slope. The average velocity during a time interval is determined by finding the slope of the line connecting the initial and the final positions of the object for the time interval. The instantaneous velocity is calculated by finding the slope of the tangent to the line of the graph at a particular instant in time.
- Acceleration is the rate of change of velocity of an object over a time interval.
  $\vec{a}_{ave} = \dfrac{\Delta\vec{v}}{\Delta t}$
- Velocity-time graphs reveal patterns of uniform and non-uniform acceleration. Uniform or constant acceleration appears as a straight slope. The average acceleration during a time interval is determined by finding the slope of the line connecting the initial and the final velocities of the object for the time interval. The instantaneous acceleration is calculated by finding the slope of the tangent to the line of the graph at a particular instant in time.
- The displacement of an object during a particular time interval can be found by determining the area under the curve of a velocity-time graph.
- The mathematical equations which are used to analyze the motion of an object undergoing constant acceleration relate various combinations of five variables: the object's initial velocity v_i, its final velocity v_f, its acceleration a, a time interval Δt, the object's displacement Δd during the time interval.
  $a = \dfrac{(v_f - v_i)}{\Delta t}$
  $\Delta d = v_i\Delta t + \dfrac{1}{2}a\Delta t^2$
  $\Delta d = \dfrac{1}{2}(v_i + v_f)\Delta t$
  $v_f = v_i + a\Delta t$

Knowledge/Understanding

1. Define the following: **(a)** kinematics **(b)** dynamics **(c)** mechanics **(d)** velocity **(e)** acceleration **(f)** frame of reference **(g)** centre of mass **(h)** vector **(i)** scalar
2. What is meant by the illusion of motion while watching a movie or video?
3. In terms of graphing distinguish between the following:
   (a) average velocity and instantaneous velocity
   (b) average acceleration and instantaneous acceleration
4. Describe, using dynamics, how one could produce a non-uniform acceleration of an object?
5. Describe how to determine the area under a velocity-time curve with a non-uniform acceleration (i.e. increasing or decreasing slope).
6. Distinguish between position and displacement.
7. Identify the quantity that is changing every second when an object is accelerating.

8. Describe some practical applications of acceleration.
9. What does a negative area calculation under a velocity-time graph mean?

Inquiry

10. You are given the results of a 60 Hz recording ticker tape timer experiment of a cart rolling down a ramp onto a level lab bench. By analyzing the dots on the ticker tape describe how you know the cart was
    (a) moving with a positive uniform acceleration
    (b) moving with a negative uniform acceleration
    (c) moving with constant velocity
    (d) at rest.
11. A student's school is directly north of her home. While she roller blades to school she accelerates uniformly from rest to a modest velocity and then maintains this velocity, until she meets a friend half way to school at which point she stops for a while. She then continues to move at the same constant velocity until she gets near the school, where she slows uniformly until she stops.
    (a) Sketch a position-time graph for her motion
    (b) Sketch a velocity-time graph for her motion.

Communication

12. Explain what physical quantity is measured by a car's speedometer.

Making Connections

13. Refer to kinematics principles to suggest solutions to improve road safety. Consider such aspects as: vehicle design and safety features, driver training, reaction time, roadway design, construction and maintenance, road signs, maximum driving speed, and road safety enforcement.
14. Make a list of the of the advantages and disadvantages of the following means of transportation: **(a)** train **(b)** plane **(c)** car **(d)** ship. Which means of transportation do you feel is adapting the most and least to meet the needs of our Canadian society.

Problems for Understanding

15. A truck is transporting new cars to a car dealership. There are 8 cars on the truck's trailer. Describe a frame of reference in which a car is:
    (a) moving.
    (b) at rest.
16. Draw a dot diagram to illustrate the motion of a car travelling from one traffic light to the next. When the traffic light turns green the car's speed increases, it then travels at a constant speed, and then brakes to slow down to a stop at the next traffic light.
17. A girl is taking her dog for a walk. They walk 5.0 km[N] and then turn around and walk 12 km[S].
    (a) What is the total distance that they travelled?
    (b) What is their displacement?
    (c) What displacement would they have to walk to get back to their starting point?
18. A cyclist is travelling with an average velocity of 5.9 m/s[W]. What will be his displacement after 1.2 h?
19. A canoeist paddles 1.6 km downstream and then turns around and paddles back upstream for 1.2 km. The entire trip takes 45 minutes.
    (a) What is the displacement of the canoeist?
    (b) Calculate the average velocity of the canoeist.
20. The closest star to our solar system is Alpha Centauri, which is 4.12×10^{16} m away. How long would it take light from Alpha Centauri to reach our solar system if the speed of light is 3.00×10^{8} m/s? (Provide an answer in both seconds and in years.)
21. Vectorville and Scalartown are 20.0 km apart. A cyclist leaves Vectorville and heads for Scalartown at 20.0 km/h. A second cyclist leaves Scalartown for Vectorville at exactly the same time at a speed of 15.0 km/h.
    (a) Where will the two cyclists meet between the two towns?
    (b) How much time passes before they meet (in minutes)?

22. Describe each of the situations below as either uniform motion or non-uniform motion.
    (a) a car on the highway travels with its cruise control set at 90 km/h
    (b) a skydiver jumps from a plane and falls faster and faster through the air
    (c) a piece of paper that is dropped, flutters to the ground
    (d) a satellite travels in a circular orbit above the earth at a constant speed
    (e) you sit quietly, enjoying an autumn day.

23. Graph the following data. Find the slope at different intervals and sketch a speed-time graph of the motion.

t (s)	d (m)
0	0
1	4
2	8
3	12
4	16
5	20
6	24
7	28
8	32
9	35.5
10	38.5
11	41
12	43
13	44.5
14	45.5
15	46
16	46
17	46
18	46
19	46
20	46

24. A car is travelling at 14 m/s when the traffic light ahead turns red. The car brakes and comes to a stop in 5.0 s. Calculate the acceleration of the car.

25. At the very end of their race, a runner accelerates at 0.3 m/s^2 for 12 s to attain a speed of 6.4 m/s. Determine the initial velocity of the runner.

26. The acceleration due to gravity on the moon is 1.6 m/s^2[down]. If a baseball was thrown with an initial velocity of 4.5 m/s[up], what would its velocity be after 4.0 s?

27. When the traffic light turns green the car's speed increases, it then travels at a constant speed, and then brakes to slow down to a stop at the next traffic light.
    (a) Sketch a position-time graph to represent the car's motion.
    (b) Sketch a velocity-time graph to represent the car's motion.

28. A car that starts from rest can travel a distance of 5.0×10^1 m in a time of 6.0 s.
    (a) What is the final velocity of the car at this time?
    (b) What is the acceleration of the car?

29. A cyclist is travelling at 5.6 m/s when she starts to accelerate at 0.60 m/s^2 for a time interval of 4.0 s.
    (a) How far did she travel during this time interval?
    (b) What velocity did she attain?

30. A truck is travelling at 22 m/s when the driver notices a speed limit sign for the town ahead. He slows down to a speed of 14 m/s. He travels a distance of 125 m while he is slowing down.
    (a) Calculate the acceleration of the truck.
    (b) How long did it take the truck driver to change his speed?

31. A skydiver falling towards the ground accelerates at 3.2 m/s^2. Calculate his displacement if after 8.0 s he attained a velocity of 28 m/s[down].

32. A car is travelling on the highway at a constant speed of 24 m/s. The driver misses the posted speed limit sign for a small town she is passing through. The police car accelerates from rest at 2.1 m/s^2. From the time that the speeder passes the police car:
    (a) How long will it take the police car to catch up to the speeder?
    (b) What distance will the cars travel in that time?

Numerical Answers to Practice Problems

1. –1.0 m/s **2.** 1.2 m/s[N57°W] **3. (a)** 0.29 m/s **(b)** 75 m or 175 m **(c)** 75 m **(d)** 0.87 m/s **4.** for linear segments: 2.5 m/s, –7.5 m/s, 0.0 m/s, 3.8 m/s **6.** 8.0 m/s^2 **7.** 2.5 m/s^2[up] **8.** 24 m/s **9. (a)** 5.0 m **(b)** 1.6 m/s^2 **10.** 34 s **11.** 6×10^2 m **12.** 10 m/s

CHAPTER 3 Motion in a Plane

CHAPTER CONTENTS

Why do some people find water skiing so exhilarating? Certainly, travelling at high speeds is thrilling, but for many, the challenge of sports has another dimension — the desire to gain and maintain control over the motion of your body or that of the vehicle you are operating.

Although a water-skier depends on the towboat for propulsion, the skier can travel in a different direction and at a different speed than the boat. Similarly, windsurfers rely on the wind, but learn how to harness its energy to sail in directions other than that of the wind. The challenge is to understand what affects the direction of the motion and use that knowledge to create the desired motion. The water-skier and windsurfer develop a sense or "feel" for the techniques that they need to control their motion. However, to put a satellite into orbit or to build a guidance system for a rocket, the knowledge of motion and its causes must be much more precise and based on calculations.

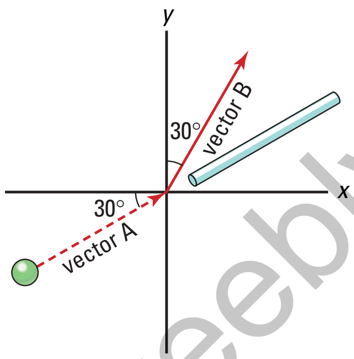
You began your study of motion in the last chapter by developing the concepts of displacement, velocity, and acceleration. You performed detailed analyses of these quantities in one dimension, or a straight line. In this chapter, you will expand your knowledge to two dimensions and learn more about the vector nature of the quantities that describe motion.

MULTI LAB

Pushed Around

TARGET SKILLS
- Identifying variables
- Analyzing and interpreting

Changing Course



How is the *direction of acceleration* related to the *change in velocity* of a marble rolling in a plane? Try this activity to explore the answer to this question. Draw an *x*–*y*-coordinate system on a piece of easel paper, and place the paper flat on your desk or lab bench. Draw vectors A and B on your chart, as shown in the diagram.

Roll a marble so that it travels along vector A at a reasonably slow speed. As the marble approaches the origin, gently blow on the marble through a straw, causing the marble to leave the origin, travelling along vector B. Practise this procedure until you have perfected your technique. On the easel paper, sketch the direction in which you needed to blow in order to create the desired change in direction of the motion of the marble. Repeat the procedure several more times with other pairs of vectors. Predict the direction you will need to blow to cause the change in velocity. Test your predictions.

Analyze and Conclude

1. Analyze your sketches and look for a pattern that relates the direction of the push you exerted on the marble by blowing on it and the change in direction of the motion of the marble.
2. Describe the marble's motion by using the concepts of constant velocity, changes in velocity, and acceleration. Explain your reasoning.

Watch Those Curves!

Draw a curved line on the easel paper. This time, investigate how you can cause the marble to follow the curve. Set the marble rolling toward the curve and then either blow or tap on it gently so that the marble follows the curved line. Carefully describe what you must do to keep the marble curving.

Analyze and Conclude

1. Describe the marble's *speed* throughout its journey along the curved path.
2. Does the marble maintain a *constant velocity* during this experiment? Explain your reasoning.
3. Summarize the pattern you have found between the direction in which you blow or tap on the marble and its change in velocity as it follows the curve.

3.1 Vectors in a Plane

SECTION EXPECTATIONS

- Draw vector scale diagrams to visualize and analyze the nature of motion in a plane.
- Analyze motion by using scale diagrams to add and subtract vectors.
- Solve problems involving motion in a horizontal plane.

KEY TERMS

- vector diagram
- coordinate system
- resultant vector

Imagine describing the motion of an expert water-skier to someone who had not watched the skier demonstrate his technique. You would probably do a lot of pointing in different directions. In a sense, you would be using vectors to describe the skier's motion. You have probably used vectors and even **vector diagrams** many times without realizing it. Did you ever draw a "treasure map" as a child? Have you ever gone hiking and drawn routes on a topographical map? If so, you already have a sense of the clarity with which vector diagrams help you to describe, analyze, and plan motion.

Representing Vectors

You will represent all vector quantities with arrows that point in the direction of the quantity. The length of the arrow is proportional to the magnitude of the quantity you are representing. Vector quantities have direction, so you need a frame of reference or **coordinate system** to represent a direction. Vectors also have magnitude, so you need a scale to indicate and calculate magnitude.

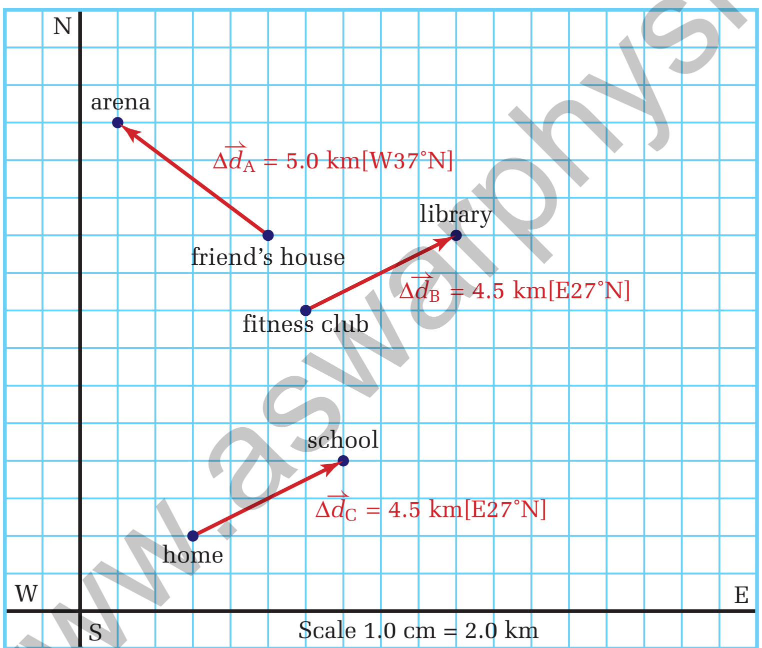


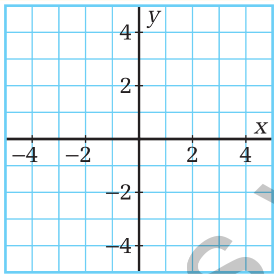
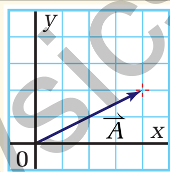
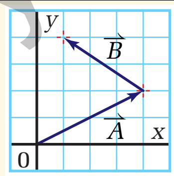
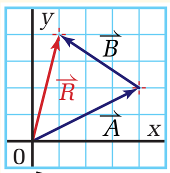
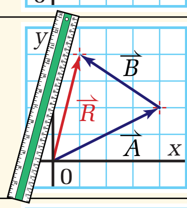
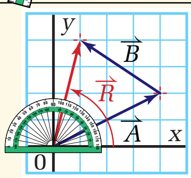
Figure 3.1 The three displacement vectors are drawn to a scale of 1.0 cm to 2.0 km. To draw the directions from the symbols used here, start by pointing in the first compass direction. Then, rotate the stated number of degrees toward the last compass direction.

Since you are probably comfortable with maps, they provide a good frame of reference to familiarize yourself with the rules for drawing vectors. For example, the map in Figure 3.1 shows displacement vectors between your home and school and between the fitness club and the library. The vectors are drawn to scale. On the map, 1.0 cm represents 2.0 km. Have you noticed that two of the displacement vectors are identical? The direction of displacement vectors B and C is 27 degrees north of east and the magnitude of each is 4.5 km. The beginning and ending points of a vector do not define the vector, only the length and direction. You can move a vector in its frame of reference as long as you do not change the length or the direction in which it points.

Adding Vectors Graphically

Addition of vectors starts with some basic rules of arithmetic and then includes a few more rules. You have known for a long time that you cannot add "apples and oranges" or centimetres and metres. Similarly, you can add only vectors that represent the same quantity and are drawn to the same scale. Follow the steps listed in Table 3.1 to learn the graphical method for adding vectors. Any two vectors having the same units can be added according to the procedure in Table 3.1. The vector representing the sum is often called the **resultant vector.**

Table 3.1 Graphical Vector Addition ($\vec{R} = \vec{A} + \vec{B}$)

Procedural step	Graph
Establish a coordinate system and choose a scale.	
Place the first vector ($\vec{A}$) in a coordinate system.	
Place the tail of the second vector ($\vec{B}$) at the tip of the first vector.	
Draw a vector from the tail of the first vector ($\vec{A}$) to the tip of the second ($\vec{B}$). Label it "$\vec{R}$."	
With a ruler, measure the length of $\vec{R}$.	
With a protractor, measure the angle between $\vec{R}$ and the horizontal axis.	

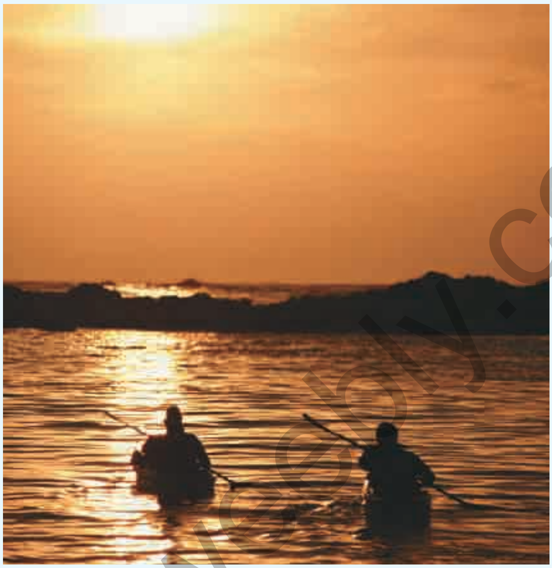
ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner to visualize the process of adding vectors.

MODEL PROBLEM

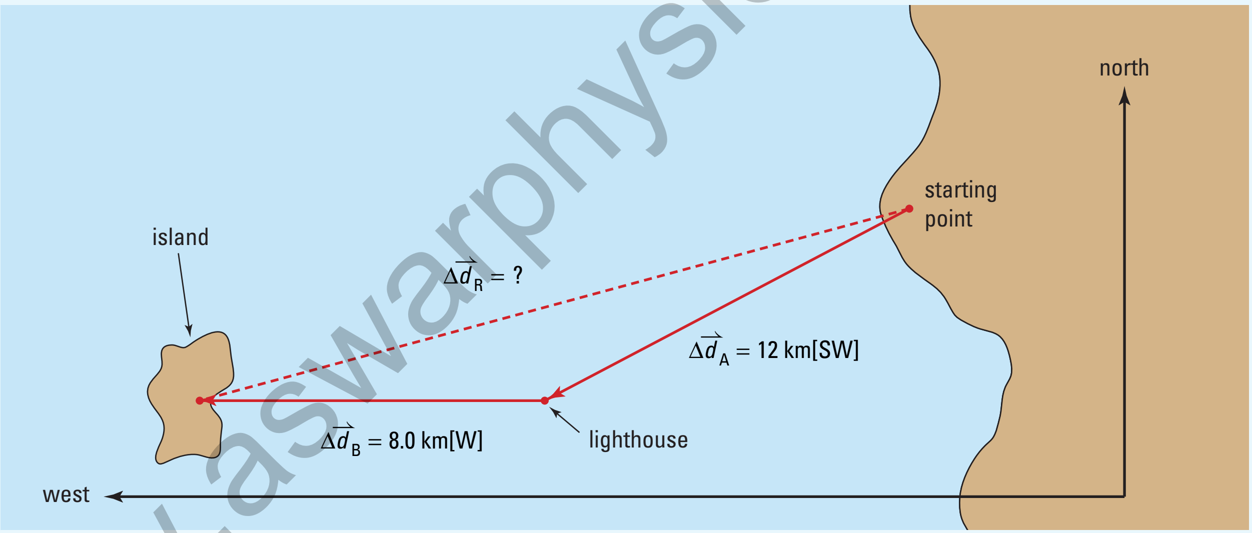
Adding Vectors

A kayaker sets out for a paddle on a broad stretch of water. She heads toward the west, but is blown off course by a strong wind. After an hour of hard paddling, she arrives at a lighthouse that she knows is 12 km southwest of her starting point. She lands and waits for the wind to die down. She then paddles toward the setting sun and lands on a small island that is 8 km west of the lighthouse. In the calm of the evening, the kayaker plans to paddle straight back to her starting point. Use a vector diagram to determine her displacement from her starting point to the island. In which direction should she now head and how far will she have to paddle to go directly to the point from which she originally started paddling?



Frame the Problem

- Make a scale diagram of the problem from the following sketch (not to scale). Your scale should be 1.0 cm: 2.0 km.



- The kayaker's journey consisted of two separate steps represented by the *two displacement vectors* in the diagram.
- The *vector sum* of the two vectors yields one *resultant vector* that shows the kayaker's final displacement.
- To return to the point she left earlier in the day, the kayaker will have to paddle a *displacement* that is *equal in magnitude* to her *resultant vector* and *opposite* in *direction.*

PROBLEM TIP

Make the scale on a vector diagram as large as possible – the larger the scale, the more accurate your result will be. Use graph paper when drawing vectors, because it provides many reference lines.

Identify the Goal

(a) The displacement, $\Delta\vec{d}_R$, of the first two legs of the kayaker's trip

(b) The displacement, $\Delta\vec{d}$, needed to return to the point from which she originally started

Variables and Constants

Involved in the problem		Known	Unknown
$\Delta\vec{d}_A$	$\Delta\vec{d}_R$	$\Delta\vec{d}_A = 12$ km[SW]	$\Delta\vec{d}_R$
$\Delta\vec{d}_B$	$\Delta\vec{d}$	$\Delta\vec{d}_B = 8.0$ km[W]	$\Delta\vec{d}$

Strategy	Calculations
Measure the length of the resultant displacement vector in the scale diagram.	$\Delta\vec{d}_R = 4.75$ cm
Multiply the length of the vector by the scale factor.	$\Delta\vec{d}_R = 4.75\ \cancel{\text{cm}}\left(\frac{4.0\ \text{km}}{1.0\ \cancel{\text{cm}}}\right)$ $\Delta\vec{d}_R = 19$ km
With a protractor, measure the angle between the horizontal axis and the resultant vector.	$\theta = 27^\circ$

(a) The resultant displacement is 19 km[W27°S].

(b) To return to the point from which she originally started her trip, the kayaker would have to paddle 19 km in the direction opposite to [W27°S], or 19 km[E27°N].

Validate

The total distance that the kayaker paddled was 20 km (8 km + 12 km). However, her path was not straight. In paddling back to shore, her trip formed a triangle. Since any side of a triangle must be shorter than the sum of the other two, you expect that her direct return trip will be shorter than 20 km. In fact, it was 1.0 km shorter.

PRACTICE PROBLEMS

1. An airplane flies with a heading of [N50.0°W] from Toronto to Sault Ste. Marie, a distance of 500 km (5.0×10^2 km). The airplane then flies 750 km on a heading of [E10.0°S] to Ottawa.

(a) Determine the airplane's displacement for the trip.

(b) In what direction will the plane have to fly in order to return directly to Toronto?

2. A canoeist starts from her campsite, paddles 3.0 km due north, and then 4.0 km due west.

(a) Determine her displacement for the trip.

(b) In what direction would she have to head her canoe in order to paddle straight home?

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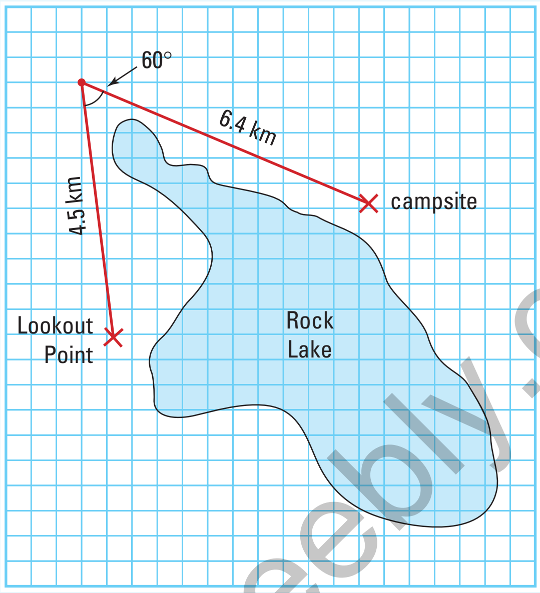
3. From a lookout point, a hiker sees a small lake ahead of her. In order to get around it, she walks 4.5 km in a straight line toward the end of the lake. She makes a 60.0˚ turn to the right and walks to a campsite that is 6.4 km in the new direction. Determine her displacement from the lookout point when she has reached the campsite. (See the map on the right.)



4. A boat heads out from port for a day's fishing. It travels 21.0 km due north to the first fishing spot. It then travels 30.0 km[W30.0˚S] to a second spot. Finally, it turns and heads [W10.0˚N] for 36.0 km.

(a) Determine the boat's displacement for the entire journey.

(b) In what direction should the boat point so as to head straight to its home port?

Subtracting Vectors Graphically

The equations of motion with uniform acceleration include several cases in which you must subtract vector quantities. For example, displacement is defined as the difference of position vectors ($\Delta\vec{d} = \vec{d}_2 - \vec{d}_1$). To find acceleration, you must first find a change in velocity, which is a difference in vector quantities ($\Delta\vec{v} = \vec{v}_2 - \vec{v}_1$). In Chapter 2, you applied these equations to one dimension, so subtracting these quantities involved only arithmetic subtraction. However, when you work in two (or three) dimensions, you must account for the vector nature of these quantities.

Fortunately, vector subtraction is very similar to vector addition. Recall from basic math the expression, "A – B is equivalent to A + (–B)." The only additional piece of information that you need is the definition of the negative of a vector. In Figure 3.2, you can see that the negative of a vector is the same in magnitude and opposite in direction. Now, follow the directions in Table 3.2 for the first method for subtracting vectors graphically.

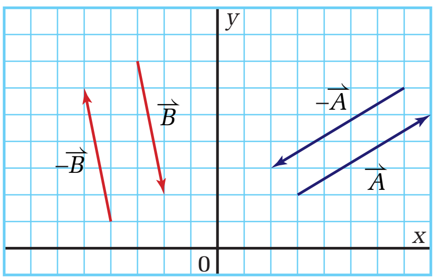
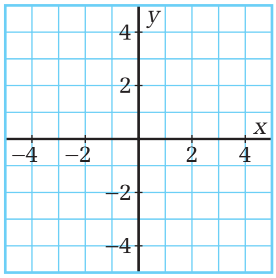
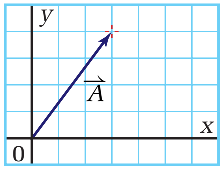
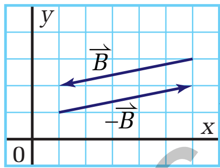
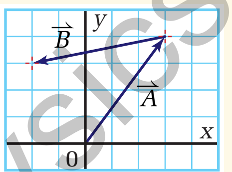
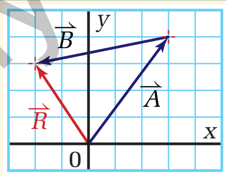
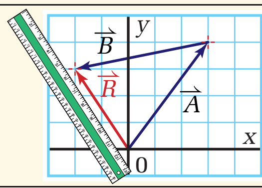
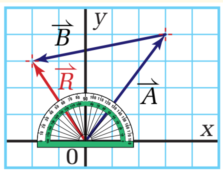


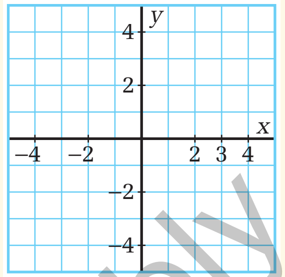
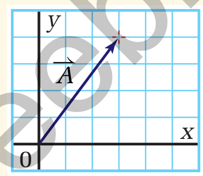
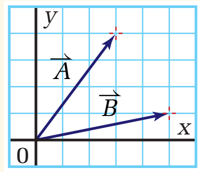
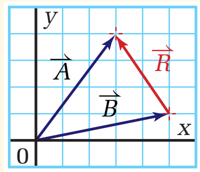
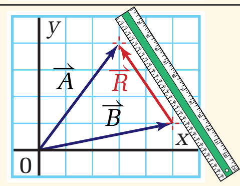
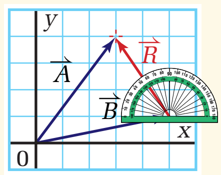
Figure 3.2 To draw the negative of a vector, draw a line parallel to the positive vector and with an identical length. Then put an arrow head on the opposite end relative to the original vector.

Table 3.2 Graphical Vector Subtraction ($\vec{R} = \vec{A} - \vec{B}$): Method 1

Procedural step	Graph
Establish a coordinate system and choose a scale.	
Place the first vector ($\vec{A}$) in the coordinate system.	
Draw the negative of vector $\vec{B}$.	
Place the tail of $-\vec{B}$ at the tip of $\vec{A}$.	
Draw a vector from the tail of $\vec{A}$ to the tip of $-\vec{B}$. Label it "$\vec{R}$."	
With a ruler, measure the length of $\vec{R}$.	
With a protractor, measure the angle between $\vec{R}$ and the horizontal axis.	

When subtracting vectors, you have an option of two different methods. Table 3.3 describes the second procedure.

Table 3.3 Graphical Vector Subtraction ($\vec{R} = \vec{A} - \vec{B}$): Method Two

Procedural step	Graph
Establish a coordinate system and choose a scale.	
Place the first vector ($\vec{A}$) in the coordinate system.	
Place the tail of the second vector ($\vec{B}$) at the *tail* of the first vector ($\vec{A}$).	
Draw a vector from the *tip* of the second vector ($\vec{B}$) to the *tip* of the first vector ($\vec{A}$). Label this vector "$\vec{R}$."	
With a ruler, measure the length of $\vec{R}$.	
With a protractor, measure the angle between $\vec{R}$ and the horizontal axis.	

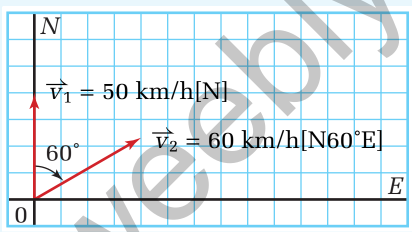
MODEL PROBLEM

Subtracting Vectors

A water-skier begins his ride by being pulled straight behind the boat. Initially, he has the same velocity as the boat (50 $\frac{\text{km}}{\text{h}}$[N]). Once up, the water-skier takes control and cuts out to the side. In cutting out to the side, the water-skier changes his velocity in both magnitude and direction. His new velocity is 60 $\frac{\text{km}}{\text{h}}$[N60°E]. Find the water-skier's *change* in velocity.

Frame the Problem

- Make a scale diagram of the water-skier's initial and final velocities.
- The water-skier follows directly behind the boat, while rising to the surface.
- He then *changes* the *magnitude* and *direction* of his motion.



Identify the Goal

The change in the velocity, $\Delta\vec{v}$, of the water-skier

Variables and Constants

Involved in the problem	Known	Unknown
$\vec{v}_1$	$\vec{v}_1 = 50\ \frac{\text{km}}{\text{h}}$[N]	$\Delta\vec{v}$
$\vec{v}_2$	$\vec{v}_2 = 60\ \frac{\text{km}}{\text{h}}$[N60°E]	
$\Delta\vec{v}$		

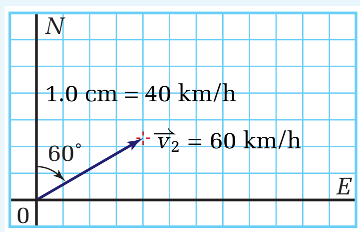
Strategy

Write the mathematical definition for the change in velocity.

Draw a coordinate system and choose a scale. Put $\vec{v}_2$ in the coordinate system.

Calculations

$$\Delta\vec{v} = \vec{v}_2 - \vec{v}_1$$



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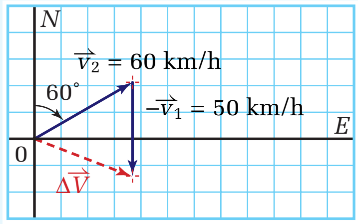
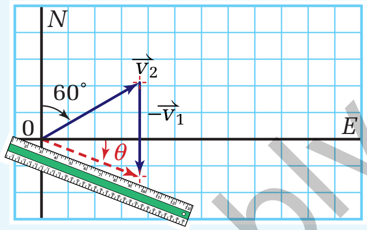
Place the tail of vector $-\vec{v}_1$ at the tip of $\vec{v}_2$ and draw $\Delta\vec{v}$.



Measure the magnitude and direction of $\Delta\vec{v}$.



$|\Delta\vec{v}| = 1.4\ \text{cm},\ \theta = 21^\circ$

Multiply the magnitude of the vector by the scale factor 1.0 cm = 40 km/h.

$$|\Delta\vec{v}| = 1.4\ \cancel{\text{cm}}\left(\frac{40\ \frac{\text{km}}{\text{h}}}{1.0\ \cancel{\text{cm}}}\right)$$

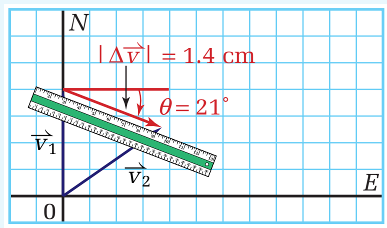
The water-skier's change in velocity was 56 km/h[E21°S].

$$|\Delta\vec{v}| = 56\ \frac{\text{km}}{\text{h}}$$

Validate

The magnitude of the change in the water-skier's velocity is smaller than the sum of the two velocities, which it should be.

Use the alternative method to check the answer. Draw a coordinate system to the same scale. Draw vectors $\vec{v}_1$ and $\vec{v}_2$ with their tails together. Draw a vector from the tip of $\vec{v}_1$ to the tip of $\vec{v}_2$. Measure the magnitude and direction of the resultant vector. As you can see in the diagram, these values are identical to those obtained using the first method.



PRACTICE PROBLEMS

Use both methods of vector subtraction to solve the following problems.

5. Given: $\vec{P} = 12$ km[N], $\vec{Q} = 15$ km[S], $\vec{R} = 10$ km[N30°E]

(a) Use method 1 of graphical vector subtraction to solve each of the following:
(i) $\vec{P} - \vec{Q}$ **(ii)** $\vec{R} - \vec{Q}$ **(iii)** $\vec{Q} - \vec{R}$

(b) Use method 2 of graphical vector subtraction to solve each of the following:
(i) $\vec{P} - \vec{Q}$ **(ii)** $\vec{R} - \vec{Q}$ **(iii)** $\vec{P} - \vec{R}$

6. A car is travelling east at 45 km/h. It then heads north at 50 km/h (5.0×10^1 km/h). Determine its change in velocity.

7. An airplane is flying at 2.00×10^2 km/h [S30.0°W]. It makes a smooth wide turn and heads east at 2.00×10^2 km/h. Find its change in velocity.

8. A hockey puck hits the boards at a velocity of 12 m/s at an angle of 30° to the boards. It is deflected with a velocity of 10 m/s at an angle of 25° to the boards. Determine the puck's change in velocity.

9. A runner's velocity is recorded at four different points along the route, $\vec{v}_1 = 3.5$ m/s[S], $\vec{v}_2 = 5.0$ m/s[N12°W], $\vec{v}_3 = 4.2$ [W], and $\vec{v}_4 = 2.0$ m/s[S76°E].
   (a) Graphically determine the change in velocity between $\vec{v}_1$ and $\vec{v}_2$.
   (b) Calculate the change in velocity between $\vec{v}_1$ and $\vec{v}_3$.
   (c) Graphically determine the change in velocity between $\vec{v}_1$ and $\vec{v}_4$.

Think It Through

- Review your findings in the "Changing Course" lab at the beginning of this chapter. Assume that the marble rolls with a constant speed of 25 cm/s. Use method 2 for subtracting vectors to show $\Delta\vec{v}$ for the rolling marble when it changes direction. Do you see a relationship between the direction you find for $\Delta\vec{v}$ and the direction in which you blew on the marble to make it change directions?
- A marble is rolling across a lab bench. In what direction would you need to give the marble a sharp poke so that it would turn and travel at an angle of 90° to its original direction? Illustrate your thinking by drawing a sketch to show the original direction of the marble, the new direction of the marble, and the direction of the poke. Verify your thinking by conducting a mini-experiment.
- Two identical cars, travelling at the same speed, approach an intersection at right angles to each other on a day when the streets are very icy. Unfortunately, neither car is able to stop. During the collision, the cars are jammed together and the combined wreckage slides off the street. Draw a sketch of the accident and illustrate the direction in which the wreckage will travel.

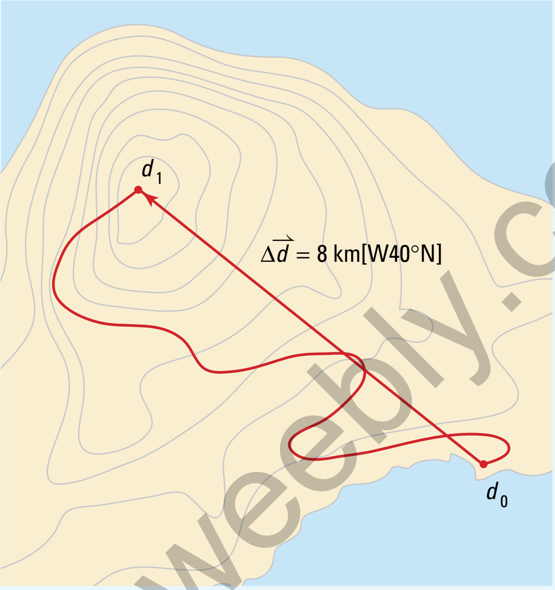
Multiplying and Dividing Vectors by Scalars

A brief review of the equations of motion will reveal one more important type of mathematical operation on vector quantities. These quantities are often multiplied or divided by the scalar quantity, Δt, the time interval. What happens to a vector when it is multiplied or divided by a scalar? To help answer that question, review the definition of average velocity: $\vec{v}_{ave} = \frac{\Delta\vec{d}}{\Delta t}$. When the displacement vector is divided by the time interval, the magnitude changes and the units change. The only thing that does *not* change is the direction of the vector. In summary, when a vector is multiplied or divided by a scalar, a different quantity is created, but the direction remains the same.

MODEL PROBLEMS

Dividing Vectors by Scalars

1. A hiker sets out for a trek along a mountain trail. After 2 h, she checks her global positioning system and finds that she is 8 km[W40°N] from her starting point. What was her average velocity for the trek?



Frame the Problem

- The hiker follows a meandering path; however, *displacement* is a *vector* that depends only on the *initial* and *final positions*.
- *Velocity* is the vector quotient of *displacement* and the *time interval*.
- The *direction* of the hiker's *velocity* is therefore the same as the *direction* of her *displacement*.

Identify the Goal

The hiker's average velocity, $\vec{v}_{ave}$, for the trip

Variables and Constants

Involved in the problem	Known	Unknown
Δt	$\Delta t = 2$ h	$\vec{v}_{ave}$
$\Delta\vec{d}$	$\Delta\vec{d} = 8$ km[W40°N]	
$\vec{v}_{ave}$		

Strategy

Use the equation that defines average velocity to calculate the magnitude of the average velocity.

The direction of the velocity is the same as the direction of the displacement.

Calculations

$$\vec{v}_{ave} = \frac{\Delta\vec{d}}{\Delta t}$$

$$\vec{v}_{ave} = \frac{8 \text{ km[W40°N]}}{2 \text{ h}}$$

$$\vec{v}_{ave} = 4\,\frac{\text{km}}{\text{h}}\text{[W40°N]}$$

The average velocity for the trip was 4 km/h[W40°N].

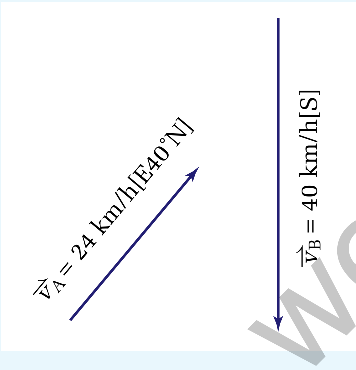
Validate

The magnitude, 4 km/h, is quite reasonable for a hike. The direction can only be the same as the direction of the displacement.

2. A hot-air balloon rises into the air and drifts with the wind at a rate of 24 km/h[E40°N] for 2 h. The wind shifts, so the balloon changes direction and drifts south at a rate of 40 km/h for 1.5 h before landing. Determine the balloon's displacement for the flight.

Frame the Problem

- Make a diagram of the problem.
- The balloon trip takes place in *two stages* (Phase A and Phase B).
- Data for the trip is given in terms of *velocities* and *time intervals*.
- The *total displacement* is the *vector sum* of the two *displacement vectors*.



PROBLEM TIP

Average velocity is the *displacement divided by time interval*. You should *never* attempt to find an overall average velocity by taking the vector sum of two velocities.

Identify the Goal

Total displacement, $\Delta\vec{d}_{total}$, for the balloon trip

Variables and Constants

Involved in the problem		Known	Unknown
Δt_A	$\Delta\vec{d}_A$	$\Delta t_A = 2.0$ h	$\Delta\vec{d}_A$
Δt_B	$\Delta\vec{d}_B$	$\Delta t_B = 1.5$ h	$\Delta\vec{d}_B$
$\vec{v}_{A\ ave}$	$\Delta\vec{d}_{total}$	$\vec{v}_{A\ ave} = 24\ \frac{km}{h}$	$\Delta\vec{d}_{total}$
$\vec{v}_{B\ ave}$		$\vec{v}_{B\ ave} = 40\ \frac{km}{h}$	

Strategy

Use the velocity for Phase A to calculate the displacement for Phase A.

Select a scale and draw scale diagrams for Phase A.

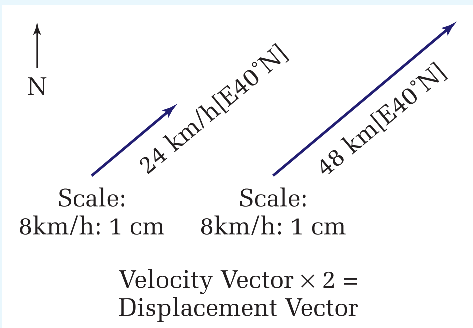
Calculations

$$\Delta\vec{d}_A = \vec{v}_A \Delta t_A$$

$$\Delta\vec{d}_A = 24\ \frac{km}{\cancel{h}}[E40°N](2.0\ \cancel{h})$$

$$\Delta\vec{d}_A = 48\ km[E40°N]$$

Phase A



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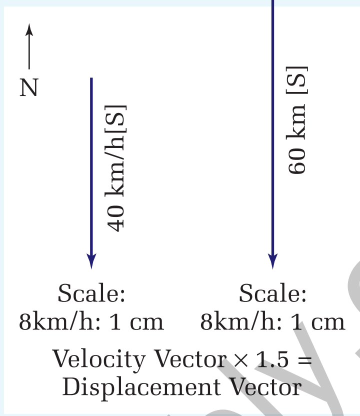
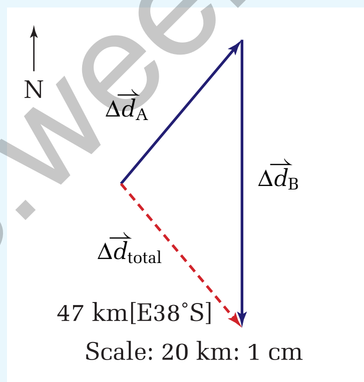
Strategy	Calculations
Use the velocity for Phase B to calculate the displacement for Phase B.	$\Delta\vec{d}_B = \vec{v}_B \Delta t_B$ $\Delta\vec{d}_B = 40\ \frac{\text{km}}{\cancel{\text{h}}}[\text{S}](1.5\ \cancel{\text{h}})$ $\Delta\vec{d}_B = 60\ \text{km}[\text{S}]$
Draw diagrams for Phase B using the scale you selected for Phase A.	
On a graph, draw displacement vector A with its tail at the origin.	
Draw displacement vector B with its tail at the tip of vector A.	
Draw the resultant velocity vector from the tail of A to the tip of B. Label it "$\Delta\vec{d}_{total}$."	
Measure the magnitude and direction of the total displacement vector.	
Multiply the magnitude of the vector by the scale factor (1 cm = 20 km)	$\lvert\Delta\vec{d}_{total}\rvert = 2.35\ \cancel{\text{cm}} \times \left(\frac{20\ \text{km}}{\cancel{\text{cm}}}\right)$ $\lvert\Delta\vec{d}_{total}\rvert = 47\ \text{km}$ $\theta = 38^\circ$

Phase B



Total Displacement



The balloon trip had a displacement of 47 km[E38°S].

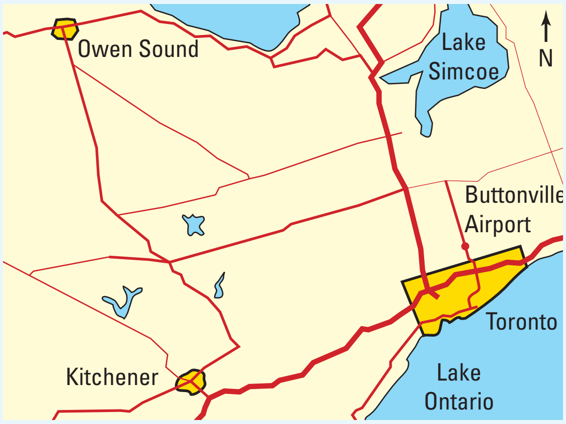
Validate

The wind caused a significant change in course. Since the balloon made a fairly sharp turn, you would expect that the total displacement would be shorter than the sum of the two legs of the trip. This was, in fact, the case (47 km is much shorter than 48 km + 60 km).

PRACTICE PROBLEMS

10. A hang-glider launches herself from a high cliff and drifts 6.0 km south. A wind begins to blow from the southeast, which pushes her 4.0 km northwest before she lands in a field. Calculate her average velocity for the trip if she is in the air for 45 min.

11. A light plane leaves Buttonville Airport, north of Toronto, and flies 80.0 km[W30.0°S] to Kitchener. After picking up a passenger, it flies to Owen Sound, which is 104 km[N20.0°W] of Kitchener. The entire trip took 2.5 h.



(a) Calculate the average velocity of the plane for the entire trip from Toronto to Owen Sound.

(b) If the pilot wants to fly straight back to Buttonville from Owen Sound in 1.0 h, with what velocity will she need to fly? Assume that there is no wind.

12. A canoeist paddles across a calm lake with a velocity of 3.0 m/s north for 30.0 min. He then paddles with a velocity of 2.5 m/s west for 15.0 min. Determine his displacement from where he began paddling.

13. A hiker sets out on a trek heading [N35°E] at a pace of 5.0 km/h for 48.0 min. He then heads west at 4.5 km/h for 40.0 min. Finally, he heads [N30°W] for 6.0 km, until he reaches a campground 1.5 hours later.

(a) Draw a displacement vector diagram to determine his total displacement.

(b) Determine his average velocity for the trip.

(Hint: Remember the definition of average velocity.)

3.1 Section Review

1. C Describe the difference between

(a) vectors and scalars

(b) positive and negative vectors of the same magnitude

(c) a resultant vector for displacement during of trip and the vector representing the return trip

(d) vector addition and vector subtraction

(e) a coordinate system and a frame of reference

2. K/U A map has a scale where 50 km is equal to 1 cm. If two towns are 7 cm apart on the map, what is their actual separation in km?

3. I Investigate how the resultant vector will change when vector A is added to:

(a) vector $\vec{A}$

(b) vector $-\vec{A}$

(c) vector $2\vec{A}$

(d) vector $-5\vec{A}$

4. K/U Define average velocity.

5. K/U A hiker sets out down the trail at a pace of 5 km/h for one hour and then returns to her camp at the same pace to pick up her trail map. What is her average velocity upon arriving back at camp?

3.2 Relative Velocities and Vectors

SECTION EXPECTATIONS

- Describe the motion of an object that is in a moving medium using velocity vectors.
- Analyze quantitatively, the motion of an object relative to different reference frames.

KEY TERM

- relative velocity

Figure 3.3 The dog is moving relative to the water, and the water is moving relative to the river bank. How would you describe the dog's velocity relative to the river bank?

Have you ever been stopped at a stoplight and suddenly felt that you were starting to roll backward? Your immediate instinct was to slam on the brakes, but then you realized that you were not moving after all. You sheepishly realized that, in fact, the car beside you was creeping forward. Your mind had been tricked. Subconsciously, you assumed that the car beside you had remained stopped and that your car was moving backward. Indeed, you *were* moving, but not in the way in which your instincts were telling you. You were moving backward relative to the car beside you, because the other car was moving forward relative to the ground. Relative motion can be deceiving. The dog in the photograph may think that the river bank is moving sideways while he is swimming directly across the river. Is it?

Relative Velocity

Vector addition is a critical tool in calculating **relative velocities**. You have discovered that it is necessary to define a reference frame to describe any velocity. How do you relate velocities in two different reference frames? For example, an aviator must use the ground as a frame of reference to plot an airplane trip. However, when the plane is airborne, the air itself is moving relative to the ground, carrying the plane with it. So the aviator must account for both the motion of the plane relative to the air and the air relative to the ground. By defining velocity vectors for the plane relative to

COURSE CHALLENGE

Staying in Orbit

Investigate the question, "Are geosynchronous satellites ever in the shade?" A quick lab idea to help you solve this problem is presented on the following web site (follow the **Science Resources** and **Physics 11** links), and on the Electronic Learning Partner. ***www.school.mcgrawhill.ca/resources/***

the air and for the air relative to the ground, the aviator can use vector addition to calculate the velocity of the plane relative to the ground, the critical piece of information.

An understanding of relative velocities is not a new problem. Imagine sailing on the high seas on a ship such as the one in Figure 3.4, in the days before communication technology was highly developed. Understanding wind and ocean currents was critical for navigation. The following model problems show you how to perform such calculations.

Figure 3.4 The lives of early sailors depended on their ability to accurately predict and control the motion of their ships, without any modern technology.

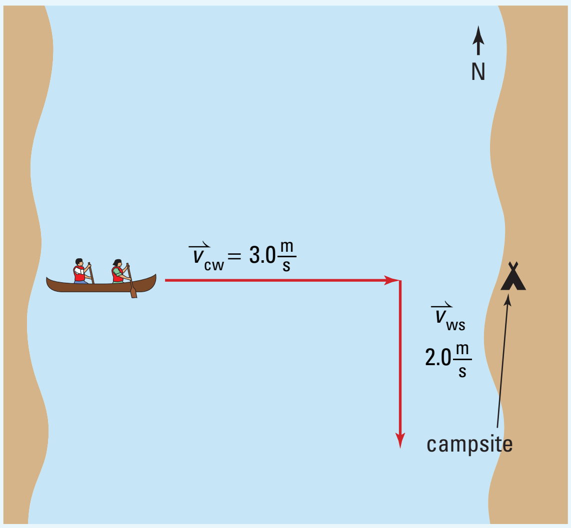
PHYSICS FILE

Nearly everyone has heard of Einstein's theory of relativity, but very few people understand it. According to the theory, relative velocities, as well as lengths of objects and time intervals, would appear to be very strange if you could travel close to the speed of light. For example, imagine that a train travelling close to the speed of light is passing through a short tunnel. An observer, who is stationary relative to the ground, would see the last car disappear into the tunnel before seeing the engine come out the other end. An observer on the train would perceive that the engine was leaving one end of the tunnel before the last car entered the other end. Now that's relativity!

MODEL PROBLEMS

Calculating Relative Velocities

1. A canoeist is planning to paddle to a campsite directly across a river that is 624 m wide. The velocity of the river is 2.0 m/s[S]. In still water, the canoeist can paddle at a speed of 3.0 m/s. If the canoeist points her canoe straight across the river, toward the east: (a) How long will it take her to reach the other river bank? (b) Where will she land relative to the campsite? (c) What is the velocity of the canoe relative to the point on the river bank, where she left?



Frame the Problem

- Make a sketch of the situation described in the problem.
- The *canoe* is *moving* relative to the *river*.

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- The *river* is *moving* relative to the *shore*.
- The *motion* of the *river* toward the south will *not* affect the *eastward motion* of the canoe.
- While the canoeist is *paddling east* across the river, the river is *carrying the canoe* downstream [S] with the current.
- The vector sum of the velocity of the *canoe relative* to the *water* and the *water* relative to the *shore* is the velocity of the *canoe* relative to the *shore*.

PROBLEM TIP

When several different values of a quantity such as velocity occur in the same problem, use subscripts to identify each value of that quantity. In the diagram for this problem, you have three relative velocities. Assign subscripts that identify the object and the reference frame, as shown below.

$\vec{v}_{cs}$ = velocity of the **c**anoe relative to the **s**hore

$\vec{v}_{cw}$ = velocity of the **c**anoe relative to the **w**ater

$\vec{v}_{ws}$ = velocity of the **w**ater relative to the **s**hore

Identify the Goal

(a) The time, Δt_{SE}, it takes for the canoe to reach the far bank

(b) The displacement, $\Delta\vec{d}_S$, of the canoe from the campsite at the point where the canoe comes ashore

(c) The velocity, $\vec{v}_{cs}$, of the canoe relative to the shore

Variables and Constants

Involved in the problem	Known	Unknown
$\Delta\vec{d}_E$ (width of river)	$\Delta\vec{d}_E = 624$ m	$\Delta\vec{d}_S$
$\Delta\vec{d}_s$ (distance from campsite point where canoe went ashore)	$\vec{v}_{ws} = 2.0\ \frac{\text{m}}{\text{s}}$[S]	$\vec{v}_{ws}$
$\vec{v}_{ws}$ $\vec{v}_{cs}$ Δt_E	$\vec{v}_{cw} = 3.0\ \frac{\text{m}}{\text{s}}$[E]	$\vec{v}_{cw}$
$\vec{v}_{cw}$ θ Δt_{SE}		$\vec{v}_{cs}$

Strategy

The time it takes to cross the river depends *only* on the velocity of the canoe relative to the river and is independent of the motion of the river. Calculate the time it takes to paddle across the river from the expression that defines average velocity. Since time is a scalar, use absolute magnitudes for velocity and displacement.

Calculations

Substitute first

$$|\vec{v}_{cw}| = \frac{|\Delta\vec{d}_E|}{\Delta t_{SE}}$$

$$3.0\ \frac{\text{m}}{\text{s}} = \frac{624\ \text{m}}{\Delta t_{SE}}$$

$$3.0\ \frac{\text{m}}{\text{s}}\Delta t_{SE} = \frac{624\ \text{m}}{\cancel{\Delta t_{SE}}}\cancel{\Delta t_{SE}}$$

$$3.0\ \frac{\text{m}}{\text{s}}\Delta t_{SE} = 624\ \text{m}$$

$$\frac{\cancel{3.0\ \frac{\text{m}}{\text{s}}}\Delta t_{SE}}{\cancel{3.0\ \frac{\text{m}}{\text{s}}}} = \frac{624\ \cancel{\text{m}}}{3.0\ \frac{\cancel{\text{m}}}{\text{s}}}$$

$$\Delta t_{SE} = 208\ \text{s}$$

Solve for Δt first

$$|\vec{v}_{cw}| = \frac{|\Delta\vec{d}_E|}{\Delta t_{SE}}$$

$$|\vec{v}_{cw}|\Delta t_{SE} = \frac{|\Delta\vec{d}_E|}{\cancel{\Delta t_{SE}}}\cancel{\Delta t_{SE}}$$

$$\frac{\cancel{|\vec{v}_{cw}|}\Delta t_{SE}}{\cancel{|\vec{v}_{cw}|}} = \frac{|\Delta\vec{d}_E|}{|\vec{v}_{cw}|}$$

$$\Delta t_{SE} = \frac{|\Delta\vec{d}_E|}{|\vec{v}_{cw}|}$$

$$\Delta t_{SE} = \frac{624\ \cancel{\text{m}}}{3.0\frac{\cancel{\text{m}}}{\text{s}}}$$

$$\Delta t_{SE} = 208\ \text{s}$$

(a) It took the canoeist 2.1×10^2 s (or 3.5 min) to paddle across the river when her canoe was pointed directly east across the river.

Strategy

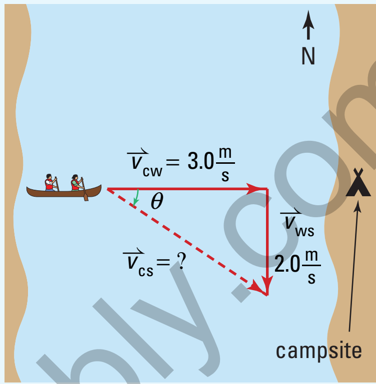
During the 208 s that the canoeist was paddling, the river current was carrying her south, down the river. To find the distance down river that she landed, simply find the distance that she would travel at the velocity of the current. Use the equation for the definition of average velocity. (**Note:** When using an answer to a previous part of a problem in another calculation, use the unrounded value.)

Calculations

Substitute first

$$\Delta\vec{d}_S = \vec{v}_{ws}\,\Delta t_{SE}$$
$$\Delta\vec{d}_S = 2.0\,\frac{\text{m}}{\cancel{\text{s}}}[\text{S}](208\,\cancel{\text{s}})$$
$$\Delta\vec{d}_S = 416\text{ m[S]}$$

Solve for Δt first



(b) The river carried the canoeist 4.2×10^2 m down river from the campsite.

To find the velocity of the canoe relative to the shore, find the vector sum of the velocity of the canoe relative to the water and the velocity of the water relative to the shore. Since the two vectors that you are adding are perpendicular to each other, the resultant is the hypotenuse of a right triangle. You can use the Pythagorean theorem to find the magnitude of the velocity.

$$|\vec{v}_{cs}|^2 = |\vec{v}_{cw}|^2 + |\vec{v}_{ws}|^2$$
$$|\vec{v}_{cs}|^2 = \left(3.0\,\frac{\text{m}}{\text{s}}\right)^2 + \left(2.0\,\frac{\text{m}}{\text{s}}\right)^2$$
$$|\vec{v}_{cs}|^2 = 9.0\left(\frac{\text{m}}{\text{s}}\right)^2 + 4.0\left(\frac{\text{m}}{\text{s}}\right)^2$$
$$|\vec{v}_{cs}|^2 = 13.0\left(\frac{\text{m}}{\text{s}}\right)^2$$
$$|\vec{v}_{cs}| = 3.6\,\frac{\text{m}}{\text{s}}$$

From the diagram, you can see that the tangent of the angle, θ, is the velocity of the water relative to the shore divided by the velocity of the canoe relative to the water. Use this expression to find θ.

$$\tan\theta = \frac{|\vec{v}_{ws}|}{|\vec{v}_{cw}|}$$
$$\tan\theta = \frac{2.0\,\frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{3.0\,\frac{\cancel{\text{m}}}{\cancel{\text{s}}}}$$
$$\tan\theta = 0.6666$$
$$\theta = \tan^{-1} 0.6666$$
$$\theta = 33.69^\circ$$

(c) The velocity of the canoe relative to the shore was 3.6 m/s[E34°S].

Validate

In every case, the units cancelled to give the correct unit, (a) time in seconds, (b) displacement in metres and direction, and (c) velocity in metres per second and direction.

You would expect the velocity of the canoe relative to the shore to be larger than either the canoe relative to water and the water relative to the shore. You would also expect it to be less than the sum of the two magnitudes. All of these values were observed. The answers were all reasonable.

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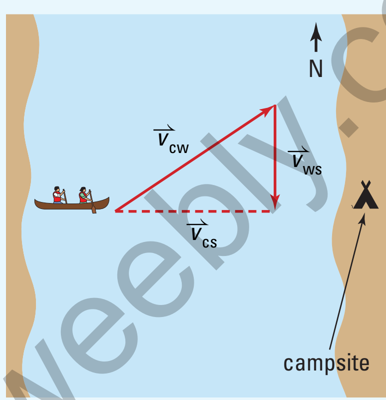
2. The canoeist in question 1 wants to head her canoe in such a direction that she will actually travel straight across the river to the campsite. (a) In what direction must she point the canoe? (b) Find the magnitude of her velocity relative to the shore. (c) How long will it take the canoeist to paddle to the campsite?

Frame the Problem



- Make a sketch of the problem.
- As the canoeist is paddling across the river, she must continuously *paddle upstream* to make up for the *current* carrying her *downstream*.
- Her *velocity relative* to the *shore* will have a *direction of east*, but the *magnitude* will be *less* than the *3.0 m/s* that she paddles *relative* to the *water*.
- The effective *distance* that she *paddles* will be *greater* than the *width* of the river, because she is, in a sense, going upstream.

Identify the Goal

(a) The direction, θ, in which the canoe must point

(b) The magnitude of the velocity, $|\vec{v}_{cs}|$, of the canoe relative to the shore

(c) The time interval, Δt, to paddle to the campsite

Variables and Constants

Involved in the problem		Known	Unknown
$\vec{v}_{ws}$	$\vec{v}_{cs}$	$\vec{v}_{ws} = 2.0\ \frac{\text{m}}{\text{s}}[\text{S}]$	$\lvert\vec{v}_{cs}\rvert$
$\vec{v}_{cw}$	θ	$\lvert\vec{v}_{cw}\rvert = 3.0\ \frac{\text{m}}{\text{s}}$	θ
	Δt		Δt

Strategy

In this case, the magnitudes of the hypotenuse and opposite side of the triangle are known. Find the angle.

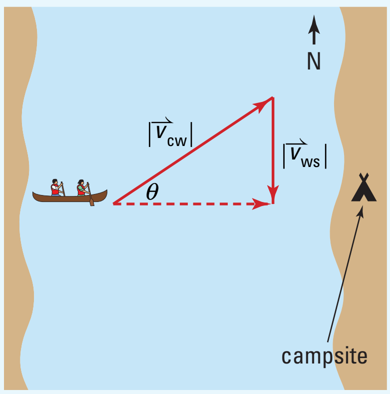
Calculations

$$\sin\theta = \frac{2.0\ \cancel{\frac{\text{m}}{\text{s}}}}{3.0\ \cancel{\frac{\text{m}}{\text{s}}}}$$

$$\sin\theta = 0.6667$$

$$\theta = \sin^{-1} 0.6667$$

$$\theta = 41.8^\circ$$



(a) The canoeist must point the canoe 42° upstream in order to paddle directly across the river to the campsite.

Strategy

Use the Pythagorean theorem to find the magnitude of the velocity of the canoe relative to the shore.

Calculations

Substitute first

$$|\vec{v}_{cw}|^2 = |\vec{v}_{cs}|^2 + |\vec{v}_{ws}|^2$$
$$\left(3.0\ \frac{m}{s}\right)^2 = |\vec{v}_{cs}|^2 + \left(2.0\ \frac{m}{s}\right)^2$$
$$9.0\left(\frac{m}{s}\right)^2 - 4.0\left(\frac{m}{s}\right)^2 = |\vec{v}_{cs}|^2 + 4.0\left(\frac{m}{s}\right)^2 - 4.0\left(\frac{m}{s}\right)^2$$
$$9.0\left(\frac{m}{s}\right)^2 - 4.0\left(\frac{m}{s}\right)^2 = |\vec{v}_{cs}|^2$$
$$5.0\left(\frac{m}{s}\right)^2 = |\vec{v}_{cs}|^2$$
$$|\vec{v}_{cs}| = 2.24\left(\frac{m}{s}\right)$$

Solve for $|\vec{v}_{cs}|$ first

$$|\vec{v}_{cw}|^2 = |\vec{v}_{cs}|^2 + |\vec{v}_{ws}|^2$$
$$|\vec{v}_{cw}|^2 - |\vec{v}_{ws}|^2 = |\vec{v}_{cs}|^2 + |\vec{v}_{ws}|^2 - |\vec{v}_{ws}|^2$$
$$|\vec{v}_{cs}|^2 = |\vec{v}_{cw}|^2 - |\vec{v}_{ws}|^2$$
$$|\vec{v}_{cs}| = \sqrt{|\vec{v}_{cw}|^2 - |\vec{v}_{ws}|^2}$$
$$|\vec{v}_{cs}| = \sqrt{\left(3.0\ \frac{m}{s}\right)^2 - \left(2.0\ \frac{m}{s}\right)^2}$$
$$|\vec{v}_{cs}| = \sqrt{9.0\left(\frac{m}{s}\right)^2 - 4.0\left(\frac{m}{s}\right)^2}$$
$$|\vec{v}_{cs}| = \sqrt{5.0\left(\frac{m}{s}\right)^2}$$
$$|\vec{v}_{cs}| = 2.24\ \frac{m}{s}$$

(b) The magnitude of the velocity of the canoe relative to the shore was 2.2 m/s.

Use the calculated velocity of the canoe relative to the shore and the known distance across the river to find the time interval for crossing the river.

Substitute first

$$\vec{v}_{cs} = \frac{\Delta\vec{d}}{\Delta t}$$
$$2.23\ \frac{m}{s}[E] = \frac{624\ m[E]}{\Delta t}$$
$$2.23\ \frac{m}{s}[E]\Delta t = \frac{624\ m[E]}{\cancel{\Delta t}}\cancel{\Delta t}$$
$$\frac{\cancel{2.23\ \frac{m}{s}[E]}\Delta t}{\cancel{2.23\ \frac{m}{s}[E]}} = \frac{624\ \cancel{m[E]}}{2.23\ \frac{\cancel{m}}{s}\cancel{[E]}}$$
$$\Delta t = 279\ s$$

Solve for Δt first

$$\vec{v}_{cs} = \frac{\Delta\vec{d}}{\Delta t}$$
$$\vec{v}_{cs}\Delta t = \frac{\Delta\vec{d}}{\cancel{\Delta t}}\cancel{\Delta t}$$
$$\frac{\cancel{\vec{v}_{cs}}\Delta t}{\cancel{\vec{v}_{cs}}} = \frac{\Delta\vec{d}}{\vec{v}_{cs}}$$
$$\Delta t = \frac{\Delta\vec{d}}{\vec{v}_{cs}}$$
$$= \frac{624\ \cancel{m[E]}}{2.23\ \frac{\cancel{m}}{s}\cancel{[E]}}$$
$$= 279\ s$$

(c) It took 2.8×10^2 s (or 4.7 min) for the canoe to cross the river and reach shore at the campsite.

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Validate

In every case, the units cancelled to give the correct units for the desired quantity.

You would expect that it would take longer to paddle across the river when taking the current into account than it would to paddle directly across relative to the water. It took about 70 s, or more than a minute, longer.

PRACTICE PROBLEMS

14. A kayaker paddles upstream in a river at 3.5 m/s relative to the water. Observers on shore note that he is moving at only 1.7 m/s upstream. Determine the velocity of the current in the river.

15. A jet-ski speeds across a river at 11 m/s relative to the water. The jet ski's heading is due south. The river is flowing west at a rate of 5.0 m/s. Determine the jet-ski's velocity relative to the shore.

16. A bush pilot wants to fly her plane to a lake that is 250.0 km [N30.0°E] from her starting point. The plane has an air speed of 210.0 km/h, and a wind is blowing from the west at 40.0 km/h.

(a) In what direction should she head the plane to fly directly to the lake?

(b) If she uses the heading determined in (a), what will be her velocity relative to the ground?

(c) How long will it take her to reach her destination?

17. An airplane travels due north for 1.0×10^2 km, then due west for 1.5×10^2 km, and then due south for 5.0×10^2 km.

(a) Use vectors to find the total displacement of the airplane.

(b) The time the airplane takes to fly the three different parts of the trip are as follows: 20.0 minutes, 40.0 minutes, and 12.0 minutes. Calculate the velocities for each of the three segments of the trip.

(c) Calculate the average velocity for the total trip. (Hint: this is not the same as the average speed.)

18. A swimmer is standing on the south shore of a river that is 120 m wide. He wants to swim straight across and knows that he can swim 1.9 m/s in still water. He drops a stick in the water and finds that it floats with the current to a point 24 m west in 30.0 s.

(a) Determine the direction in which the swimmer should head so that he lands directly across the river on the north bank.

(b) If he follows your advice, determine how long it will take him to reach the far shore.

19. A hiker heads [N40.0°W] and walks in a straight line for 4.0 km. She then heads [E10.0°N] and walks in a straight line for 3.0 km. Finally, she heads [S40.0°W] and walks in a straight line for 2.5 km.

(a) Determine the hiker's total displacement for the trip.

(b) In what direction would she have to head in order to walk straight back to her starting position?

(c) If her average walking speed was 4.0 km/h, how long did the total trip take?

20. A lone canoeist paddles from Tobermory heading directly east. When there is no wind, the velocity of the canoe is 1.5 m/s. However, a strong wind is blowing from the north, and the canoe is pushed southwards at a rate of 0.50 m/s.

(a) Use vectors to calculate the resultant velocity of the canoe relative to the shore.

(b) Check your solution by using the Pythagorean theorem.

INVESTIGATION 3-A

Go with the Flow

TARGET SKILLS

- Initiating and planning
- Predicting
- Performing and recording
- Communicating results

In this investigation, you will simulate the motion of a canoe travelling across a river. This process will help you to sharpen your skills of working with relative velocities and clarify your understanding of these concepts.

Prediction

Predict the point at which your "canoe" will come ashore on the "river bank" under several different conditions.

Problem

Test your predictions about the point where your canoe will come ashore on the river bank under several different conditions.

Determine the direction in which the canoe must head in order to reach the river bank directly across the river from where it started.

Equipment

- battery-powered toy car (or physics bulldozer)
- 2 retort stands
- stopwatch
- protractor
- metre stick
- newspaper
- masking tape
- string

Procedure

1. Make a paper river by taping together six sheets of newspaper. Newspaper sizes vary, but your river should end up being approximately 1 m wide and 3 m long. (A piece of brown wrapping paper can be used as an alternative to the newspaper.) Measure and record the exact width of your river.
2. A toy car will serve as the canoe. Design and carry out a procedure to determine
   (a) the canoe's speed
   (b) whether the canoe travels at a constant velocity

   Record your procedure, data, calculations, and conclusions.
3. Have one member of your group pull the river along at a constant velocity. Develop a technique for ensuring that the river "flows" at the same constant velocity throughout the investigation.
4. Design and carry out a procedure for determining the velocity of the river.

   Record your procedure, data, calculations, and conclusions.

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5. Predict how long it will take the canoe to cross the river from one edge to the other when the river is *not* flowing. Test your prediction.
6. Make the following predictions about the motion of the canoe when the river is flowing.
   (a) Predict whether the motion of the river will affect the time it takes for the canoe to travel from one bank to the other. Explain your reasoning. Include in your explanation a sketch of what you think will happen, and the frames of reference that you considered.
   (b) Assume that the canoe is pointed directly across the river. Predict where the canoe will come ashore on the opposite river bank.
   (c) Predict the direction in which the canoe must be pointed for it to travel directly across the river. Draw a vector diagram to support your predictions.
   (d) Predict the time it will take for the canoe to cross the river when pointed in the direction you determined in part (c).
7. Test your predictions according to the following procedures.
   (a) Measure the time it takes for the canoe to cross the river when the river is not flowing.
   (b) Based on your prediction in step 6(b), mark the starting point and the predicted ending point of the river-crossing when the river is flowing. Place a retort stand at each of the two positions and tie a string from one to the other along the predicted path. Start the river flowing. Start a stopwatch when you start the canoe, and time the crossing. Observe the crossing to see how well the canoe followed the predicted path.
   (c) Develop a method to ensure that you can align the canoe in the direction predicted in step 6(c). Start the river flowing, then start the canoe crossing at the predetermined angle. Time the crossing with a stopwatch. Observe the motion of the canoe and the point where it goes ashore on the far side of the river.
8. If the direction that you predicted in step 6(c) and tested in step 7(c) did not result in the canoe going ashore directly across the river, re-evaluate your velocities and calculations. Refine and repeat your experiment several times until your observations match your predictions as closely as is reasonable.

Analyze and Conclude

1. What was your prediction about the effect of the motion of the river and the time it took for the canoe to cross the river when the canoe was pointed directly across the river? How well did your observations support your prediction? Explain.
2. Use the concept of frames of reference to answer the following question in two different (opposite) ways. Does the canoe move in the direction in which it is pointing?
3. How well did your observations support your predictions about the time interval of the crossing when the canoe was pointed in a direction that resulted in its moving directly across the flowing river? Explain.
4. How well were you able to predict the correct direction in which to point the canoe in order to cause it to move directly across the flowing river? If you had to make adjustments to your prediction and re-test the procedure, explain why this was necessary.
5. Discuss any problems you encountered in making and testing predictions involving relative velocities.

3.2 Section Review

1. **C** Explain why the concept of relative velocity is useful to pilots and canoeists.

2. **C** Discuss whether all velocities can be considered relative velocities.

3. **K/U** When you are in a car moving at 50 km/h,
   (a) what is your velocity relative to the car?
   (b) what is your velocity relative to the ground?

4. **K/U** On a moving train, you walk to the dining car, which is forward of your own car. Draw velocity vectors of the train relative to the ground, you relative to the train, and you relative to the ground for a point on your trip towards and away from the dining car.

5. **K/U** State the object and reference frame of the resultant vector when the following velocity vectors are added.
   (a) plane relative to air + air relative ground
   (b) canoe relative to water + water relative ground
   (c) balloon relative to ground + ground relative to air
   (d) swimmer relative to ground + ground relative to water

6. **C** Use common language to communicate
   (a) air speed relative to the ground
   (b) the heading of someone in a kayak
   (c) water speed relative to the ground

ELECTRONIC LEARNING PARTNER

Your Electronic Learning Partner has more information about motion in a plane.

7. **K/U** A canoe is headed directly across a river that is 200 m wide. Instead of moving with constant velocity, the canoe moves with a constant acceleration of 4.0×10^{-2} m/s^2. If the river is flowing with a constant velocity of 2.0 m/s, how long will it take for the canoe to reach the other side? How far down the river will it land? Sketch the shape of the path the canoe will follow.

8. **I** A boy heads north across a river at a speed of x m/s. A current of $\frac{x}{2}$ m/s heads west.
   (a) Develop a vector diagram to indicate where he will land on the opposite beach.
   (b) Develop a vector diagram to indicate the direction that he should head in order to land at the dock directly north of his starting position.

UNIT PROJECT PREP

Simple visual effects can be impressive when they play with the viewer's expectations.

- How can other objects and changing backgrounds be used to create the illusion of motion?
- Can relative velocities be used to create comic or dramatic situations?
- Try using a strobe light to create interesting velocity effects.

  CAUTION Strobe lights can cause seizures in people with certain medical conditions.

3.3 Vector Components

SECTION EXPECTATIONS

- Apply vector definitions of position, displacement, velocity and acceleration to motion in a plane.
- Solve quantitative problems of motion in a plane.

KEY TERMS

- resolved
- components

When solving vector addition and subtraction problems graphically, you probably noticed that the method is very imprecise. Measurements with rulers and protractors create a large uncertainty. So you will not be surprised to learn that there is a more precise method. If you want more precision, you can choose to use the method presented in this section.

An important clue to the more precise method lies in the canoe investigation and other problems in which you added vectors that were at an angle of 90°, or right angles, relative to each other. When you determined the vector sum of the canoe's velocity and the river's velocity (pages 105–107), you were able to use the Pythagorean theorem to calculate precisely. You did not have to measure with a ruler. The precise method for adding and subtracting vectors is based on right triangles and the rules of trigonometry.

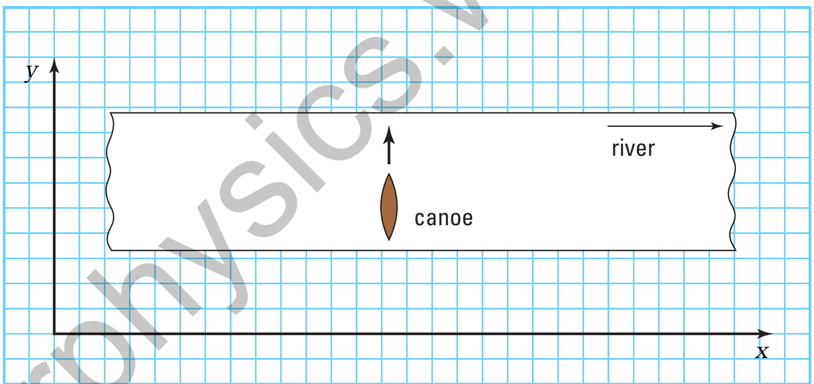


Figure 3.5 Use the Pythagorean theorem to calculate vectors precisely.

Vector Components

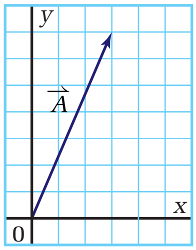
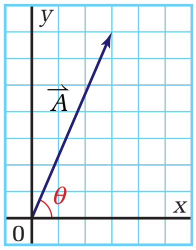
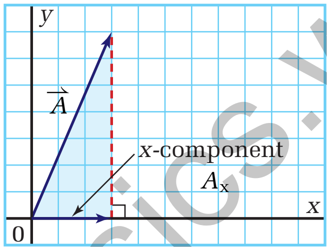
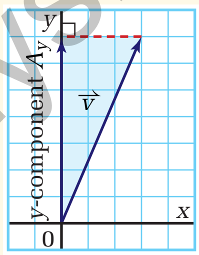
The vectors that you want to add or subtract are rarely at right angles to each other; however, any vector can be separated, or **resolved**, into components that *are* at right angles to each other. **Components** are parts of a vector that lie on the axes of a coordinate system. Since components are confined to one direction, they are scalar quantities, not vectors.

When working with vector components, the *x*–*y*-coordinate system is much more convenient to use than a system based on compass directions. Follow the steps in Table 3.4 to learn how to resolve a vector into components. If you need to review the definitions of the trigonometric functions, sine, cosine, and tangent, turn to Skill Set 4.

ELECTRONIC LEARNING PARTNER

To learn more about vector components, go to your Electronic Learning Partner.

Table 3.4 Resolving Vectors into *x*- and *y*-Components

Procedural Step	Graph
Draw the vector with its tail at the origin of the coordinate system.	
Identify the angle that the vector makes with the *x*-axis and label it "θ."	
Draw a vertical line from the tip of the vector to the *x*-axis. The line from the origin to the base of this vertical line is the *x*-component of the vector.	
Draw a horizontal line from the tip of the vector to the *y*-axis. The line from the origin to the base of this line is the *y*-component.	
Write the equation that defines $\sin\theta$. Notice that the *y*-component (A_y) of the vector is identical to the line from the tip of the vector to the *x*-axis.	$\sin\theta = \frac{A_y}{\lvert\vec{A}\rvert}$
Solve for the *y*-component, A_y.	$A_y = \lvert\vec{A}\rvert \sin\theta$
Write the equation that defines $\cos\theta$.	$\cos\theta = \frac{A_x}{\lvert\vec{A}\rvert}$
Solve for the *x*-component, A_x.	$A_x = \lvert\vec{A}\rvert \sin\theta$

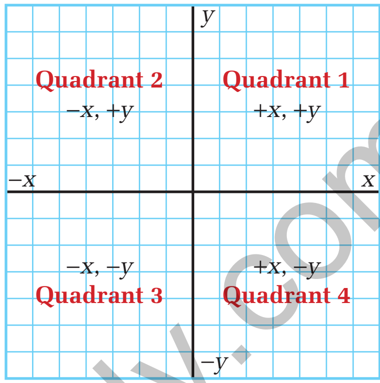


Figure 3.6 Vector components are scalars, but the sign, positive or negative, is very important.

PHYSICS FILE

When working in an *x*–*y*-coordinate system, mathematicians and physicists report the direction of a vector by giving the angle that the vector makes with the positive *x*-axis. You find the angle by starting at the positive *x*-axis and rotating until you reach the location of the vector. If a vector has an angle greater than 90°, it lies in a quadrant other than the first. Vectors in the second, third, or fourth quadrants have at least one component that is negative. Figure 3.6 summarizes the signs of the *x*- and *y*-components in the four quadrants. When you use an angle to calculate the magnitude of the components, you would use the angle the vector makes with the nearest *x*-axis. The model problems show you how to find the components of a vector.

Resolving Vectors

1. Find the x- and y-components of vector $\Delta\vec{d}$, which has a magnitude of 64 m at an angle of 120°.

Frame the Problem

- The angle is between 90° and 180°, so it is in the *second quadrant*. Therefore, the *x-component* is *negative* and the *y-component* is *positive*.
- Use *trigonometric functions* to find the components of the vector.

Identify the Goal

The components, Δd_x and Δd_y, of vector $\Delta\vec{d}$

Variables and Constants

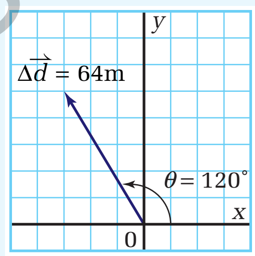
Involved in the problem		Known	Unknown
Δd_x	$\Delta\vec{d}$	$\Delta\vec{d} = 64$ m	Δd_x
Δd_y	θ	$\theta = 120°$	Δd_y

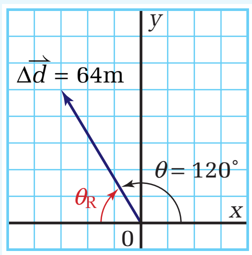
Strategy

Draw the vector with its tail at the origin of an x–y-coordinate system.

Identify the angle with the closest x-axis. Label it "θ_R".

Calculations



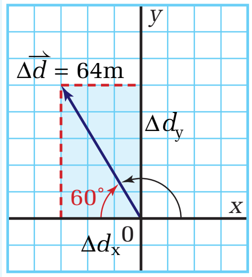


$\theta_R = 180° - 120°$
$\theta_R = 60°$

Strategy

Draw lines from the tip of the vector to each axis, so that they are parallel to the axes.

Calculations



Calculate the components according to the directions in Table 3.4.

$\Delta d_x = |\overrightarrow{\Delta d}| \cos\theta$

$\Delta d_x = 64\ \text{m}\ \cos 60^\circ$

$\Delta d_x = 64\ \text{m}\ (0.5000)$

$\Delta d_x = 32\ \text{m}$

$\Delta d_y = |\overrightarrow{\Delta d}| \sin\theta$

$\Delta d_y = 64\ \text{m}\ \sin 60^\circ$

$\Delta d_y = 64\ \text{m}\ (0.8660)$

$\Delta d_y = 55.4\ \text{m}$

Determine signs of the components.

The *x*-component lies on the negative *x*-axis so it is negative. The *y*-component lies on the positive *y*-axis so it is positive.

The *x*-component of the vector is –32 m and the *y*-component is +55 m.

Validate

Use the Pythagorean theorem to check your answers.

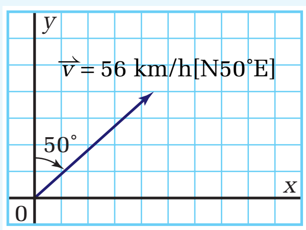
$$|\overrightarrow{\Delta d}|^2 = \Delta d_x{}^2 + \Delta d_y{}^2$$
$$|\overrightarrow{\Delta d}|^2 = (32\ \text{m})^2 + (55.4\ \text{m})^2$$
$$|\overrightarrow{\Delta d}|^2 = 1024\ \text{m}^2 + 3069.2\ \text{m}^2$$
$$|\overrightarrow{\Delta d}|^2 = 4093.2\ \text{m}^2$$
$$|\overrightarrow{\Delta d}| = 64\ \text{m}$$

The value agrees with the original vector.

2. Resolve the vector, $\vec{v} = 56\ \frac{\text{km}}{\text{h}}$[N50°E], into components.

Frame the Problem

- Make a sketch of the vector.
- The vector is described in compass directions.
- *Converting* to an *x–y-coordinate* system will simplify the process of finding components. Let +*y* be north, making –*y* south. East will become +*x* and west will be –*x*.
- You will need to find the *angle* with the closest *x-axis*.



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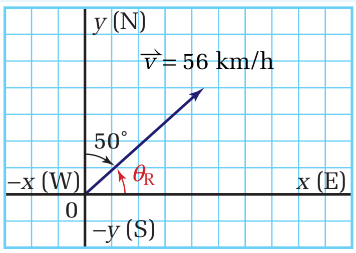
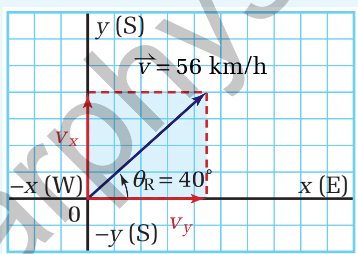
Identify the Goal

The x- and y-components of the vector $\vec{v} = 56\,\frac{\text{km}}{\text{h}}$[N50°E]

Variables and Constants

Involved in the problem		Known	Unknown
$\vec{v}$	v_x	$\vec{v} = 56\,\frac{\text{km}}{\text{h}}$ [N50°E]	v_x
θ_R	v_y		v_y
			θ_R

> **PROBLEM TIP**
>
> To avoid confusion, always choose to use the angle that the vector makes with the x-axis. Regardless of the quadrant in which the vector is located, the x-component will always be the cosine of the angle times the magnitude of the vector. The y-component will always be the sine of the angle times the magnitude of the vector. Mathematicians call the angle that the vector makes with the closest x-axis the "reference angle."

Strategy	Calculations
Draw an x–y-coordinate system and indicate that the axes also represent the compass directions. Draw the vector with its tail at the origin of the coordinate system. Identify the angle, θ_R.	
Since the 50° is the angle made by the vector and the y-axis [N], use it to find θ_R, the angle the vector makes with the x-axis.	$\theta_R = 90° - 50°$ $\theta_R = 40°$
Draw lines from the tip of the vector to each axis, so that they are parallel to the axes.	

Calculate the components according to the directions in Table 3.4.

$$v_x = |\vec{v}|\cos\theta$$
$$v_x = 56\,\frac{\text{km}}{\text{h}}\;\cos 40°$$
$$v_x = 56\,\frac{\text{km}}{\text{h}}\;(0.7660)$$
$$v_x = 42.9\,\frac{\text{km}}{\text{h}}$$

$$v_y = |\vec{v}|\sin\theta$$
$$v_y = 56\text{ m }\sin 40°$$
$$v_y = 56\,\frac{\text{km}}{\text{h}}\;(0.6428)$$
$$v_y = 36\,\frac{\text{km}}{\text{h}}$$

Determine the signs of the components. The vector lies in the first quadrant, so all of the components are positive.

The x-component of the vector is 43 km/h and the y-component is 36 km/h.

Validate

Apply the Pythagorean theorem to the components in their unrounded form.

$$|\vec{v}|^2 = v_x^2 + v_y^2$$

$$|\vec{v}|^2 = \left(42.9\ \frac{\text{km}}{\text{h}}\right)^2 + \left(36\ \frac{\text{km}}{\text{h}}\right)^2$$

$$|\vec{v}|^2 = 3136.28\left(\frac{\text{km}}{\text{h}}\right)^2$$

$$|\vec{v}| = 56\ \frac{\text{km}}{\text{h}}$$

The value agrees with the magnitude of the original vector.

PRACTICE PROBLEMS

21. Resolve the following vectors into their components.

(a) a position of 16 m at an angle of 75°

(b) an acceleration of 8.1 m/s^2 at an angle of 145°

(c) a velocity of 16.0 m/s at an angle of 225°

22. Resolve the following vectors into their components.

(a) a displacement of 20.0 km[N20.0°E]

(b) a velocity of 3.0 m/s[E30.0°S]

(c) a velocity of 6.8 m/s[W70.0°N]

23. A hot-air balloon has drifted 60.0 km [E60.0°N] from its launch point. It lands in a field beside a road that runs in a north-south direction. The balloonists radio back to their ground crew to come and pick them up. The ground crew can travel only on roads that run north-south or east-west. The roads are laid out in a grid pattern, with intersections every 2.0 km. How far east and then how far north will the pickup van need to travel in order to reach the balloon?

Vector Addition and Subtraction by Using Components

Examine Figure 3.7 to begin to see how resolving vectors into their components will allow you to add or subtract vectors in a precise yet uncomplicated way. In the figure, $\vec{R}$ is the resultant vector for the addition of $\vec{A}$, $\vec{B}$, and $\vec{C}$. You can also see that R_x is equal in length to $A_x + B_x + C_x$. The same is true for the y-components.

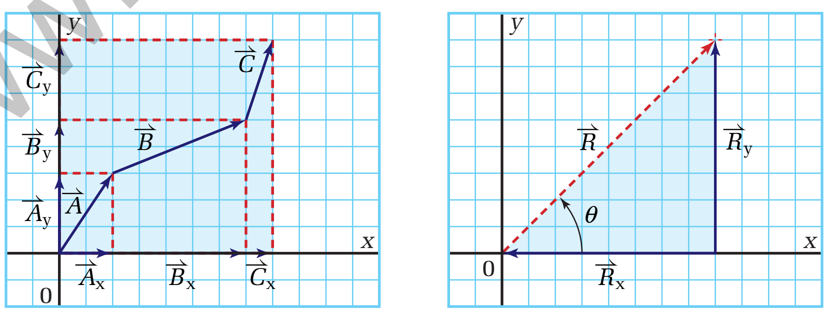


Figure 3.7 The projection of each vector on the x- and y-axes are the components of the vector.

When you want to add or subtract vectors, you can separate the vectors into their components, add or subtract the components, and then find the resultant vector by using the Pythagorean theorem.

$$R_x = A_x + B_x + C_x + \cdots \quad R_y = A_y + B_y + C_y + \cdots \quad |\vec{R}|^2 = R_x{}^2 + R_y{}^2$$

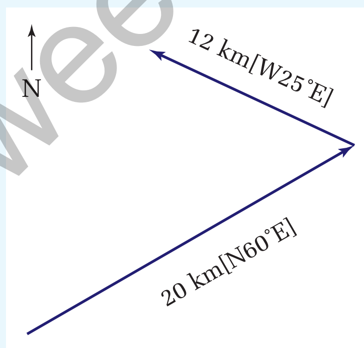
You can find the angle, θ, from the components of the resultant vector, because they make the sides of a right triangle. Find the ratio of R_y to R_x, then use your calculator to find the angle for which the tangent is the ratio.

$$\tan\theta = \frac{R_y}{R_x}$$

MODEL PROBLEMS

Using Vector Components

1. A sailboat sailed [N60°E] for 20.0 km. A strong wind began to blow, causing the boat to travel an additional 12.0 km[W25°N]. Determine the boat's displacement for the entire trip.



Frame the Problem

- Make a sketch of the problem.
- The trip consisted of *two displacements* in two *different directions*.
- The *vector sum* of the *displacements* is the total displacement.

Identify the Goal

The total displacement, $\Delta\vec{d}_T$, for the trip

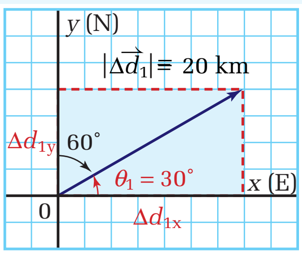
Variables and Constants

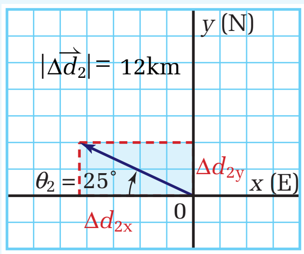
Involved in the problem			Known	Unknown		
$\Delta\vec{d}_1$	Δd_{1x}	Δd_{1y}	$\Delta\vec{d}_1 = 20$ km[N60°E]	$\Delta\vec{d}_T$	Δd_{1x}	Δd_{1y}
$\Delta\vec{d}_2$	Δd_{2x}	Δd_{2y}	$\Delta\vec{d}_2 = 12$ km[W25°N]	θ_1	Δd_{2x}	Δd_{2y}
$\Delta\vec{d}_T$	Δd_{Tx}	Δd_{Ty}		θ_2	Δd_{Tx}	Δd_{Ty}
θ_1	θ_2	θ		θ		

Strategy

Draw vectors $\Delta\vec{d}_1$ and $\Delta\vec{d}_2$ on x–y-coordinate systems, where the positive y-axis coincides with north. Identify θ_1 and θ_2, the angles that the vectors make with the x-axis.

Calculations





Strategy | **Calculations**

The angle [N60°E] refers to the angle that the vector makes with the y-axis. Find the size of the angle the vector makes with the x-axis.

$\theta_2 = 25^\circ$

Draw the lines from the tips of the vectors to the axes that are parallel to the axes.

$\theta_1 = 90^\circ - 60^\circ$
$\theta_1 = 30^\circ$

Calculate the x- and y-components of the vectors:
$\Delta\vec{d}_1 = 20$ km[N60°E]
$\Delta\vec{d}_2 = 12$ km[W25°N]

$\Delta d_{1x} = |\Delta\vec{d}_1| \cos\theta_1$
$\Delta d_{1x} = 20 \text{ km} \cos 30^\circ$
$\Delta d_{1x} = 20 \text{ km } (0.8660)$
$\Delta d_{1x} = 17.3 \text{ km}$

$\Delta d_{2x} = |\Delta\vec{d}_2| \cos\theta_2$
$\Delta d_{2x} = 12 \text{ km} \cos 25^\circ$
$\Delta d_{2x} = 12 \text{ km } (0.9063)$
$\Delta d_{2x} = 10.88 \text{ km}$

$\Delta d_{1y} = |\Delta\vec{d}_1| \sin\theta_1$
$\Delta d_{1y} = 20 \text{ km} \sin 30^\circ$
$\Delta d_{1y} = 20 \text{ km } (0.5000)$
$\Delta d_{1y} = 10 \text{ km}$

$\Delta d_{2y} = |\Delta\vec{d}_2| \sin\theta_2$
$\Delta d_{2y} = 12 \text{ km} \sin 25^\circ$
$\Delta d_{2y} = 12 \text{ km } (0.4226)$
$\Delta d_{2y} = 5.07 \text{ km}$

Identify the signs of the components.

$\Delta\vec{d}_1$ is in the first quadrant so both of the components are positive.

$\Delta\vec{d}_2$ is in the second quadrant, so the x-component is negative and the y-component is positive.

Make a table in which to list the x- and y-components. Add them to find the components of the resultant vector.

Vector	***x*-component**	***y*-component**
$\Delta\vec{d}_1$	17.3 km	10.0 km
$\Delta\vec{d}_2$	–10.9 km	5.07 km
$\Delta\vec{d}_T$	6.4 km	15.07 km

Use the Pythagorean theorem to find the magnitude of the resultant vector.

$$|\Delta\vec{d}_T|^2 = (\Delta d_{Tx})^2 + (\Delta d_{Ty})^2$$
$$|\Delta\vec{d}_T|^2 = (6.4 \text{ km})^2 + (15.07 \text{ km})^2$$
$$|\Delta\vec{d}_T|^2 = 40.96 \text{ km}^2 + 227.1 \text{ km}^2$$
$$|\Delta\vec{d}_T|^2 = 248.06 \text{ km}^2$$
$$|\Delta\vec{d}_T| = 16.4 \text{ km}$$

Calculate the angle, θ, using the components of the resultant vector.

$$\tan\theta = \frac{\Delta d_{Ty}}{\Delta d_{Tx}}$$
$$\tan\theta = \frac{15.07 \text{ km}}{6.4 \text{ km}}$$
$$\tan\theta = 2.35$$
$$\theta = \tan^{-1} 2.35$$
$$\theta = 66.98^\circ$$

The total displacement was 16 km at an angle of 67°, or $\Delta\vec{d}_T = 16$km[E67°N].

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Validate

In the original diagram of the trip, you can see that the sailboat makes a sharp turn. Therefore, you would expect that the total displacement (16 km) would be much smaller than the total distance (32 km) that the boat travelled. The answer is quite reasonable. You can also use the Pythagorean theorem to show that the original components were calculated correctly.

$$|\Delta\vec{d}_1|^2 = (17.3\text{ km})^2 + (10.0\text{ km})^2 = 299.29\text{ km}^2 + 100\text{ km}^2 = 399.29\text{ km}^2$$
$$|\Delta\vec{d}_1| = 20\text{ km}$$
$$|\Delta\vec{d}_2|^2 = (-10.9\text{ km})^2 + (5.07\text{ km})^2 = 118.81\text{ km}^2 + 25.7\text{ km}^2 = 144.5\text{ km}^2$$
$$|\Delta\vec{d}_2| = 12\text{ km}$$

2. You are the pilot of a small plane and want to reach an airport, 600 km due south, in 4.0 h. A wind is blowing at 50 km/h[S35˚E]. With what heading and airspeed should you fly to reach the airport on time?

Frame the Problem

- Your destination is directly *south*.
- A strong wind is blowing *east of south*. The *heading* of the plane will have to account for the wind.
- The *vector sum* of the *velocity* of the plane in relation to the air and the *velocity* of the air in relation to the ground, must be the same as the needed *total velocity* of the plane in relation to the ground.
- You must use *vector addition*.

Identify the Goal

The velocity, $\vec{v}_{pg}$, of the plane
(**Note:** A velocity has not been reported until both the magnitude and direction are given.)

Variables and Constants

Involved in the problem			Known	Unknown		
$\vec{v}_{pa}$	$v_{pa\,x}$	$v_{pa\,y}$	$\vec{v}_{ag} = 50\,\frac{\text{km}}{\text{h}}[\text{S}35^\circ\text{E}]$	$\vec{v}_{pa}$	$v_{pa\,x}$	$v_{pa\,y}$
$\vec{v}_{ag}$	$v_{ag\,x}$	$v_{ag\,y}$	$\Delta\vec{d}_{pg} = 600\text{ km[S]}$	θ_{ag}	$v_{ag\,x}$	$v_{ag\,y}$
$\vec{v}_{pg}$	$v_{pg\,x}$	$v_{pg\,y}$	$\Delta t = 4.0\text{ h}$	$\vec{v}_{pg}$	$v_{pg\,x}$	$v_{pg\,y}$
θ_{ag}	$\Delta\vec{d}_{pg}$	Δt_{pg}		θ_{pg}		
θ_{pg}						

Strategy

You can find the ground speed and direction that the plane must attain to arrive on time by using the mathematical definition for velocity.

Calculations

$$\vec{v} = \frac{\Delta \vec{d}}{\Delta t}$$

$$\vec{v}_{pg} = \frac{\Delta \vec{d}_{pg}}{\Delta t_{pg}}$$

$$\vec{v}_{pg} = \frac{600 \text{ km[S]}}{4.0 \text{ h}}$$

$$\vec{v}_{pg} = 125 \frac{\text{km}}{\text{h}}\text{[S]}$$

Since you now know the wind velocity and the necessary velocity of the plane in relation to the ground, you can use the expression for the vector sum of the velocities to find the velocity of the plane in relation to the air. This quantity *is* the heading and airspeed of the plane. First, solve for $\vec{v}_{pa}$.

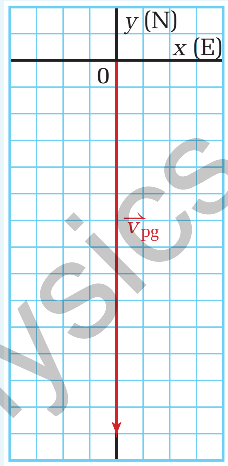
$$\vec{v}_{pg} = \vec{v}_{pa} + \vec{v}_{ag}$$

$$\vec{v}_{pg} - \vec{v}_{ag} = \vec{v}_{pa} + \vec{v}_{ag} - \vec{v}_{ag}$$

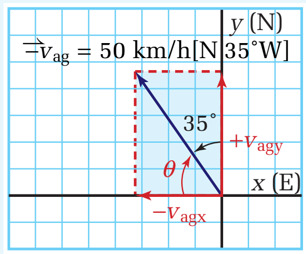
$$\vec{v}_{pg} - \vec{v}_{ag} = \vec{v}_{pa}$$

$$\vec{v}_{pa} = \vec{v}_{pg} - \vec{v}_{ag}$$

Draw the two known vectors on an x–y-coordinate system ($+y$ coincides with north), with their tails at the origin.



Identify the angles they make with the x-axis.



Define and draw the vector $-\vec{v}_{ag}$.

$$\theta_{ag} = 90^\circ - 35^\circ = 55^\circ$$

Find the x- and y-components of the vectors $\vec{v}_{pg}$ *and* $-\vec{v}_{ag}$.

$\vec{v}_{pg}$ is pointed directly south, or along the negative y-axis. Therefore, it has no x-component. Its y-component is the same as the vector.

$$v_{pg\,y} = |\vec{v}_{pg}|$$

$$v_{pg\,y} = -125 \frac{\text{km}}{\text{h}}$$

$$v_{ag\,x} = |\vec{v}_{ag}| \cos \theta_{ag}$$

$$v_{ag\,x} = 50 \frac{\text{km}}{\text{h}} \cos 55^\circ$$

$$v_{ag\,x} = 50 \frac{\text{km}}{\text{h}} (0.5736)$$

$$v_{ag\,x} = 28.68 \frac{\text{km}}{\text{h}}$$

$$v_{ag\,y} = |\vec{v}_{ag}| \sin \theta_{ag}$$

$$v_{ag\,y} = 50 \frac{\text{km}}{\text{h}} \sin 55^\circ$$

$$v_{ag\,y} = 50 \frac{\text{km}}{\text{h}} (0.8191)$$

$$v_{ag\,y} = 40.96 \frac{\text{km}}{\text{h}}$$

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Strategy

Determine the signs of the components.

Calculations

$\vec{v}_{pg}$ has no x-component and the y-component is negative.

$-\vec{v}_{ag}$ is in the second quadrant, so the x-component is negative and the y-component is positive.

Add the components of $\vec{v}_{pg}$ and $-\vec{v}_{ag}$ to obtain the components of $\vec{v}_{pa}$.

Vector	*x*-component	*y*-component
$\vec{v}_{pg}$	$0.0\ \frac{\text{km}}{\text{h}}$	$-125\ \frac{\text{km}}{\text{h}}$
$\vec{v}_{ag}$	$-28.68\ \frac{\text{km}}{\text{h}}$	$40.96\ \frac{\text{km}}{\text{h}}$
$\vec{v}_{pa}$	$-28.68\ \frac{\text{km}}{\text{h}}$	$-84.04\ \frac{\text{km}}{\text{h}}$

Use the Pythagorean theorem to find the magnitude of $\vec{v}_{\text{pa}}$.

$$|\vec{v}_{\text{pa}}|^2 = v_{\text{pa}\ x}^{\ 2} + v_{\text{pa}\ y}^{\ 2}$$

$$|\vec{v}_{\text{pa}}|^2 = \left(-28.68\ \frac{\text{km}}{\text{h}}\right)^2 + \left(-84.04\ \frac{\text{km}}{\text{h}}\right)^2$$

$$|\vec{v}_{\text{pa}}|^2 = 822.54\left(\frac{\text{km}}{\text{h}}\right)^2 + 7062.7\left(\frac{\text{km}}{\text{h}}\right)^2$$

$$|\vec{v}_{\text{pa}}|^2 = 7885.3\left(\frac{\text{km}}{\text{h}}\right)^2$$

$$|\vec{v}_{\text{pa}}| = 88.8\ \frac{\text{km}}{\text{h}}$$

Find the angle the resultant makes with the x-axis.

Since the components are both negative, the vector lies in the third quadrant. However, use positive values to find the tangent. The result will give the angle from the negative x-axis into the fourth quadrant.

$$\tan\theta_{\text{pa}} = \frac{84.04\ \frac{\text{km}}{\text{h}}}{28.68\ \frac{\text{km}}{\text{h}}} = 2.93$$

$$\theta_{\text{pa}} = \tan^{-1} 2.93$$

$$\theta_{\text{pa}} = 71.1^\circ$$

The plane's airspeed must be 89 km/h and it must fly at a heading of [W71°S].

Validate

The wind is blowing toward the southeast and the pilot wants to fly directly south. The component of the wind blowing south will help the plane to get there faster, but the component of the wind blowing east will blow the plane off course if the pilot does not compensate. The pilot must head slightly west to make up for the wind blowing east, so you would expect that the pilot would have to fly slightly west of south. (Note that [W71°S] is the same as [S19°W].) This is in perfect agreement with the calculations.

PRACTICE PROBLEMS

24. Use components to verify any three of your scale-diagram solutions for Practice Problems 12 through 20 in Section 3.2.

25. A pleasure boat heads out of a marina for sightseeing. It travels 2.7 km due south to a small island. Then it travels 3.4 km[S26°E] to another island. Finally, it turns and heads [E12°N] for 1.9 km to a third island.

(a) Determine the boat's displacement for the entire journey.

(b) In what direction should the boat be pointed to head straight home?

26. A jet-ski driver wants to head to an island in the St. Lawrence River that is 5.0 km [W20.0°S] away. If he is travelling at a speed of 40.0 km/h and the St. Lawrence is flowing 6.0 km/h[E]

(a) in what direction should he head the jet-ski?

(b) how long will it take him to reach the island?

27. A space shuttle is approaching the Alpha International Space Station at a velocity of 12 m/s relative to the space station. A landing cable is fired toward Alpha with a velocity of 3.0 m/s, at an angle of 25° relative to the shuttle. What velocity will the cable appear to have to an observer looking out of a window in the space station?

Acceleration Vectors in a Plane

Imagine yourself enjoying the thrill of making a smooth turn on a jet-ski, as shown in Figure 3.8. Feel the forces on your body as you lean into the turn. Now, think about the meaning of acceleration in a way you might not have considered it before.

Suppose that the jet-ski was originally travelling north with a speed of 60 km/h. The driver makes a sharp turn so that the jet-ski is travelling west at the same speed. If the turn took 12 s, what was the average acceleration of the jet-ski?

Your first thought might be that the jet-ski does not accelerate at all, because its speed did not change, but remember that acceleration is the rate of *change* of *velocity*.

$$\vec{a}_{\text{ave}} = \frac{\Delta\vec{v}}{\Delta t}$$

The velocity of an object is a vector quantity that includes a magnitude and a direction. If either magnitude or direction changes, the velocity changes. Therefore, the object has accelerated. In the current example, the magnitude of the jet-ski's velocity did not change, but its direction did. The jet-ski was accelerating for 12 s, the time interval during which the direction was changing. To calculate this average acceleration, you must use vector subtraction, as well as division by a scalar. The direction of acceleration is the same as the direction of the *change* in velocity.

Figure 3.8 No matter how smooth you make the turn, you still must accelerate.

You can qualitatively determine the direction of the acceleration by drawing the initial and final velocity vectors on a coordinate system, with both of their tails at the origin. Then, determine the direction in which you would have to push on the initial velocity vector to convert it into the final velocity vector.

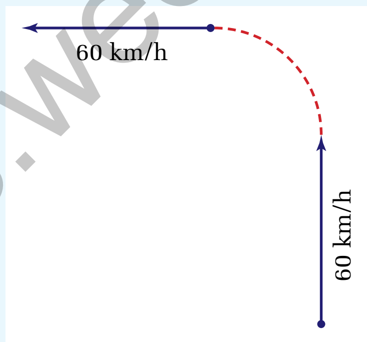
MODEL PROBLEM

Acceleration on a Curve

Calculate the acceleration of the jet-ski as described in the text.

Frame the Problem

- Make a sketch of the motion in the problem.
- The *speed* of the jet-ski does not change; however, the *direction* does.
- The jet-ski accelerated.
- The equations of motion for constant acceleration do *not* apply.
- To calculate *acceleration* in *two dimensions*, you must use *vector* subtraction.
- Calculating *acceleration* in two dimensions also involves *dividing* a vector by a *scalar*.
- The *direction* of the acceleration will be the *same* as the direction of the *change in velocity*.



Identify the Goal

The average acceleration, $\vec{a}_{ave}$, of the jet-ski during the turn

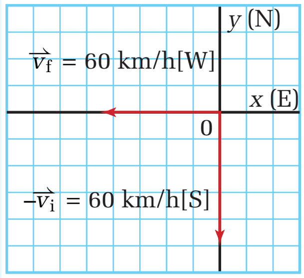
Variables and Constants

Involved in the problem		**Known**	**Unknown**	
$\vec{v}_i$	v_{ix}	$\vec{v}_i = 60\ \dfrac{km}{h}$ [N]	$\vec{a}_{ave}$	v_{ix}
$\vec{v}_f$	v_{fx}	$\vec{v}_f = 60\ \dfrac{km}{h}$ [W]	θ	v_{fx}
$\vec{a}_{ave}$	v_{iy}	$\Delta t = 12$ s		v_{iy}
Δt	v_{fy}			v_{fy}
θ	$\Delta\vec{v}$			

Strategy

Calculations

Make a sketch of the initial and final velocity vectors on an x–y-coordinate system, where $+y$ coincides with north. Define and sketch the negative of the initial velocity vector.



Determine the values of the x- and y-components of $-\vec{v}_i$ and $\vec{v}_f$. Add these components to obtain the components of $\Delta\vec{v}$.

Vector	***x*-component**	***y*-component**
$-\vec{v}_i$	$0.0\ \frac{\text{km}}{\text{h}}$	$-60\ \frac{\text{km}}{\text{h}}$
$\vec{v}_f$ +	$-60\ \frac{\text{km}}{\text{h}}$ +	$0.0\ \frac{\text{km}}{\text{h}}$ +
$\Delta\vec{v}$	$-60\ \frac{\text{km}}{\text{h}}$	$-60\ \frac{\text{km}}{\text{h}}$

Use the Pythagorean theorem to calculate the magnitude of $\Delta\vec{v}$.

$$|\vec{v}|^2 = v_x^2 + v_y^2$$

$$|\Delta\vec{v}|^2 = \left(-60\ \frac{\text{km}}{\text{h}}\right)^2 + \left(-60\ \frac{\text{km}}{\text{h}}\right)^2$$

$$|\Delta\vec{v}|^2 = 3600\left(\frac{\text{km}}{\text{h}}\right)^2 + 3600\left(\frac{\text{km}}{\text{h}}\right)^2$$

$$|\Delta\vec{v}|^2 = 7200\left(\frac{\text{km}}{\text{h}}\right)^2$$

$$|\Delta\vec{v}| = 84.85\ \frac{\text{km}}{\text{h}}$$

Convert velocity to SI units, so that you can use it to calculate acceleration.

$$\frac{84.85\ \cancel{\text{km}}}{\cancel{\text{h}}} \times \frac{\cancel{\text{h}}}{3600\ \text{s}} \times \frac{1000\ \text{m}}{\cancel{\text{km}}} = 23.57\ \frac{\text{m}}{\text{s}}$$

Calculate the direction of $\Delta\vec{v}$ by determining the angle, θ. Since both of the components are negative, the vector lies in the third quadrant.

$$\tan\theta = \frac{-60\ \frac{\text{km}}{\text{h}}}{-60\ \frac{\text{km}}{\text{h}}} = 1$$

$$\theta = \tan^{-1} 1$$

$$\theta = 45^\circ$$

Since both components are negative, the angle is in the third quadrant.

$$\theta = 45^\circ[\text{W}45^\circ\text{S}]$$

Calculate the acceleration, $\vec{a}$.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$$

$$\vec{a} = \frac{23.57\ \frac{\text{m}}{\text{s}}[\text{W}45^\circ\text{S}]}{12\ \text{s}}$$

$$\vec{a} = 1.96\ \frac{\text{m}}{\text{s}^2}[\text{W}45^\circ\text{S}]$$

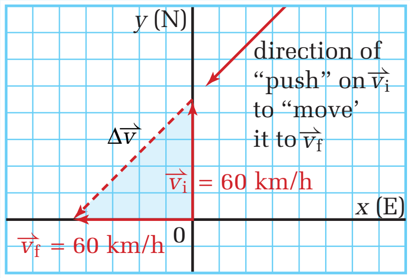
The acceleration of the jet-ski was 2.0 m/s^2[W45°S].

continued ►

continued from previous page

Validate

The direction of the acceleration [SW] is correct because, as the diagram shows, that is the direction in which you would have to push on the initial velocity vector in order to change its direction to match the final velocity vector.

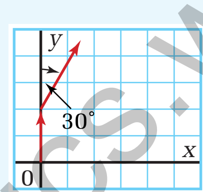


PRACTICE PROBLEMS

28. You are jogging south down the street at a pace of 2.5 m/s. You come to an intersection and maintain your pace as you turn and head east down a side street. It takes you 4 s to make the turn. Determine your average acceleration during the turn.

29. A soccer player is running down the field with the ball at a speed of 4.0 m/s. He cuts to the right at an angle of 30.0° to his original direction to receive a pass. If it takes him 3.0 s to change his direction, what is his average acceleration during the turn?

30. A marble is rolling across the table with a velocity of 21 cm/s. You tap on the marble with a ruler at 90.0° to its direction of motion. The marble accelerates in the direction of the tap for 0.50 s at a rate of 56 cm/s^2. Determine the new velocity of the marble.



3.3 Section Review

1. **C** Explain how to resolve a vector.
2. **C** What use is the Pythagorean theorem in resolving vectors?
3. **K/U** Draw examples of velocity vectors for the following cases:
   (a) the *x*- and *y*-components are both positive
   (b) the *x*-component is positive and the *y*-component is negative
   (c) the *x*-component is negative and the *y*-component is positive
   (d) the *x*-component is zero and the *y*-component is negative
4. **C** Explain whether it is possible to drive around a curve with zero acceleration.
5. **C** Describe situations where the average acceleration is zero, positive, and negative.
6. **K/U** If a car travels at 50 km/h east and then turns to travel 50 km/h north, what direction is the acceleration?
7. **K/U** Consider a standard *x*–*y*-coordinate system. In which quadrant(s) does a vector have:
   (a) two positive components?
   (b) two negative components?
   (c) one positive and one negative component?

CHAPTER 3 Review

REFLECTING ON CHAPTER 3

- Vectors are represented by arrows that point in the direction of the quantity with respect to a frame of reference or coordinate system. The length of the arrow is proportional to the magnitude.
- To add vectors graphically, place the first vector in a coordinate system. Place the tail of the second vector at the tip of the first. The vector formed along the third side of this triangle by connecting the tail of the first vector to the tip of the second represents the sum of both vectors, and is called the resultant vector.
- Two methods for subtracting vectors graphically are provided. In method 1, place the first vector in a coordinate system. Draw the negative of the second vector, and place its tail at the tip of the first. The vector along the third side of the triangle represents the difference between the two vectors. For method 2, place the two vectors on a coordinate system, *tail* to *tail*. The difference of the two vectors is represented by the vector drawn from the tip of the first vector to the tip of the second vector.
- The direction of a vector does not change when multiplied or divided by a scalar quantity. The magnitude and the units are affected.
- Relative velocity describes motion with respect to a specific coordinate system. A dog's velocity swimming directly across a fast-flowing river could be given relative to the moving water or to the ground.
- Vector components are parts of a vector that are at right angles to each other. They lie on the axes of a coordinate system. Since components are confined to one direction, they are scalar quantities.
- Resolving a vector involves separating it into its components.
- Turning a corner at constant speed involves a change in velocity (the direction is changing) and therefore is associated with an acceleration given by: $\vec{a}_{\text{ave}} = \frac{\Delta\vec{v}}{\Delta t}$

Knowledge/Understanding

1. Define or describe the following:
   (a) horizontal plane
   (b) scale vector diagram
   (c) coordinate system
   (d) frame of reference
   (e) resultant vector
   (f) vector components
2. Why are vectors so useful in solving physics problems?
3. When an airplane travels in a series of straight line segments, you can find the displacement for the whole trip by adding the various displacement vectors.
   (a) Why can't you add up the various velocity vectors for the different segments of the trip, to get the average velocity?
   (b) Describe how you would obtain the average velocity for the trip?
4. Suppose you swim across a river, heading towards a position on the far bank directly opposite from where you started from. If there is a strong current in the river, and you end up downstream from the position you were headed for, were you moving faster than you would be moving if there were no current? Explain.
5. A pilot wants to fly due north. However, a strong wind is blowing from the west. Therefore the pilot maintains a heading of a few degrees west of north so that her final ground speed will be in a direction due north. Is the airplane accelerating in this situation? Why or why not?

Inquiry

6. In the Multi-Lab at the beginning of the chapter, a marble rolled along straight line A, then changed direction and rolled along straight line B. The lines made an angle of 30 degrees with each other. If the marble's speed, both before and after changing direction was 24 cm/s, calculate its *change in velocity.*

Communication

7. Summarize the ideas about vectors and motion presented in this chapter, by using one or both of the following organizers:

   Make a table listing the vector quantities introduced in this chapter (i.e. displacement, velocity, acceleration) and the various rules used to work with the quantities (i.e., sum, difference, product, components, etc.). In the first column, list the quantity or rule. In the second column, give a definition. In the third column, illustrate with a small diagram.

   Organize the vector quantities and rules you learned in this chapter into a *concept map*. This map should show the connection between the various concepts, quantities, and rules you learned.

8. Brainstorm as a class, or in a small group, the common mistakes students make when working with vectors. Make a list and give a concrete example for each item in the list (i.e., adding the speed of various flight segments to get the average speed).

Making Connections

9. Why do airplane pilots usually take off and land at airports so that they are facing the wind?

10. Imagine that you are a transportation consultant. You are hired by the province of Ontario, in the year 2015, to help plan a series of high-speed train lines across the province that connect the 20 most populous cities in the province. On the one hand, you want to minimize the time it takes for business people to travel between any two Ontario cities. On the other hand, you want to minimize the total amount of high speed track that will be constructed, as the construction, maintenance, and environmental impact of high speed lines is very high.

    Work in a group and brainstorm a list of the different things you would want to know in order to design the network of high speed railways.

    Critique the list of items that you came up with, and decide which items are the most important to know with certainty.

    Your options include setting up straight lines between two cities, or "crooked" lines that connect a series of cities more or less in the same direction. For which cities would it make sense to set up a single high-speed line?

Problems for Understanding

11. An airplane, going from Toronto to Ottawa, flies due east for 290 km and then due north for 190 km. Compare this trip with the trip the airplane makes if it flies in a straight line from Toronto to Ottawa. What is the same about both trips? What is different? When might a pilot want to fly along the component paths rather than in a direct line from one place to another?

12. A boat travels 10.0 km in a direction [N20.0°W] over still water. What are the components of its displacement in each of the four directions of the compass: N, S, E, and W?

13. A car travelling at 50.0 km/h due north, turns a corner and continues due west at 50.0 km/h. If the turn takes 5.0 s to complete, calculate the car's (a) change in velocity and (b) acceleration during the turn.

14. A person walks 3.0 km[S] and then 2.0 km[W], to go to the movie theatre.
    (a) Draw a vector diagram to illustrate the displacement.
    (b) What is the total displacement?

15. A person in a canoe paddles 5.6 km[N] across a calm lake in a time of 1.0 h. He then turns west and paddles 3.4 km in 30.0 minutes.
    (a) Calculate the displacement of the canoeist from his starting point.
    (b) Determine the average velocity for the trip.

16. A cyclist is moving with a constant velocity of 5.6 m/s[E]. He turns a corner and continues cycling at 5.6 m/s[N].
    (a) Draw a vector diagram to represent the change in velocity.
    (b) Calculate the change in velocity.

17. A cyclist travels with a velocity of 6.0 m/s[W] for 45 minutes. She then heads south with a speed of 4.0 m/s for 30.0 minutes.

(a) Calculate the displacement of the cyclist from her starting point.
(b) Determine the average velocity for the trip.

18. Thao can swim with a speed of 2.5 m/s if there is no current in the water. The current in a river has a velocity of 1.2 m/s[S]. Calculate Thao's velocity relative to the shore if
(a) she swims upstream
(b) she swims downstream

19. A physics teacher is on the west side of a small lake and wants to swim across and end up at a point directly across from his starting point. He notices that there is a current in the lake and that a leaf floating by him travels 4.2 m[S] in 5.0 s. He is able to swim 1.9 m/s in calm water.
(a) What direction will he have to swim in order to arrive at a point directly across from his position?
(b) Calculate his velocity relative to the shore.
(c) If the lake is 4.8 km wide, how long will it take him to cross?

20. Resolve the following vectors into their components:
(a) a displacement of 20.0 m[N25°E]
(b) a displacement of 48 km[S35°E]
(c) a velocity of 15 m/s[S55°W]
(d) an acceleration of 24 m/s^2[N30.0°W]

21. A canoeist is paddling across a lake with a velocity of 3.2 m/s[N]. A wind with a velocity of 1.2 m/s[N20.0°E] starts and alters the path of the canoeist. What will be the velocity of the canoeist relative to the shore?

22. A person is jogging with a velocity of 2.8 m/s[W] for 50.0 minutes, and then runs at 3.2 m/s[N30.0°W] for 30.0 minutes. Calculate the displacement of the runner (answer in km).

23. A jogger runs 15 km[N35°E], and then runs 7.5 km[N25°W]. It takes a total of 2.0 hours to run.
(a) Determine the displacement of the jogger.
(b) Calculate the jogger's average velocity.

24. A sailboat is moving with velocity of 11.0 m/s[E] when it makes a turn to continue at a velocity of 12.0 m/s[S40.0°E]. The turn takes 45.0 seconds to execute. Calculate the acceleration of the sailboat.

25. An airplane heads due north from Toronto towards North Bay, 300 km away with a velocity relative to the wind of 400 km/h. There is a strong wind of 100 km/h blowing due south.
(a) What is the velocity of the airplane with respect to the ground?
(b) How long will it take the airplane to fly from Toronto to North Bay?
(c) From North Bay back to Toronto (assuming the same wind velocity)?
(d) Would the total trip take the same time if the wind velocity was 200 km/h?

26. A canoeist wants to travel straight across a river that is 0.10 km wide. However, there is a strong current moving downstream with a velocity of 3.0 km/hr. The canoeist can maintain a velocity relative to the water of 4.0 km/hr.
(a) In what direction should the canoeist head to arrive at a position on the other shore directly opposite to his starting position?
(b) How long will the trip take him?

Numerical Answers to Practice Problems

1. (a) 4.0×10^2 km[E28°N] **(b)** W28°S **2. (a)** 5.0 km **(b)** E37°S **3.** 9.5 km, 36° to the right of the lookout **4. (a)** 62.6 km [W11.3°S] **(b)** E12°S **5. (a) (i)** 27 km[N] **(ii)** 24 km[N12°E] **(iii)** 24 km[S12°W] **(b) (i)** 27 km[N] **(ii)** 24 km[N12°E] **(iii)** 6.0 km [W34°S] **6.** 67 km/h [W48°N] **7.** 346 km/h[E30.0°N] **8.** 10 m/s in direction 7° from the normal to the boards, towards the puck's initial direction **9. (a)** 8.4 m/s[N7.1°W] **(b)** 5.5 m/s [W4.0×10^1°N] **(c)** 3.6 m/s[E57°N] **10.** 5.7 km/h[S42°W] **11. (a)** 48 km/h[W29°N] **(b)** 1.2×10^2 km/h[E29°S] **12.** 5.8×10^3 m[N23°W] **13. (a)** 9.2 km[N24°W] **(b)** 3.1 km/h [N24°W] **14.** –1.8 m/s **15.** 12 m/s[S24°W] **16. (a)** N20.5°E **(b)** 227 km/h[N30.0°E] **(c)** 1.10 h **17. (a)** 1.6×10^2 km[W18°N] **(b)** 3.0×10^2 km/h[N], 2.2×10^2 km/h[W], 2.5×10^2 km/h[S] **(c)** 1.3×10^2 km/h[W18°N] **18. (a)** N25°E **(b)** 69 s **19. (a)** 2.1 km [W54°N] **(b)** S54°E **(c)** 2.4 h **20. (a)** 1.6 m/s[E18°] **21. (a)** 4.1 m, 15 m **(b)** –6.6 m/s^2, 4.6 m/s^2 **(c)** –11.3 m/s, –11.3 m/s **22. (a)** 6.84 km, 18.8 km **(b)** 2.6 m/s, –1.5 m/s **(c)** –2.3 m/s, 6.4 m/s **23.** 3.0×10^1 km[E], 5.2×10^1 km[N] **25. (a)** 5.9 km[E34°] **(b)** [W56°N] **26. (a)** W17°S **(b)** 8.7 min **27.** 15 m/s in a direction 4.9° to the shuttle **28.** 0.9 m/s^2[NE] **29.** 0.7 m/s^2 at 104° to the right of his original direction **30.** 35 cm/s in a direction 53° away from its original direction

CHAPTER 4 Newton's Laws

CHAPTER CONTENTS

The forest of steel and cables shown here manipulates enormous amounts of mass by exerting huge forces with intricate precision. Rebuilding a city after a natural or political disaster requires hauling, lifting, and fastening millions of kilograms of concrete and steel. The technology that enables societies to build and rebuild structures at a breathtaking rate is rooted in an understanding of forces that dates back more than 400 years.

The inset photograph provides a close look at one of the hundreds of cranes used to build the high-rise buildings of a large city. The crane must be relatively easy to assemble and take apart. At the same time, it must be capable of lifting great masses and moving them to specific places within a new building's perimeter. The crane's slender arm belies its tremendous strength. By controlling the movement of a series of massive counterweights, the crane operator can guide the crane to every corner of the growing structure.

The ability to lift, balance, and move objects from feather-light sheet music to massive steel girders requires forces. Chapter 4 explores the development of the concept of force. Why do stationary objects remain at rest and why do moving objects tend to continue to move? You will study Newton's laws of physics and learn how to use them to predict the motion of macroscopic objects. You will also discover how Newton's model fits into the current theories of motion of subatomic particles and Einstein's theories of relativity. You will also survey the fundamental forces of nature, which are governed by the properties of the universe that emerged in the first few seconds after the Big Bang.

MULTI LAB

Predicting Motion

TARGET SKILLS
- Predicting
- Analyzing and interpreting
- Communicating results

Marbles

What will happen when you roll a marble horizontally across the floor? First, predict what will happen to the marble after it leaves your hand. Using a diagram, explain your prediction to your partner. Now, try the experiment.

Analyze and Conclude

1. Was your prediction correct?
2. Provide a reasonable explanation for the results.

Tossing a Coin

Toss a coin vertically up into the air with a quick motion of your hand. Predict the motion of the coin from the moment it leaves your fingers. Draw a diagram that illustrates your prediction and explain it to your partner. If you and your partner do not agree, make separate predictions. Try the experiment and carefully observe the outcome.

Analyze and Conclude

1. Attempt to explain why the coin follows the path it does.
2. If you and your partner do not agree on an explanation, try to find a flaw in one of the explanations.

Thinking about Space

Imagine that you are in a spaceship out in intergalactic space, very far away from any stars. You fire the ship's rockets for a while and then shut them down.

Analyze and Conclude

1. Describe the motion of your spacecraft after you turn the engines off.
2. Explain your answer to your partner using diagrams and a written explanation.
3. Discuss the possibilities with your partner and try to agree on a reasonable answer.

Air Table

What will happen if you tap on a puck that is lying on an air table or on a cart on an air track? Make a prediction then justify your answer to your partner using a diagram. Carry out the experiment.

Analyze and Conclude

1. Was your prediction correct?
2. Explain the results.

4.1 Inertia

SECTION EXPECTATIONS

- Describe and assess Galileo's contribution to the study of dynamics.
- Design and perform simple experiments to verify Galileo's predictions.

KEY TERMS

- inertia
- kinematics
- dynamics
- mechanics
- force

Figure 4.1 This photograph shows how an object is affected by forces. Forces sometimes stop, sometimes propel, and sometimes restrain an object.

The crash-test dummy in the photograph was in motion before the car abruptly stopped. The dummy continued to move until it experienced a stopping force. Because the dummy was not restrained by a seatbelt, the windshield was the first object to make contact and thus provide a stopping force. The seatbelt would have been a far better option.

If you have ever ridden on a public transit bus or a subway, you may recall being flung backward as the vehicle accelerated away from the stop. Later, upon arriving at the next stop, you were thrown forward when the vehicle came to a halt. In this example, as in the above photo, you see evidence of a property that is shared by all matter — the tendency of an object to resist any change in its motion. This property is called **inertia**.

ELECTRONIC LEARNING PARTNER

A video clip of a crash test can be found on the Electronic Learning Partner.

DEFINITION OF INERTIA

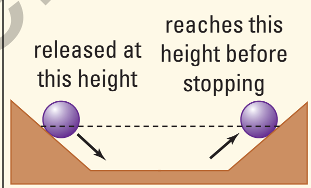
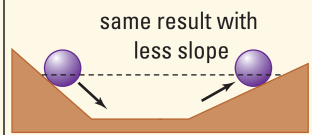
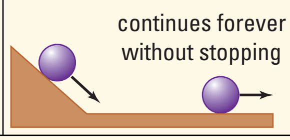
Inertia is the natural tendency of an object to remain in its current state of motion. The amount of an object's inertia is directly related to its mass.

Galileo's Perception of Inertia

Throughout history, inquisitive people have attempted to understand why an object moves or remains at rest. Aristotle's (384–322 B.C.E.) observations led him to conclude that a constant force will yield a constant speed. His idea went unchallenged for nearly 2000 years, but it is, in fact, false. French philosopher, Jean Buridan (1300–1358) believed that objects stayed in motion because they possessed "impetus" — something inside that makes them continue to move.

Galileo carefully considered both ideas. He conducted a three-part thought experiment in an attempt to understand why objects move the way they do.

Table 4.1 Galileo's Thought Experiment on Motion

Observations	Predictions	Assumptions	Diagram
A ball rolling down a slope speeds up. A ball rolling up a slope slows down.	Therefore, a ball rolling on a horizontal surface should continue without speeding up or slowing down	The reason objects do slow down on horizontal surfaces is the result of the force of friction.	
A ball rolling up a slope that is not as steep as the slope it rolled down will continue farther along the shallower slope.	The ball will continue up the shallow slope until it has reached the height from which it was originally released.	The reason objects do not quite reach the same height is due to the force of friction.	
When the second slope is zero (horizontal), the ball will continue to roll.	The ball would continue forever.	Again, the force of friction will prevent this from occurring naturally.	
Summary: An object will naturally remain at rest or in uniform motion unless acted on by an external force.			

Galileo's thought experiment challenged the commonly held belief that an object's uniform motion was the result of continued force. Instead, he viewed uniform motion as being a state just as natural as rest. The experiment also contradicted the "impetus" theory proposed by Buridan. According to Galileo, an object's movement remains unchanged, not because of something inside of it, but because there is no force resisting the motion.

Language Link

Impetus is commonly used in the English language to describe a stimulus that incites action. For example, "The energetic audience gave the actors the *impetus* to give their very best performances." Notice that, even in this context, the impetus — the motivating force — is external. That is, the impetus comes from the energetic audience, not from within the actors. What other common terms are derived from the word *impetus*?

TRY THIS...

Test Galileo's ideas using a Hot Wheel's™ track and a marble. Although friction is not completely removed, it will be sufficiently reduced to observe what Galileo envisioned in his thought experiments.

Galileo had identified the natural tendency of mass to continue doing what it is already doing — that is, to continue in uniform motion or remain at rest. Galileo was defining inertia. His ingenious ideas were not immediately accepted, but his concept of inertia has stood the test of time and is the only classical law incorporated into Einstein's theories about the nature of our universe.

Examples of Inertia

Revisit the Multi Lab, Thinking about Space. Your spacecraft will continue to move forever, at a constant speed in one direction, unless something causes it to stop or change direction. This motion is natural, in the same way that it is natural for the rocks of Stonehenge to remain stationary. There is no actual force involved in inertia. In fact, motion remains constant due to the absence of any force.

Figure 4.2 These stones were moved without the aid of powerful machines. Once placed, not even a tornado could exert enough force to move them.

How Forces Affect Motion

As you learned in Chapter 2, predicting and describing an object's motion in terms of its displacement, velocity, and acceleration, are aspects of a branch of physics called **kinematics**. The branch of physics that explains *why* objects move the way they do is called **dynamics**. Together, kinematics and dynamics form a branch of physics called **mechanics**. The study of dynamics involves **forces**, which you can regard as a push or a pull on an object. Forces cause *changes* in motion.

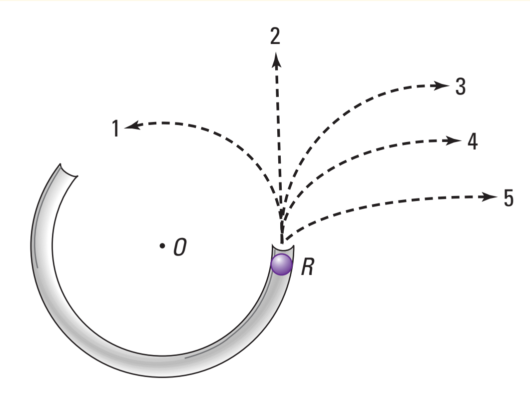
Table 4.2 lists examples of moving objects that could be studied within the field of dynamics.

Table 4.2 Objects and Their Motion

Object	Motion	Theoretical Explanation
electron	remains in motion near the nucleus of its atom	attracted by positively charged protons in the nucleus
snowflake	drifts toward the ground	Earth's gravity
baseball	flies off after contact with the bat	contact with bat
skydiver	reaches terminal speed while falling to Earth	air friction
Earth	orbits around the Sun	Sun's gravity

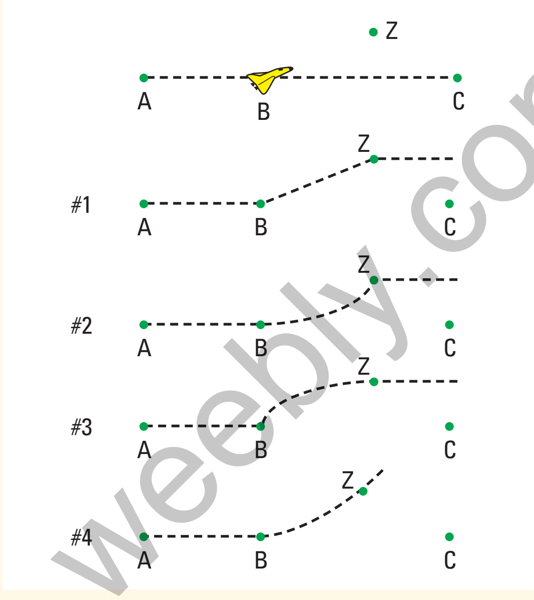
4.1 Section Review

1. K/U A marble is fired into a circular tube that is anchored onto a frictionless tabletop. Which of the five paths will the ball take as it exits the tube and moves across the tabletop? Justify your answer.



2. MC Imagine the following scenario. In a sudden burst of energy, you cleaned your room. A few moments later, your mother saw your room and appeared surprised, but you were not surprised. About an hour later, you went back into your room to find that the books were all on the floor. Your bed was on the wrong side of the room and all of the dresser drawers were on the bed. You were shocked! Use technical terms, including inertia, to explain why you were so surprised.

3. K/U A spacecraft is lost in deep space, far from any objects, and is drifting along from point A toward point C. The crew fires the on-board rockets that exert a constant force exactly perpendicular to the direction of drift. If the constant thrust from the rockets is maintained from point B until point Z is reached, which diagram best illustrates the path of the spacecraft?



4. C Decide whether each of the following statements is true or false. If the statement is false, rewrite it to make it true.
   (a) Inertia is the result of stationary mass.
   (b) An object will be at rest or slowing down if no force is acting on it.

5. C Galileo thought deeply about motion and its causes.
   (a) Describe his thought experiments, including any assumptions that he made.
   (b) How did Galileo's conclusions challenge current beliefs of his time?

6. C
   (a) Define kinematics, dynamics, and mechanics.
   (b) Produce a table similar to Table 4.2 listing the motion and a theoretical explanation of three different objects.

4.2 Common Forces

SECTION EXPECTATIONS

- Describe the nature of gravitational and frictional forces.
- Investigate and describe different interactions between objects.
- Calculate frictional forces acting on objects.
- Analyze the motion of objects using free-body diagrams.

KEY TERMS

- contact force
- non-contact force
- weight
- acceleration due to gravity
- static frictional force
- kinetic frictional force
- coefficient of friction
- normal force
- net force
- free body diagram

Objects interact with other objects by exerting forces on each other. You move your pencil across your page, the desk at which you are sitting supports your books, and the air you breathe circulates around the room. Your desk is in direct contact with your books, so this interaction is an example of a **contact force**. Conversely, **non-contact forces** act over a distance, as is the case when two magnets attract or repel each other without touching.

Gravitational Force

Figure 4.3 Vince Carter is able to exert a large force in a short period of time, allowing him to jump extremely high, as he demonstrated during the 2000 Olympics in Sydney.

In Section 4.1, you studied an important property of matter — inertia. You learned that the inertia of an object was directly related to its mass. A second and equally important property of matter is gravity. Any two masses exert a mutual gravitational attractive force on each other. If you hold a tennis ball in each hand, you do not notice any force acting between them because gravitational forces are very weak. It is only because Earth has such an enormous mass that you are aware that it is exerting a strong force on you. Did you know, however, that you are exerting an equal force on Earth? Gravitational forces always act in pairs.

According to Newton's law of universal gravitation, the mutual attractive force between any two masses acts along a line joining their centres. Therefore, the force of gravity between Earth and any object is directed along a line between the centre of the object and the centre of Earth. Newton's law also states that the strength of the gravitational attractive force diminishes as the distance between their centres increases. The lengths of the arrows in Figure 4.4 represent the relative strength of the gravitational attractive force at different distances from Earth's centre. Although the attractive force decreases with distance it never truly reaches zero. The force of gravity, although relatively weak, has an infinite range. It is, therefore, a non-contact force.

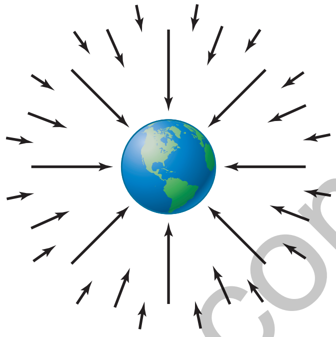


Figure 4.4 The gravitational force exerted by Earth on an object diminishes as the object's distance from Earth increases.

Think It Through

- Consider the last sentence in the preceding paragraph. If it is true, then compare, qualitatively, the *force of gravity* acting on you due to the mass *of Earth* when you are on Earth's surface to
  (a) the force of gravity acting on you when you are aboard the International Space Station,
  (b) the force of gravity acting on you when you are out past the orbit of Pluto.

Weight

You have probably seen pictures of astronauts bouncing along the surface of the Moon. Even in their bulky space suits and oxygen tanks, they can jump significantly higher and drop back down more slowly than they could on Earth. What makes the difference? If an astronaut had a mass of 60 kg on Earth, he or she would still have a mass 60 kg when arriving on the Moon. However, astronauts weigh much less on the Moon than on Earth. The distinction between mass and weight becomes clear when you compare the effects of Earth's gravity to the Moon's gravity. You have a specific mass regardless of where you are located — on Earth, the Moon, or in intergalactic space. Your weight, however, is influenced by the force of gravity. In fact, **weight** is defined as the force of gravity acting on a mass. Therefore, your weight would be much lower on the Moon than it is on Earth. On the other hand, if Jupiter had a surface that astronauts could walk on, they would find themselves pinned to the ground weighing 2.5 times more than they weigh on Earth.

TRY THIS...

Poke a small hole in the side of a plastic cup near the bottom. Predict what will happen when you fill the cup with water and then allow it to fall toward the ground in the upright position. Record your prediction with the aid of a diagram. Test your prediction. Explain the results.

Figure 4.5 Acceleration due to gravity does not depend on mass, as demonstrated by the example of the feather and the coin in a vacuum tube.

TRY THIS...

Predict what will happen when you simultaneously drop an old textbook and a sheet of paper. Test your predictions. Why did the sheet of paper take longer to fall to the floor? Now place the paper on top of the textbook, ensuring that no part of the sheet is extending over the edge of the textbook. Predict what will happen when you drop the stacked pair. Test your predictions and explain.

As you know, the force of gravity is influenced by the masses of the two interacting objects as well as the distance between their centres. Thus you might expect that the relationship between an object's mass and the force of gravity acting on it would be very complex. Fortunately, it is not. There is a common factor that was also a topic of contemplation for Aristotle and Galileo. Aristotle believed that more massive objects fall faster than less massive objects. He predicted that a mass ten times greater than another mass would fall ten times faster. Galileo reasoned that a large mass would have more inertia than a small mass and therefore a greater force would be required to change the motion of larger mass than the smaller mass. Since the gravitational force on a large mass is greater than the gravitational force on a small mass, the masses should move in the same way under the influence of gravity. He conducted the experiment and found that all objects fell at almost exactly the same rate. He attributed the slight difference in falling time to air resistance. Galileo concluded, correctly, that, at any given location, and in the absence of air resistance, all objects will fall with the same acceleration. Physicists now call this the **acceleration due to gravity** and give it the symbol, g. You may have seen a demonstration of a coin and a feather falling at exactly the same rate when enclosed in an evacuated tube like the one shown in Figure 4.5 on the previous page.

Since the value of g is influenced by both the mass of Earth and the distance from Earth's centre, the value of g varies with location. On Earth's surface, g is approximately 9.81 m/s^2, but actually ranges from 9.7805 m/s^2 at the equator to 9.8322 m/s^2 at the poles because Earth is not perfectly round. It is really a flattened sphere that bulges in the middle. Consequently, objects at the poles are closer to the centre of Earth than are objects located at the equator. Some values of g are listed in Table 4.3 for comparison.

Table 4.3 Free-Fall Accelerations Due to Gravity on Earth

Location	Acceleration due to gravity (m/s^2)	Altitude (m)	Distance from Earth's centre (km)
North Pole	9.8322	0 (sea level)	6357
equator	9.7805	0 (sea level)	6378
Mt. Everest (peak)	9.7647	8850	6387
Mariana Ocean Trench* (bottom)	9.8331	11 034 (below sea level)	6367
International Space Station*	9.0795	250 000	6628

*These values are calculated.

COURSE CHALLENGE

What does "Weightless" Mean?

The term weightless is often used to describe astronauts in orbit. Describe a series of observations you could use to convince people that objects in Earth orbit are not truly weightless.

Learn more from the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and find the *Physics 11 Course Challenge.*

Because the mass and radius of the planets vary significantly, the acceleration due to gravity is quite different from planet to planet. Values of g for the Moon and a few planets are listed in Table 4.4.

Table 4.4 Free-Fall Accelerations Due to Gravity in the Solar System

Location	Acceleration due to gravity (m/s^2)
Earth	9.81
Moon	1.64
Mars	3.72
Jupiter	25.9

To summarize, you have discovered that weight is the force of gravity acting on a mass. You have also seen that the acceleration due to gravity incorporates all of the properties of the gravitational attractive force, except the mass of the object, that affect the strength of the force of gravity — mass of the planet and the distance between the centre of the object and the planet. Now you are ready to put them together in the form of a mathematical equation.

WEIGHT

An object's weight, F_g, is the product of its mass, m, and the acceleration due to gravity, g.

$$\vec{F}_g = m\vec{g}$$

Quantity	Symbol	SI unit
force of gravity (weight)	$\vec{F}_g$	N (newton)
mass	m	kg (kilogram)
acceleration due to gravity	$\vec{g}$	m/s^2 (metres per second squared)

Unit Analysis

(mass) (acceleration) $= \text{kg}\dfrac{\text{m}}{\text{s}^2} = \text{N}$

Note: The symbol g is reserved for acceleration due to gravity on Earth. In this textbook, g with an appropriate subscript will denote acceleration due to gravity on a celestial object other than Earth, for example, g_{Moon}.

Web Link

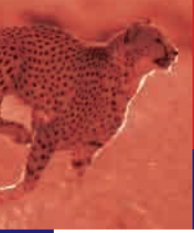
www.school.mcgrawhill.ca/resources/

Do you have a dramatic flair? Check out the Internet site above to read about — and perhaps even test — Galileo's arguments of logic refuting Aristotle's teachings concerning falling objects. Galileo actually wrote the words! He presented the arguments using two fictitious characters. Salviati voiced the beliefs of Galileo, while Aristotle's ideas were embodied in Simplicio. If you enjoy a good debate, this English translation will captivate you. Go to the Internet site and follow the links for **Science Resources** and **Physics 11** to find out where to go next.

MISCONCEPTION

Mass is not Weight

Everyday language often confuses an object's mass with its weight. You may have a *mass* of 78 kg, but you do not *weigh* 78 kg. Your weight would be $\vec{F}_g = m\vec{g} = (78\ \text{kg})(9.81\ \text{m/s}^2) = 765\ \text{N[down]}$. Many scales and balances convert the newton reading to a mass equivalent on Earth. A spring scale designed for use on Earth would give incorrect results on the Moon.



INVESTIGATION 4-A

Interactions of Objects

TARGET SKILLS
- Predicting
- Analyzing and interpreting
- Communicating results

The language of forces can sometimes seem to complicate a concept that you already understand. Attempt to *describe* the interactions between the objects listed below in terms of forces.

Problem

What interactions exist between objects and how would things change if some interactions were removed?

Hypothesis

Form a hypothesis about which interactions will always exist between these common objects, regardless of where you might go to test them, including intergalactic space.

Equipment

- small mass (for example, a pop can)
- feather
- hockey puck
- magnets (2)
- string

Procedure

1. Place the pop can on the lab bench. How are the pop can and the lab bench interacting?
   (a) Describe how the pop can interacts with the lab bench.
   (b) Describe how the lab bench interacts with the pop can.
2. Drop the feather from 2.0 m above the floor.
   (a) During its descent, is the feather interacting with any objects?
   (b) What interaction causes the feather to fall?
   (c) Describe what would happen if the feather did not interact with any objects during its descent.
3. Slide the hockey puck across the lab bench.
   (a) Describe three interactions affecting the hockey puck as it slides.
   (b) Describe one interaction between the puck and the lab bench.
4. Attach two magnets to strings. Hold the magnets by the strings and allow them to approach each other but do not allow them to touch.
   (a) Describe the interaction between the magnets.
   (b) Describe the interaction between the strings and the magnets.
   (c) What would happen if the interaction between the strings and magnets was removed?

Analyze and Conclude

1. List the interactions that are contact forces.
2. List the interactions that are non-contact forces.
3. Did your hypothesis include each interaction that you discovered during the activity?
4. Did you describe any interactions that could not be classified as a force?

Apply and Extend

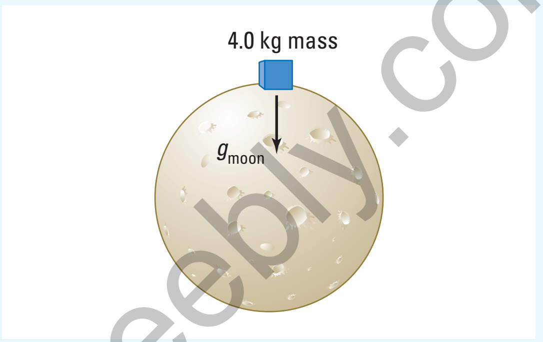
5. (a) Describe the forces acting on a skydiver as she falls to Earth with the parachute not yet deployed.
   (b) Is the skydiver accelerating during the entire descent before deploying the parachute?
   (c) Describe what force acts on the skydiver when the parachute is deployed.
6. A baseball is thrown high into the air. Describe the forces acting on the ball: (a) as it rises, (b) at the highest point, and (c) during the fall back to Earth.

MODEL PROBLEMS

Weight and Mass Calculations

1. Calculate the weight of a 4.0 kg mass on the surface of the Moon.

Frame the Problem



- The object is on the surface of the *Moon*.
- Its *weight* is the *force* of *gravity* acting on it.
- *Weight* is related to *mass* through the *acceleration* due to *gravity*.
- The *acceleration* due to *gravity* on the *Moon* is given in Table 4.4.

Identify the Goal

Weight, or force of gravity, F_g, acting on a mass on the Moon

Variables and Constants

Involved in the problem		Known	Implied	Unknown
m	$\vec{F}_g$	$m = 4.0$ kg	$\vec{g}_{\text{Moon}} = 1.64$ m/s^2[down]	$\vec{F}_g$
$\vec{g}_{\text{Moon}}$				

Strategy / Calculations

The acceleration due to gravity is known for the surface of the Moon.

Use the equation for weight.

$$\vec{F}_{g\ \text{Moon}} = m\vec{g}_{\text{Moon}}$$

Substitute in the variables and solve.

$$\vec{F}_{g\ \text{Moon}} = (4.0\ \text{kg})\left(1.64\frac{\text{m}}{\text{s}^2}\right)[\text{down}]$$

$$\vec{F}_{g\ \text{Moon}} = 6.56\ \text{kg}\frac{\text{m}}{\text{s}^2}[\text{down}]$$

1 kg$\frac{\text{m}}{\text{s}^2}$ is equivalent to 1 N.
Convert to the appropriate number of significant digits.

$$\vec{F}_{g\ \text{Moon}} = 6.6\ \text{N}[\text{down}]$$

The 4.0 kg mass would weigh 6.6 N[down] on the surface of the Moon.

Validate

Weight is a force and, therefore, should have units of newtons, N.

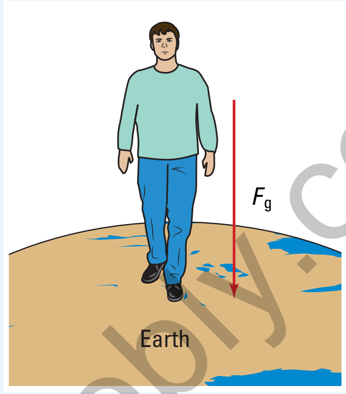
continued ▶

continued from previous page

2. A student standing on a scientific spring scale on Earth finds that he weighs 825 N. Find his mass.

Frame the Problem

- *Weight* is defined as the *force of gravity* acting on a *mass*.
- If you know the *weight* and the *acceleration* due to *gravity*, you can find the *mass*.
- The *acceleration* due to *gravity on Earth* is given in Table 4.4.



Identify the Goal

The mass, m, of the student

Variables and Constants

Involved in the problem		Known	Implied	Unknown
m	$\vec{F}_g$	$\vec{F}_g = 825$ N[down]	$\vec{g} = 9.81$ m/s^2[down]	m
$\vec{g}$				

Strategy / Calculations

Use the equation for the force of gravity.

$$\vec{F}_g = m\vec{g}$$

Substitute first

$$825\text{ N[down]} = m\ 9.81\frac{\text{m}}{\text{s}^2}\text{[down]}$$

Simplify.

$$\frac{825\text{ N}}{9.81\frac{\text{m}}{\text{s}^2}} = \frac{m\ \cancel{9.81\frac{\text{m}}{\text{s}^2}\text{[down]}}}{\cancel{9.81\frac{\text{m}}{\text{s}^2}\text{[down]}}}$$

Express N as kg$\frac{\text{m}}{\text{s}^2}$ in order to cancel units.

$$m = 84.1\frac{\text{kg}\cancel{\frac{\text{m}}{\text{s}^2}}}{\cancel{\frac{\text{m}}{\text{s}^2}}}$$

$$m = 84.1\text{ kg}$$

Solve for *m* first

$$\frac{\vec{F}}{\vec{g}} = \frac{m\cancel{\vec{g}}}{\cancel{\vec{g}}}$$

$$m = \frac{\vec{F}}{\vec{g}}$$

$$m = \frac{825\text{ N}\cancel{\text{[down]}}}{9.81\frac{\text{m}}{\text{s}^2}\cancel{\text{[down]}}}$$

$$m = 84.1\frac{\text{kg}\cancel{\frac{\text{m}}{\text{s}^2}}}{\cancel{\frac{\text{m}}{\text{s}^2}}}$$

$$m = 84.1\text{ kg}$$

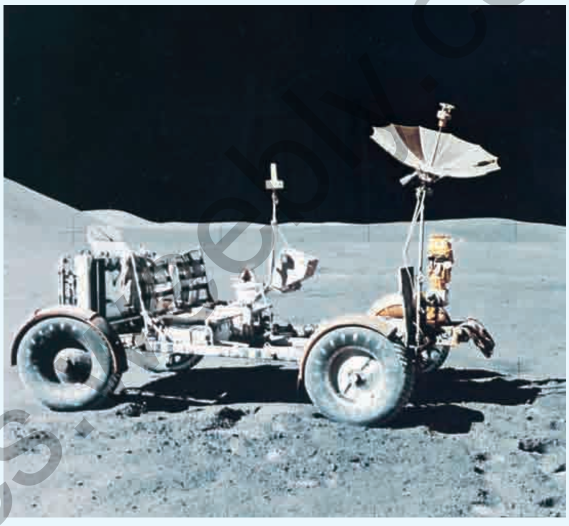
The student has a mass of 84.1 kg.

Validate

Force has units of newtons and mass has units of kilograms.
The result, 84.1 kg, is a reasonable value for a mass of a person.

PRACTICE PROBLEMS

1. Find the weight of a 2.3 kg bowling ball on Earth.
2. You have a weight of 652.58 N[down] while standing on a spring scale on Earth near the equator.
   (a) Calculate your mass.
   (b) Determine your weight on Earth near the North Pole.
   (c) Determine your weight on the International Space Station. Why would this value be impossible to verify experimentally?
3. The lunar roving vehicle (LRV) pictured here has a mass of 209 kg regardless of where it is, but its weight is much less on the surface of the Moon than on Earth. Calculate the LRV's weight on Earth and on the Moon.
4. A 1.00 kg mass is used to determine the acceleration due to gravity of a distant, city-sized asteroid. Calculate the acceleration due to gravity if the mass has a weight of 3.25×10^{-2} N[down] on the surface of the asteroid.



Friction

When Galileo developed his principles of mechanics, he attributed many phenomena to frictional forces. Hundreds of years of observations have supported his conclusions. Since frictional forces are involved in essentially all mechanical movements, a more detailed understanding of these forces is critical to making predictions and describing motion. Unlike gravity and magnetism, frictional forces are contact forces.

Frictional forces inhibit relative motion between objects in contact with each other. In this section, you will focus on friction between surfaces. The frictional forces that act on an object moving through a fluid such as air or water are much more complex and you will not deal with them quantitatively in this chapter.

Two types of frictional forces are involved when you slide an object over a surface. A **static frictional force** exists when you start to move an object from rest. A **kinetic frictional force** exists while the object is moving. You probably discovered that the static frictional force that you must overcome to start an object moving is larger the kinetic frictional force. Figure 4.6 on page 146 shows a graph of actual experimental data obtained by slowly increasing

TRY THIS...

Push a large mass horizontally across the lab bench with only one finger. Start pushing gently. Gradually increase the force you exert on the mass until it begins moving, then try to keep it moving with a constant velocity. Compare the force required to start the mass moving to the force that you must exert to keep it moving. Repeat the process until you can conclude whether there is any difference in these two forces. (You may have already experienced a similar effect if you have ever tried to slide a large box across a room.) Comment on and attempt to explain any difference in the force needed to start an object sliding and the force needed to keep the object in motion.

an applied force on an object. Once the object started to move, it maintained a constant speed. The graph clearly demonstrates how the static frictional force increases to a maximum before the object gives way and begins to move. The object then requires a smaller force to keep it moving at a constant speed.

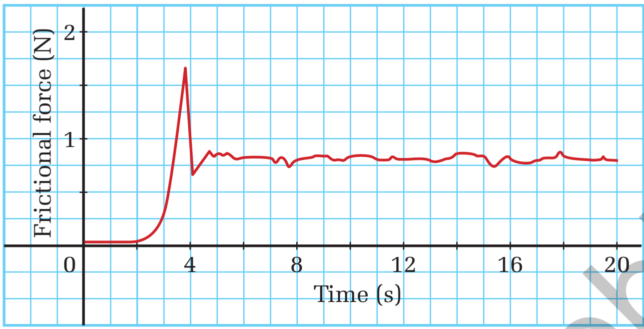


Figure 4.6 Sensitive equipment and careful experimentation yield results that clearly show how a static frictional force increases until the object begins moving. The kinetic frictional force is less than the maximum static frictional force.

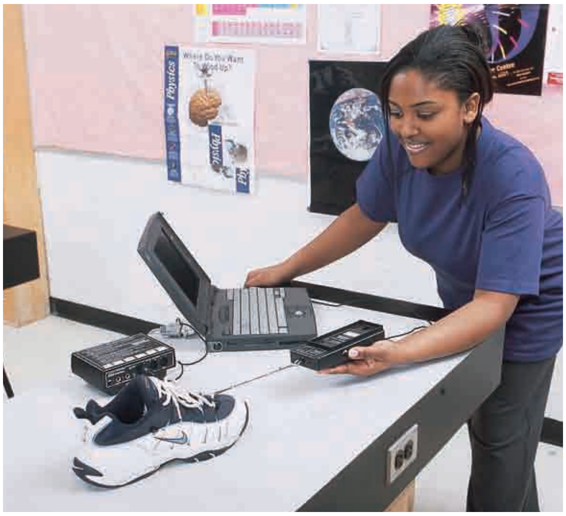
QUICK LAB How Sticky Is Your Shoe?

TARGET SKILLS
- Initiating and planning
- Analyzing and interpreting
- Communicating results

Using a force probe and a computer, determine the maximum static frictional force that you can cause your shoe to exert. Predict what factors might affect your shoe's "stickiness." Conduct an experiment to test your predictions on a variety of surfaces. (This experiment can also be conducted using a Newton spring scale.)

Analyze and Conclude

1. Describe the nature of the surfaces on which you tested your shoe.
2. Did some surfaces cause your shoe to be "stickier" than others? Offer an explanation about the differences in these surfaces.
3. Compare the static frictional force with the kinetic frictional force. Describe the results of your comparison.
4. What steps might you take to ensure that your shoe is as sticky as it possibly can be?



The strength of a frictional force between two surfaces depends on the nature of the surfaces. Although some surfaces create far more friction than others, all surfaces create some friction. The appearance of smooth surfaces can be deceiving. The photograph in Figure 4.7 shows a magnified cross section of a highly polished steel surface. The jagged peaks are far too small to see with the unaided eye or to feel with your hand, yet they are high enough to interact with objects that slide over them.

The force of friction is actually an electromagnetic force acting between the surface atoms of one object and those of another. In fact, if two blocks of highly polished steel were cleaned and placed together in a perfect vacuum, they would weld themselves together and become one block of steel. In reality, small amounts of air, moisture, and contaminants accumulate on surfaces and prevent such "ideal" interactions.

When two surfaces are at rest and in contact, the surface atoms interact to form relative strong attractive forces. When you push on one object, static friction "pushes back" with exactly the same magnitude as an applied force until the applied force is great enough to break the attractive force between the surface atoms. When the object begins to move, new "bonds" are continually being formed and broken in what you could call a stick-and-slip process. Once the object is in motion, the stick-and-slip process repeats itself over and over in rapid succession. This process is responsible for the noise produced when two objects slide past one another. The squealing of tires on dry pavement and the music created by passing a bow over a violin string are examples of such noises.

Figure 4.8 illustrates how surfaces appear to make contact. The amount of contact and the types of atoms and molecules making up the materials passing over one another play a significant role in determining how large a frictional force will be. Sliding a 5.0 kg block of ice on a sheet of ice requires much less force than sliding the same block across rubber. Experimentation yields a "stickiness" value called a **coefficient of friction** for specific combinations of surfaces. Table 4.5 lists *coefficients of static friction* for objects at rest and *coefficients of kinetic friction* for objects in motion. Coefficients of friction are experimentally obtained and depend entirely on the *two* interacting surfaces.

Figure 4.7 Highly polished steel that feels very smooth still has bumps and valleys that will collide with other surface imperfections when rubbed together.

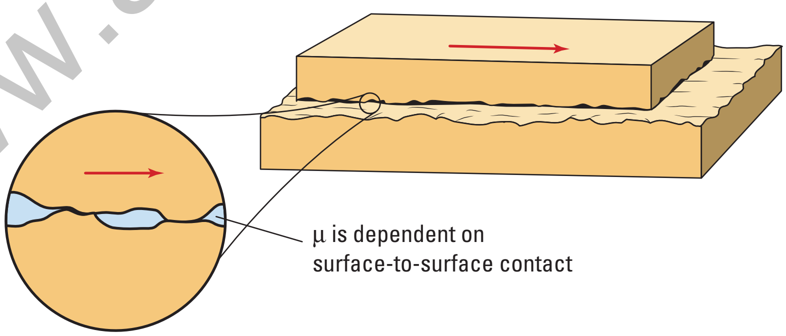


Figure 4.8 The coefficient of friction depends on each of the two surfaces in contact and must be experimentally obtained.

TRY THIS...

Hold a book against a flat wall by holding one hand under the book. With your other hand, gently press the book against the wall. Move your hand that is under the book. Catch the book if it begins to slip. Repeat the process but exert a little more pressure on the book toward the wall until the book does not fall when you remove your hand from beneath it. Summarize what your observations tell you about frictional forces.

Table 4.5 Coefficients of Friction

Surfaces	Coefficient of Static Friction μ_s	Coefficient of Kinetic Friction μ_k
rubber on dry solid surfaces	1 – 4	1
rubber on dry concrete	1.00	0.80
rubber on wet concrete	0.70	0.50
glass on glass	0.94	0.40
steel on steel (unlubricated)	0.74	0.57
steel on steel (lubricated)	0.15	0.06
wood on wood	0.40	0.20
ice on ice	0.10	0.03
Teflon™ on steel in air	0.04	0.04
lubricated ball bearings	< 0.01	< 0.01
synovial joint in humans	0.01	0.003

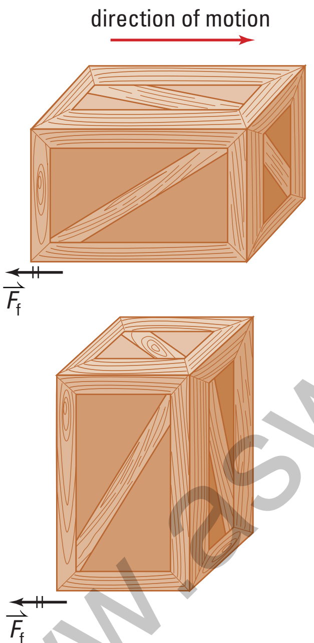


Figure 4.9 The uniform distribution of mass will yield approximately the same frictional force regardless of the side in contact with the floor.

The force of friction depends not only on the types of surfaces that are in contact, but also on the magnitude of the forces that are pressing the two surfaces together. Whenever any object exerts a force on a flat surface such as a wall, floor, or road surface, that surface will exert a force back on the object in a direction perpendicular to the surface. Such a force is called a **normal force**. If you have ever attempted to slide a dresser full of clothes across a carpeted floor, you will know that by removing the drawers as well as the clothes the job gets much easier. A full dresser weighs significantly more than an empty one. The carpeted floor must support the weight of the dresser, and does so with a normal force. By reducing the weight of the dresser, you are also reducing the normal force.

An observation that might be surprising is that the force of surface friction is independent of velocity. Fluid friction, on the other hand, is affected by velocity in a complex way. A second, possibly surprising observation is that the force of friction is independent of the area of contact. Consider the crate in Figure 4.9. If you measured the forces required to slide the crate along any of its sides, you would find that they were all the same.

When the crate was placed on sides having different areas, the materials in contact were still the same, and the weight and therefore normal forces were the same. Experiments and observations have shown that these two factors, alone, determine the magnitude of the frictional force between surfaces.

Friction is caused by a large variety of atomic and molecular interactions. These reactions are so varied that firm "laws" do not apply. The relationships that have been developed are consistent but can be applied only under the following conditions. If the conditions are met, you can consider the results of calculations to be very good approximations, but not exact predictions.

- The force of friction is independent of surface area *only* if the mass of the object is evenly distributed.
- Certain plastics and rubbers have natural properties that often do not fit the standard model of friction, (for example, adhesive tape, "ice-gripping" tires).
- The two interacting surfaces must be flat. If such things as spikes or ridges are present that penetrate the opposite surface, the principles discussed above no longer apply (See Figure 4.10).

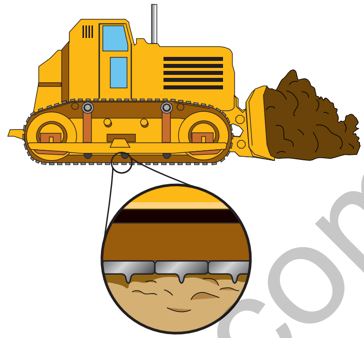


Figure 4.10 The ridges on the bulldozer tracks are penetrating the soil, creating interactions that cannot be considered as simple surface friction.

SURFACE FRICTION

The magnitude of the force of surface friction is the product of the coefficient of friction and the magnitude of the normal force. The direction of the force of friction is always opposite to the direction of the motion.

$$F_f = \mu F_N$$

Quantity	Symbol	SI unit
force of friction	F_f	N (newton)
coefficient of friction	μ	none (coefficients of friction are unitless)
normal force	F_N	N (newton)

Note: Since the direction of the normal force is perpendicular to the direction of the force of friction, vector notations are omitted.

MODEL PROBLEMS

Working with Friction

1. During the winter, owners of pickup trucks often place sandbags in the rear of their vehicles. Calculate the increased static force of friction between the rubber tires and wet concrete resulting from the addition of 200 kg (2.00×10^2 kg) of sandbags in the back of the truck.

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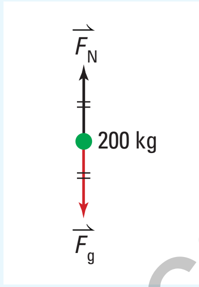
Frame the Problem



- Sketch the problem.
- The addition of the sandbags will not change the *coefficient of friction* between the tires and the wet road.
- The sandbags will increase the weight of the truck, thereby increasing the *normal* force.
- The equation relating *frictional force* to the coefficient of friction and the normal force applies to this problem.

Identify the Goal

The increase in the frictional force, F_f, resulting from placing sandbags in the back of the truck

Variables and Constants

Involved in the problem			Known	Implied	Unknown
$m_{sandbags}$	g	F_N	$m_{sandbags} = 2.00 \times 10^2$ kg	$g = 9.81$ m/s^2	$F_{g\ sandbags}$
$F_{g\ sandbags}$	μ_s			$\mu_s = 0.70$	F_N

Strategy	Calculations
In this case, the additional normal force is equal to the weight of the sandbags.	$F_N = F_g$
Use the equation for weight to find the weight and thus the normal force.	$F_g = mg$
Substitute and solve.	$F_g = (2.00 \times 10^2 \text{ kg})\left(9.81\dfrac{\text{m}}{\text{s}^2}\right)$
$\dfrac{\text{kg} \cdot \text{m}}{\text{s}^2}$ is equivalent to N.	$F_g = 1.962 \times 10^3 \dfrac{\text{kg} \cdot \text{m}}{\text{s}^2}$
	$F_N = 1.962 \times 10^3$ N
All of the values needed to find the additional frictional force are known so substitute into the equation for frictional forces.	$F_f = \mu_s F_N$
	$F_f = (0.70)(1.962 \times 10^3 \text{ N})$
	$F_f = 1.373 \times 10^3$ N

The sandbags increased the force of friction of the tires on the road by 1.4×10^3 N.

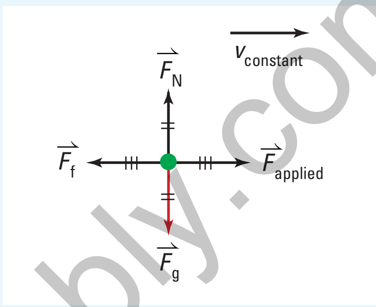
Validate

The force of friction should increase with the addition of weight, which it did.

2. **A horizontal force of 85 N is required to pull a child in a sled at constant speed over dry snow to overcome the force of friction. The child and sled have a combined mass of 52 kg. Calculate the coefficient of kinetic friction between the sled and the snow.**

Frame the Problem

- Sketch the forces acting on the child and sled.
- The applied force just overcomes the force of friction, therefore, the *applied force* must be *equal* to the *frictional force*.
- The sled is neither sinking into the snow, nor is it rising off of the snow; therefore, the *weight* of the sled must be exactly equal to the *normal force* supporting it.



Identify the Goal

The coefficient of kinetic friction, μ_k

Variables and Constants

Involved in the problem		Known	Implied	Unknown
m	F_f	$m = 52$ kg	$g = 9.81$ m/s^2	F_g
$F_{applied}$	F_N	$F_{applied} = 85$ N		F_f
F_g	μ_k			F_N
g				μ_k

Strategy

The conditions for the equation describing surface friction are met, so use the equation.

Since the normal force is equal to the weight, use the equation for weight.

Solve.

$\frac{\text{kg} \cdot \text{m}}{\text{s}^2}$ is equivalent to N.

Apply the equation for a frictional force.

Calculations

$F_f = \mu_k F_N$

$F_N = Fg$

$F_g = mg$

$F_N = mg$

$F_N = (52\ \text{kg})\left(9.81 \frac{\text{m}}{\text{s}^2}\right)$

$F_N = 510.12\ \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$

$F_N = 510.12$ N

$F_f = \mu_k F_N$

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Strategy

Calculations

Substitute first

$F_f = \mu_k F_N$

$85\ \text{N} = \mu_k 510.12\ \text{N}$

$\dfrac{85\ \text{N}}{510.12\ \text{N}} = \dfrac{\mu_k \cancel{510.12\ \text{N}}}{\cancel{510.12\ \text{N}}}$

$\mu_k = 0.1666$

Solve for μ_k first

$\dfrac{F_f}{F_N} = \dfrac{\mu_k \cancel{F_N}}{\cancel{F_N}}$

$\mu_k = \dfrac{85\ \text{N}}{510.12\ \text{N}}$

$\mu_k = 0.1666$

Therefore, the coefficient of kinetic friction between the sled and the snow is 0.17.

Validate

The coefficient of friction between a sled and snow should be relatively small, which it is.

PRACTICE PROBLEMS

5. A friend pushes a 600 g (6.00×10^2 g) textbook along a lab bench at constant velocity with 3.50 N of force.

(a) Determine the normal force supporting the textbook.

(b) Calculate the force of friction and coefficient of friction between the book and the bench.

(c) Which coefficient of friction have you found, μ_s or μ_k?

6. A 125 kg crate full of produce is to be slid across a barn floor.

(a) Calculate the normal force supporting the crate.

(b) Calculate the minimum force required to start the crate moving if the coefficient of static friction between the crate and the floor is 0.430.

(c) Calculate the minimum force required to start the crate moving if half of the mass is removed from the crate before attempting to slide it.

7. Avalanches often result when the top layer of a snow pack behaves like a piece of glass, and begins sliding over the underneath layer. Calculate the force of static friction between two layers of horizontal ice on the top of Mount Everest, if the top layer has a mass of 2.00×10^2 kg. (Refer to Table 4.5 for the coefficient of friction.)

8. Assume that, in the "Try This" experiment on page 148, you discovered that you had to push the book against the wall with a force of 63 N in order to prevent it from falling. Assume the mass of the book to be 2.2 kg. What is the coefficient of static friction between the book and the wall? (Hint: Be careful to correctly identify the source of the normal force and the role of the frictional force in this situation.)

Concept Organizer

The types of surfaces in contact directly affect the magnitude of the force of friction.

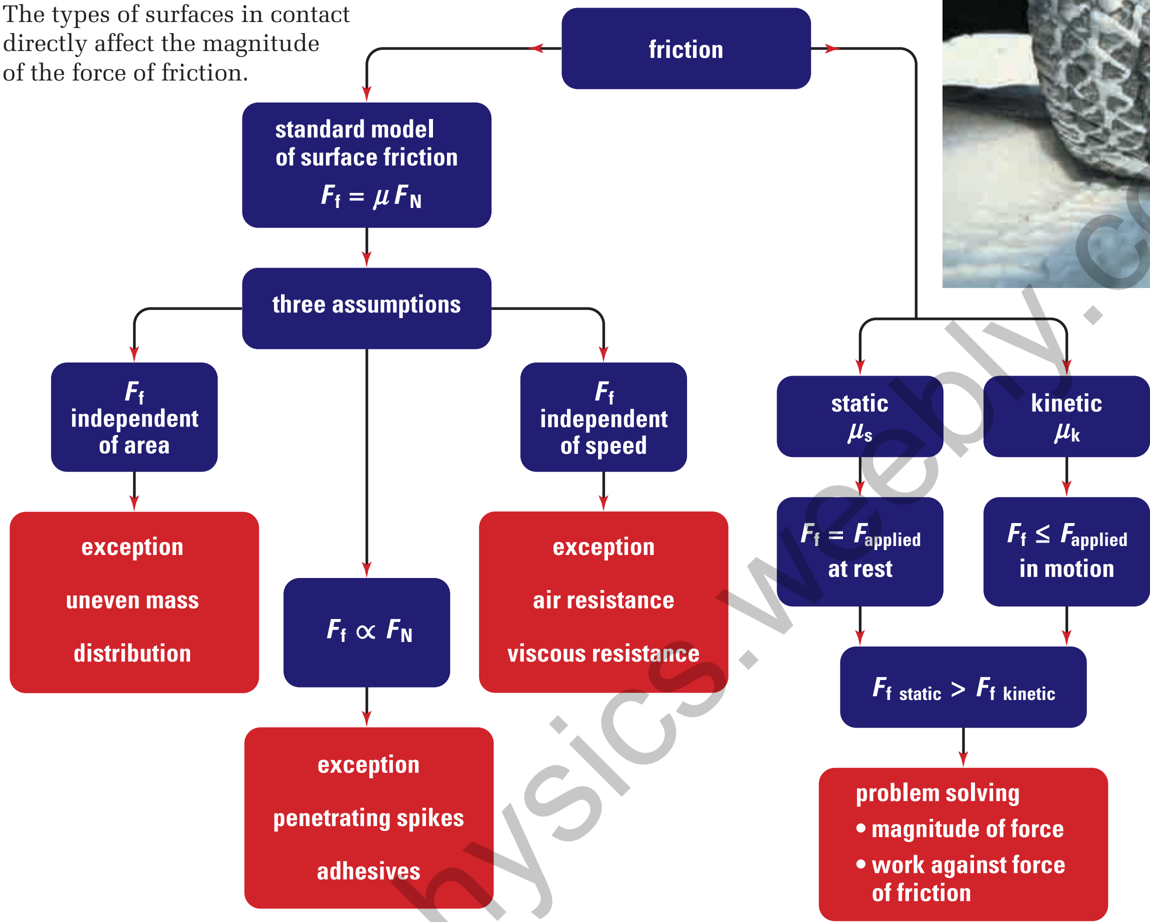


Figure 4.11 Understanding the standard model of friction and the exceptions.

Free Body Diagrams

You have seen many cases in which more than one force was acting on an object. You also learned that, according to Galileo's concepts of inertia, the motion of a body will change only if an external force is applied to it. When several forces are acting, how do you know which force might change an object's state of motion? The answer is, "All of them acting together." You must look at every force that is acting on an object and find the vector sum of all of the forces before you can predict the motion of an object. This vector sum is the **net force** on the object. A free body diagram is an excellent tool to help you keep track of all of the forces.

Free body diagrams represent all forces *acting on* one object, and only the forces acting on the object. Forces that the object exerts on other objects do not appear in free body diagrams because they have no effect on the motion of the object itself.

In drawing a free body diagram, you represent the object as a single dot to help focus interest on the forces involved and not on the creator's artistic flair. You will represent each force *acting* on the object with an arrow. The arrow's direction shows the direction of the force and the arrow's relative length provides information about the magnitude of the force. Forces that have the same magnitude should be sketched with approximately the same length, forces that are larger should be longer, and smaller forces should be shorter. Study the examples in Figure 4.12.

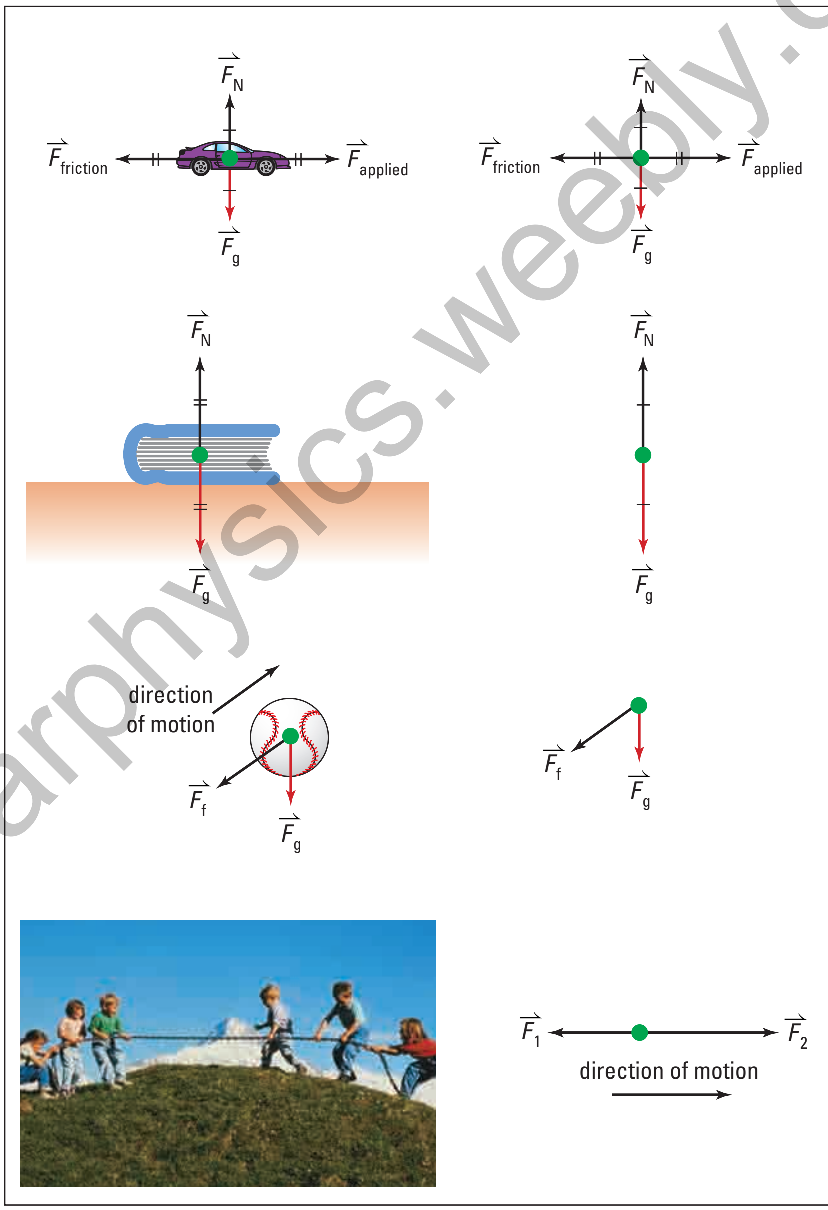


Figure 4.12 Free body diagrams for some everyday objects.

4.2 Section Review

1. K/U Describe how and why acceleration due to gravity varies around the globe.

2. K/U A Ping Pong™ ball is struck with a paddle, sails over the net, bounces off of the table, and continues to the floor. Describe the forces acting on the ball throughout the trip.

3. C Explain the difference between contact and non-contact forces and provide examples of each.

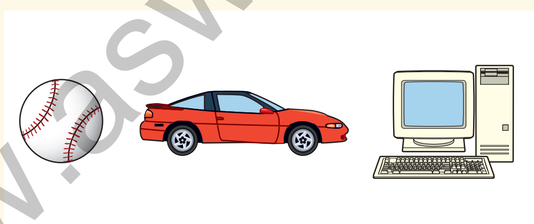
4. C Explain, using force arguments, how it is possible for a feather and a coin in a vacuum to fall toward Earth with the same acceleration.

5. C A news reporter states that the winning entry in a giant pumpkin-growing contest "had a weight of 354 kg." Explain the error in this statement and provide values for both the weight and mass of the winning pumpkin.

6. C Describe the forces acting on a bag of chips resting on a tabletop.

7. C Explain why the coefficient of static friction is greater than the coefficient of kinetic friction.

8. K/U Imagine that all of the objects pictured are on the Moon, where there is no atmosphere.



   (a) Rank the objects in order of weight, putting the heaviest object first.

   (b) Rank the objects from largest to smallest according to the magnitude of the force of gravity acting on each of them.

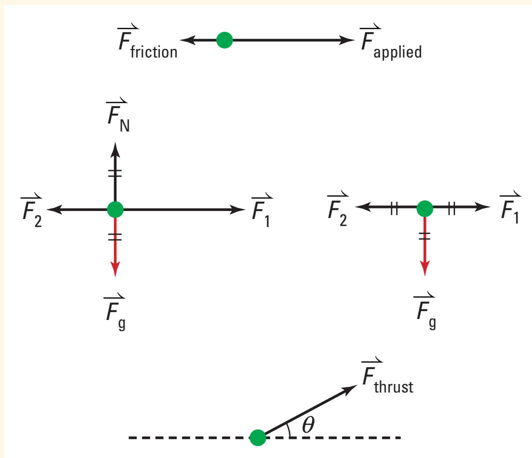
   (c) If each object was dropped simultaneously, which would hit the Moon's surface first?

9. C

   (a) State three assumptions implied by the friction equation: $F_f = \mu F_N$.

   (b) Discuss whether or not these assumptions are valid for each situation shown in the following pictures.

10. K/U Predict the motion that each object would undergo based on the free body diagrams illustrated.



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4.2 Section Review

11. K/U

(a) Why is a dot used in a free body diagram?

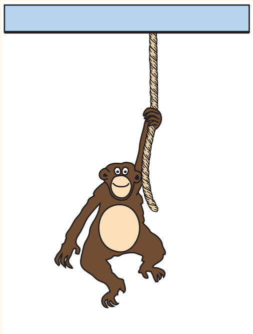
(b) Why are the lengths of the force vector sketches important?

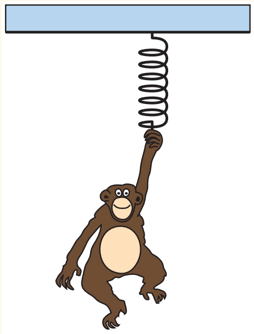
(c) Describe the purpose of a free body diagram.

12. K/U Draw a free body diagram showing the forces acting on a monkey that is hanging at rest

(a) from a vine

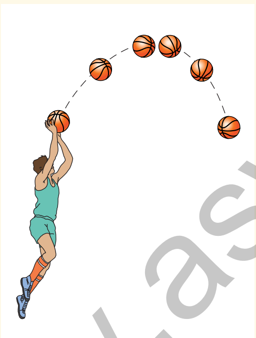
(b) from a spring





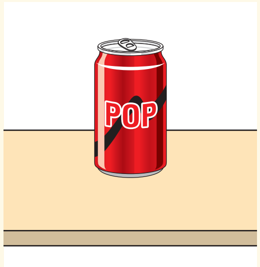
13. K/U

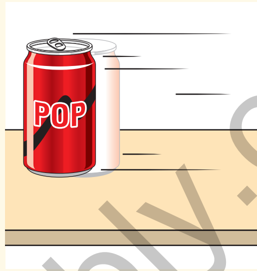
(a) Draw a free body diagram showing the forces acting on the ball during its flight.



(b) Draw a free body diagram showing the forces acting on the skydiver before he deploys his parachute.

14. K/U Draw a free body diagram showing the forces acting on the pop can.





15. K/U Draw a free body diagram for each of the following situations.

(a) A submarine moves horizontally with constant velocity through deep water.

(b) A car accelerates from a stoplight.

(c) A pail is lifted from a deep well at constant velocity using a rope.

(d) A neon sign hangs motionless, suspended by two cables. One cable runs horizontally, connecting the sign to a wall; the other cable runs up and away from the wall, connecting the sign to the ceiling.

UNIT PROJECT PREP

Friction and inertia are often involved in comic situations in the movies.

- Have you ever tried running across a skating rink and then tried to stop yourself?
- Have you ever pushed or rolled a heavy object and then had difficulty stopping it?

4.3 Forces and Newton's Laws

The understanding of force and motion progressed slowly from the time of Aristotle through to Galileo and then to Newton. Today, we use concepts summarized by Sir Isaac Newton in his book called *Principia Mathematica Philosophiae Naturalis* published in 1686. Newton's three laws of motion are currently used to predict force and motion interactions for macroscopic objects. The laws are over 400 years old. Has no progress been made in terms of understanding force and motion in the past 400 years? Yes, in fact, there has been significant progress.

The physics of force and motion is currently divided into two very different categories, classical mechanics and quantum mechanics. This textbook deals with **classical mechanics**, sometimes called **Newtonian mechanics**. Newtonian mechanics treats energy and matter as separate entities and uses Newton's laws of motion to predict the results of interactions between objects. The principles of Newtonian mechanics, although formulated 400 years ago, accurately predict and describe the behaviour of large-scale objects such as baseballs, cars, and buildings. Newtonian mechanics provides a connection between the acceleration of a body and the forces acting on it. It deals with objects that are large in comparison to the size of an atom, and with speeds that are much less than the speed of light ($c = 3.0 \times 10^8$ m/s). **Quantum mechanics**, on the other hand, attempts to explain the motion and energy of atoms and subatomic particles.

In the early part of the twentieth century, Einstein developed two ingenious theories of relativity, which, in part, deal with objects travelling close to the speed of light. Also included in his theories is the proposal that mass and energy are, in fact, different manifestations of the same entity. His famous equation, $E = mc^2$, describes how these two quantities are related. Einstein's theories predict everything that Newtonian mechanics is able to, plus much more. It is important to understand that Einstein's relativistic mechanics is an extension of Newtonian mechanics, not a replacement. Developing a conceptual framework to understand force and motion in terms of Newton's laws is necessary before attempting to grasp these more advanced theories of physics.

Newton's First Law

Newton originally considered Aristotle's ideas, but came to adopt Galileo's perspective that a body will tend to stay at rest or in uniform motion unless acted on by an external force. Clearly, many objects are at rest even though all objects on Earth are subjected to the force of gravity. So what is the meaning of "external force?"

SECTION EXPECTATIONS

- Describe and assess Newton's contribution to the study of dynamics.
- Understand Newton's laws of motion, and apply them to explain motions and calculate accelerations.
- Verify Newton's second law experimentally, and use it to relate net force, mass, and acceleration.
- Apply Newton's laws to the work of a crash investigator.

KEY TERMS

- classical/Newtonian mechanics
- quantum mechanics
- inertial frame of reference
- non-inertial frame of reference

TRY THIS...

Place a coin on a card poised above an empty glass. Predict what will happen to the coin if you use your index finger to flick the card so that it flies off horizontally. Test your prediction and explain the results.

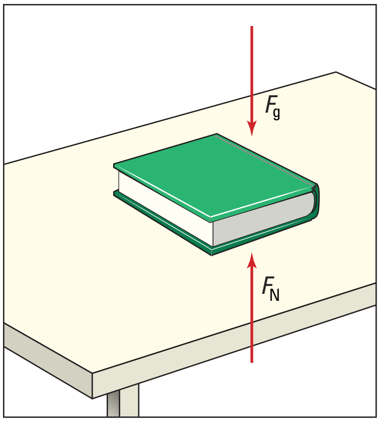


Figure 4.13 The forces on the book are balanced so the book remains at rest.

Consider the book on the desk in Figure 4.13. The book does not fall under the force of gravity because it is supported by the normal force of the desk pushing up on it. The key to understanding the meaning of "external force" is to consider all forces acting on an object. If the vector sum of all of the forces acting on an object is zero, then there is no *net force* acting on the object and its motion will not change. You would say that the forces are balanced and the object is in equilibrium.

NEWTON'S FIRST LAW — THE LAW OF INERTIA

An object at rest or in uniform motion will remain at rest or in uniform motion unless acted on by an external force.

Hockey provides concrete examples of Newton's first law. A hockey puck at rest on the ice will not spontaneously start to move. Likewise, a puck given some velocity will continue to slide in a straight line at a constant speed. If the ice was truly frictionless and the ice surface was infinitely large, the puck would continue to slide forever.

You can apply Newton's laws to each dimension, independently. Consider the case in which a cart is pulled across a smooth tabletop with constant velocity. During the trip, a steel ball bearing is fired directly upward out of the cart. Magically, the ball will travel up and then back down, all the while remaining directly above the cart. In fact it is not magic, but Newton's first law, that is demonstrated here. The ball has the same horizontal velocity as the cart before it is launched. The ball maintains a horizontal velocity equal to that of the cart as it moves through the air. The forces that caused the ball to rise and fall were in the vertical dimension and had no effect on its horizontal motion.

Figure 4.14 Hockey provides a nearly frictionless surface for the puck to slide on and plenty of opportunity to observe how forces change the speed and direction of objects.

Figure 4.15 This performer's arm is resting on a bed of nails, yet he is able to break a brick over it without suffering any injury. Use Newton's law of inertia to explain how this is possible.

Inertial Reference Frames

Situations exist where the law of inertia seems to be invalid. Imagine a car speeding away from a stoplight. A passenger appears to be abruptly pushed back against the seat. To the pedestrian observing the car from the street corner, Newton's law of inertia seems to be completely accurate. The passenger, under the influence of the unbalanced force of the seat pushing on her, is accelerating *relative to the ground*. The observer is in an **inertial frame of reference**.

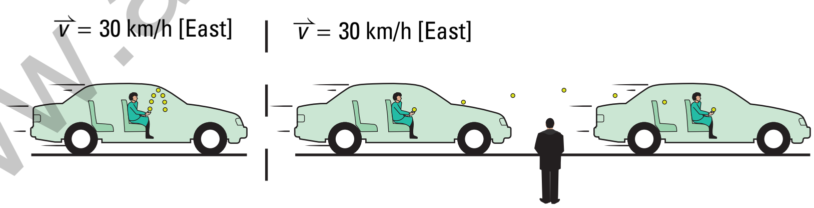
The passenger sitting in a car feels the seat pushing on her as the car accelerates away from a stoplight. The seat is exerting a strong force onto her back, and yet she is not moving *relative to the car*. To the passenger, an unbalanced force is acting on a mass (her body) and yet there is no apparent motion. This appears to violate the law of inertia. However, Newton's laws apply to inertial reference frames. The passenger is in an *accelerating* frame of reference, which is a **non-inertial reference frame**. Notice that, when the car reaches a constant velocity, the passenger no longer feels the pressure of the back of the seat pushing on her. A reference frame moving at a constant velocity is an inertial reference frame.

DEFINITION OF AN INERTIAL REFERENCE FRAME

An inertial reference frame is one in which Newton's law of inertia is valid. An inertial reference frame must not be accelerating.

Think It Through

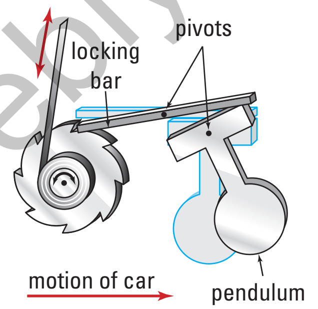
- Consider the example shown below. The passenger in a car travelling with constant velocity tosses and then catches a tennis ball. In the passenger's frame of reference, the ball goes straight up and comes straight back down under the influence of gravity. A roadside observer sees the tennis ball trace a different trajectory. Explain how different observers can see two different trajectories of the ball and yet both observers perceive that Newton's first law is validated by the observation.



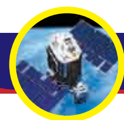
Both frames are Inertial

PHYSICS FILE

A seat belt extends and retracts to fit around any size person, but then during a sudden stop or collision it locks into position and does not move. What locks the seatbelt? Inertia. A small pendulum (see diagram) pivots during rapid decelerations; its inertia keeps it moving. It forces a lever to lock into the ratchet system that stops your seatbelt from extending.



COURSE CHALLENGE



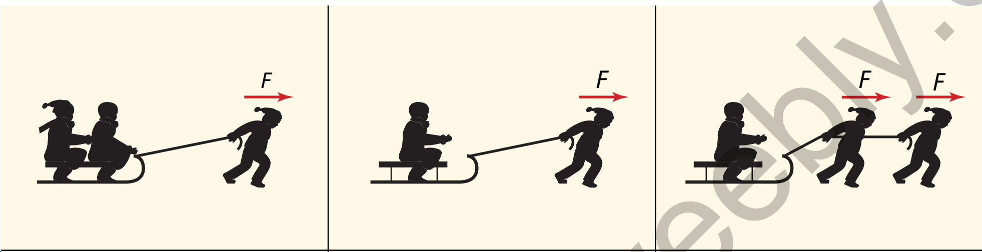
Staying in Orbit

Consider motion and the effect of perpendicular forces. Predict (a) the direction of the force on a geosynchronous satellite and (b) the source of the force.

Learn more from the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and find the *Physics 11 Course Challenge*.

Newton's Second Law

Imagine three young friends playing in the snow with a toboggan on flat ground. Assume that (a) each friend has the same mass, m, (b) can pull with the same force, F, (c) the toboggan's mass is so small that it can be ignored, and (d) the toboggan glides so easily on top of the snow that friction can be ignored. The friends take turns pulling and being pulled on the toboggan. A comparison of the resulting accelerations is shown in the chart below. Look for a pattern that relates force, mass, and acceleration.



Net force	$\lvert\vec{F}\rvert$	$\lvert\vec{F}\rvert$	$2\lvert\vec{F}\rvert$
Mass on toboggan	$2m$	m	m
Acceleration	$\frac{1}{2}\lvert\vec{a}\rvert$	$\lvert\vec{a}\rvert$	$2\lvert\vec{a}\rvert$

COURSE CHALLENGE

The Cost of Altitude

Research current costs associated with getting objects into space. Later, you may use this data to help estimate the cost of delivering electric energy through a space-based power system.

Learn more from the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and find the *Physics 11 Course Challenge*.

Newton observed motions as simple as those of the toboggan described above and as complex as the motion of planets around the sun. From these observations, he developed his second law of motion. As you may have deduced from the data in the chart above, when a net force, F, acts on a mass, m, the resulting acceleration of the mass, a, is proportional to the magnitude of the force and inversely proportional to the amount of mass. The direction of the acceleration is the same as that of the net force. The form of the law described here and the more familiar form are detailed in the box on the next page.

Think It Through

- Picture this. You and your family are moving. There are boxes everywhere. You just carried a very heavy box out to the truck and have come back for another one. You reach for a box that you believe to be full and very heavy. However, it is empty. What do you think will happen when you start to lift it? Explain, in terms of forces and acceleration, what happens when anyone starts to lift an object that they believe to be much heavier than it actually is.

ELECTRONIC LEARNING PARTNER

Your Electronic Learning Partner has an interactive activity that explores Newton's second law of motion.

NEWTON'S SECOND LAW

Force is the product of mass and acceleration, or, acceleration is the quotient of the force and the mass.

$$\vec{F} = m\vec{a} \quad \text{or} \quad \vec{a} = \frac{\vec{F}}{m}$$

Quantity	Symbol	SI unit
acceleration	$\vec{a}$	m/s^2 (metre per second squared)
force	$\vec{F}$	N (newton)
mass	m	kg (kilogram)

Unit Analysis

(mass) (acceleration) = kg m/s^2 = N

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and follow the **Physics 11** links for laboratory activities on Newton's second law and on stopping distances.

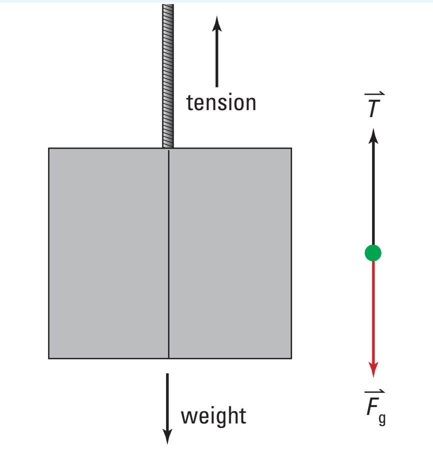
MODEL PROBLEM

Applying Newton's Second Law

1. A man is riding in an elevator. The combined mass of the man and the elevator is 7.00×10^2 kg. Calculate the magnitude and direction of the elevator's acceleration if the tension (T) in the supporting cable is 7.50×10^3 N (T is the applied force).

Frame the Problem

- Sketch a free body diagram of the man and elevator.
- The cable exerts an *upward force* on the man and elevator.
- *Gravity* exerts a *downward force* on the man and elevator.
- The net force on the man and elevator will determine the *acceleration* according to *Newton's second law.*



Identify the Goal

The acceleration, $\vec{a}$, of the elevator

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Variables and Constants

Involved in the problem		Known	Implied	Unknown
$\vec{T}$	$\vec{a}$	$\vec{T} = 7.50 \times 10^3$ N	$\vec{g} = 9.81\frac{\text{m}}{\text{s}^2}$ [down]	$\vec{F}_g$
$\vec{F}_g$	m	$m = 7.00 \times 10^2$ kg		$\vec{F}_{net}$
$\vec{F}_{net}$	$\vec{g}$			$\vec{a}$

Strategy

Calculations

Since the motion is all along one line, up and down, denote direction with signs only. Let up be positive and down be negative.

Find the force of gravity acting on the man and elevator using the equation for weight. Since "down" was chosen as negative, the acceleration due to gravity becomes negative.

$$\vec{F}_g = m\vec{g}$$

$$\vec{F}_g = (7.00 \times 10^2\ \text{kg})\left(-9.81\frac{\text{m}}{\text{s}^2}\right)$$

$$\vec{F}_g = -6.867 \times 10^3\ \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

$$\vec{F}_g = -6.87x10^3\ \text{N}$$

Find the net force acting on the man and elevator by finding the vector sum of the tension and force of gravity acting on the elevator and man.

$$\vec{F}_{net} = \vec{T} + \vec{F}_g$$

$$\vec{F}_{net} = +7.50 \times 10^3\ \text{N} - 6.867 \times 10^3\ \text{N}$$

$$\vec{F}_{net} = +6.33 \times 10^2\ \text{N}$$

Apply Newton's second law in terms of acceleration and solve.

$$\vec{a} = \frac{\vec{F}}{m}$$

Write N as $\frac{\text{kg} \cdot \text{m}}{\text{s}^2}$ so you can cancel units.

$$\vec{a} = \frac{+6.33 \times 10^2\ \text{N}}{7.00 \times 10^2\ \text{kg}}$$

$$\vec{a} = +9.043 \times 10^{-1}\ \frac{\frac{\cancel{\text{kg}} \cdot \text{m}}{\text{s}^2}}{\cancel{\text{kg}}}$$

$$\vec{a} = +9.043 \times 10^{-1}\ \frac{\text{m}}{\text{s}^2}$$

The elevator was accelerating upward at 0.904 m/s^2.

Validate

The tension was greater than the weight, causing a net upward force to exist. A net force will cause an object to accelerate upward. The units cancelled to give metres per square second, which is correct for acceleration.

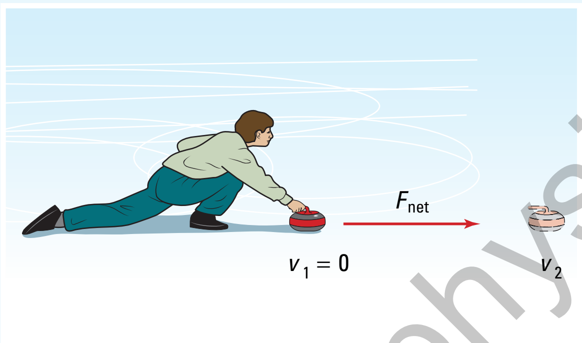
2. **A curler exerts an average force of 9.50 N[S] on a 20.0 kg stone. (Assume that the ice is frictionless.) The stone started from rest and was in contact with the girl's hand for 1.86 s.**

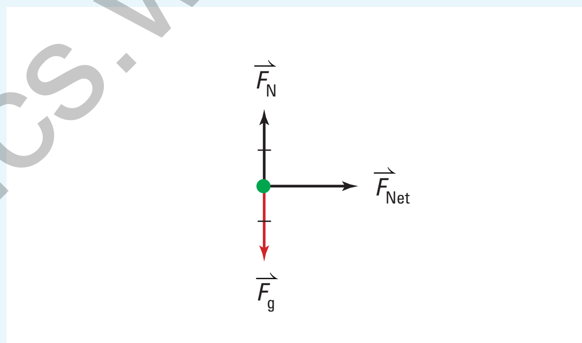
(a) **Determine the average acceleration of the stone.**

(b) **Determine the velocity of the stone when the curler releases it.**

Frame the Problem

- Draw a free body diagram of the problem.
- The *downward force of gravity* is balanced by the *upward normal force*. Therefore there is *no net force* in the vertical direction. These forces do not affect the acceleration of the stone.
- The only *horizontal force* on the stone is the *force exerted* by the curler. Therefore it is the *net force* on the stone.
- The *net force* determines the *acceleration* of the stone according to *Newton's second law* of motion.
- After the stone leaves the curler's hand, there is *no* longer a horizontal *force* on the stone and thus, it is *no* longer *accelerating*.
- The *equations of motion* for uniform acceleration apply to the motion of the stone.





Identify the Goal

(a) The acceleration, $\vec{a}$, of the curling stone

(b) The final velocity, $\vec{v}$, of the stone as it leaves her hand

Variables and Constants

Involved in the problem		**Known**	**Implied**	**Unknown**
$\vec{F}_{applied}$	$\vec{v}_1$	$\vec{F}_{applied} = 9.5\ \text{N[S]}$	$\vec{v}_1 = 0.0\ \frac{\text{m}}{\text{s}}\text{[S]}$	$\vec{a}$
m	$\vec{v}_2$	$m = 20.0\ \text{kg}$		$\vec{v}_2$
$\vec{a}$	Δt	$\Delta t = 1.86\ \text{s}$		

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Strategy

You know the net force so use Newton's second law in terms of acceleration.

Calculations

$$\vec{a} = \frac{\vec{F}}{m}$$

$$\vec{a} = \frac{9.50\ \text{N[S]}}{20.0\ \text{kg}}$$

$$\vec{a} = 0.475\ \frac{\frac{\cancel{\text{kg}} \cdot \text{m}}{\text{s}^2}}{\cancel{\text{kg}}}[\text{S}]$$

$$\vec{a} = 0.475\ \frac{\text{m}}{\text{s}^2}[\text{S}]$$

(a) The average acceleration of the stone was 0.475[S].

Recall the equations of motion from Chapter 2. Use the equation that relates initial and final velocities, acceleration, and the time interval.

$$\vec{v}_2 = \vec{v}_1 + \vec{a}\Delta t$$

Substitute in the known variables and solve for $\vec{v}_2$.

$$\vec{v}_2 = 0.0\ \frac{\text{m}}{\text{s}^2}[\text{S}] + \left(0.475\ \frac{\text{m}}{\cancel{\text{s}^2}}[\text{S}]\right)(1.86\ \cancel{\text{s}})$$

$$\vec{v}_2 = 0.8835\ \frac{\text{m}}{\text{s}}[\text{S}]$$

(b) The velocity of the stone when it left the curlers hand was $0.884\frac{\text{m}}{\text{s}}$[S].

Validate

The curling stone experienced a net force acting toward the south. A net force causes acceleration in the direction of the force. The stone accelerated in the direction of the force, gaining speed as it went. The units cancelled to give $\frac{\text{m}}{\text{s}^2}$[S] for acceleration and $\frac{\text{m}}{\text{s}}$[S] for velocity. These are the correct units.

PRACTICE PROBLEMS

9. A 4.0 kg object experiences a net force of 2.2 N[E]. Calculate the acceleration of the object.

10. A 6.0 kg object experiences an applied force of 4.4 N[E] and an opposing frictional force of 1.2 N[W]. Calculate the acceleration of the object.

11. A 15 kg object experiences an applied force of 5.5 N[N] and an opposing frictional force of 2.5 N[S]. If the object starts from rest, how far will it have travelled after 4.0 s?

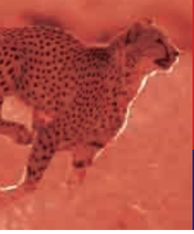
12. A 45 kg student rides his 4.0 kg bicycle, exerting an applied force of 325 N[E].

(a) Calculate the acceleration of the cyclist if frictional resistance sums to 50.0 N[W].

(b) How far will the student have travelled if he started with a velocity of at 3.0 m/s[E] and accelerated for 8.0 s?

13. A stretched elastic exerts a force of 2.5 N[E] on a wheeled cart, causing it to accelerate at 1.5 m/s^2[E]. Calculate the mass of the cart, ignoring frictional effects.

14. The driver of a 1.2×10^3 kg car travelling 45 km/h[W] on a slippery road applies the brakes, skidding to a stop in 35 m. Determine the coefficient of friction between the road and the car tires.



INVESTIGATION 4-B

Force and Acceleration

TARGET SKILLS
- Performing and recording
- Analyzing and interpreting

Children playing with a toboggan in the snow will gain an intuitive sense that force, mass, and acceleration are related. Early scientists developed the same intuition, but only through experimentation could they formulate mathematical models that accurately predicted observed results. In this investigation, you will determine the validity of Newton's second law.

Problem

Obtain experimental evidence to support Newton's second law.

Hypothesis

State Newton's second law in the form of an hypothesis.

Equipment

- elastic bands
- dynamics cart
- metre stick
- ticker-tape timer or motion sensor

Procedure

1. Tape the elastic band onto the end of the metre stick as shown. Determine the length of an unstretched elastic band. Mark the length on the ruler with a piece of tape.

2. Attach the free end of the elastic to the dynamics cart.
3. Set up your equipment to collect distance versus time data on the cart as you pull it along with the elastic.
4. Obtain data with the elastic stretched to 1.0 cm, 2.0 cm, 3.0 cm, and 4.0 cm. It is crucial that you ensure that the stretch in the elastic remains exactly the same for the entire trip.

CAUTION As you run trials with more stretch in the elastic, the cart's final speed will increase dramatically. Have a partner waiting to catch the moving cart. Ensure that your path is free of obstacles or doors that could swing open.

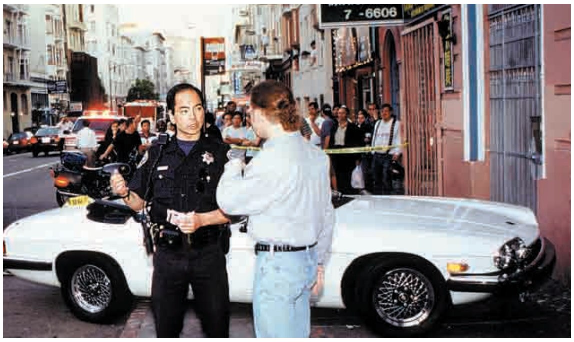
5. Generate velocity versus time graphs for each length trial.

Analyze and Conclude

1. What was the purpose of ensuring that the amount of stretch in the elastic band remained constant?
2. Use the velocity versus time graphs to obtain an average acceleration for each trial. Ensure that you select a time interval that is the same length for each trail when determining the average acceleration. (A larger time interval will yield better results.) Use the results to generate a force versus acceleration graph. You can express the force as centimetres of stretch of the elastic band.
3. Find the slope of the best-fit line from the force versus acceleration graph. What does this slope represent?
4. From your results, develop a mathematical model that relates force, mass, and acceleration.
5. Use your mathematical model to predict how the slope of the line in the force versus acceleration graph would appear if (a) two carts and (b) three carts were pulled using the same elastic. If time allows, test your prediction.

CAREERS IN PHYSICS

The Physics of a Car Crash



A car accident has occurred at a busy intersection. A passenger in one of the cars is seriously injured and both vehicles are extensively damaged.

One of the drivers says she was stopped at a green light, waiting to make a left-hand turn, when an oncoming car swerved and hit her. The driver of the other car says he hit her car because she began to turn as he was passing through the intersection. The police officers investigating the accident also hear conflicting stories from witnesses. Nobody seems to know exactly what happened. It is time to bring in an accident investigator with expertise in physics and motion to determine how the crash actually occurred.

Accident investigators use the principles of physics, such as work and the conservation of energy, to determine the cause of car accidents. The investigators consider a number of factors and make detailed measurements at the scene of an accident. They might consider road conditions, damage to vehicles, the pre- and post-accident positions of vehicles, and vehicle characteristics such as weight and size. An investigator might be asked to determine the speed of each vehicle on impact by considering their masses and the distance they travelled after impact. For example, in the accident described above, the investigator would need to determine if the driver of the car in the left-turn lane was, in fact, stationary at the time of impact.

Several different career options are available for accident investigators. Police officers with specialized training are involved in accident investigation and reconstruction, while other investigators are consultants hired on a contractual basis by police departments, insurance companies, and individual citizens. Still others might be full-time employees of insurance companies or legal firms. Accident investigators are also often called on to serve as expert witnesses in criminal or civil law cases.

The training required to become an accident investigator varies. Some investigators have earned degrees in civil or traffic engineering. An excellent understanding of physics and the ability to perform detailed tasks accurately and without bias are important requirements. A knowledge of computers is becoming increasingly important as collision analysis becomes more computerized.

For information about where and how law enforcement accident investigators receive their training, contact the Community Services branch of a municipal, provincial, or federal law enforcement agency in your area.

Going Further

1. Investigators are not always able to make actual measurements at the scene of an accident. Often they must reconstruct a scene or determine the cause of an accident from photographs and reports alone. List the factors that an investigator would need to know about the accident scenario just described.

2. How could an investigator determine these factors?

Web Link

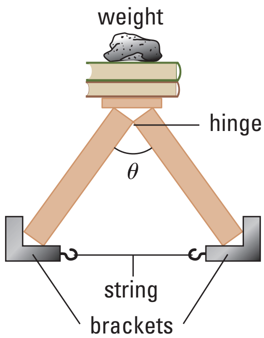
www.school.mcgrawhill.ca/resources/

In addition to motor vehicle accidents, some investigators work on air, marine, and rail accident cases. For example, investigators for the Canadian Transportation Safety Board worked on the Swissair Flight 111 disaster near Peggy's Cove in Nova Scotia. To learn about this investigation, go to the above Internet site and follow the links for **Science Resources** and **Physics 11** to find out where to go next.

QUICK LAB

The Vector Nature of Force

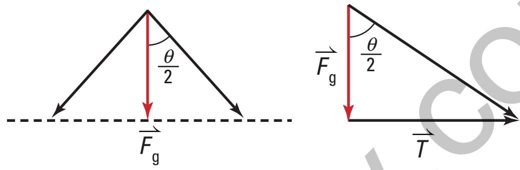
TARGET SKILLS
- Analyzing and interpreting
- Communicating results



By using the apparatus shown, you can investigate the vector nature of force. Cut five lengths of thread to connect the base of the apparatus. Shorter lengths will create a taller isosceles triangle; longer lengths will create a shorter, wider isosceles triangle. Measure the angle at the top of the triangle and then pile small masses onto the top of the apparatus until the thread snaps. Record the angle and the amount of mass. Repeat this procedure for each length of thread.

Analyze and Conclude

1. Find the weight of the total amount of mass required to break each thread.
2. The following diagram illustrates how the weight of the supported mass can be used to determine the tension in the thread. Find the breaking tension for each length of thread.



$$\tan\frac{\theta}{2} = \frac{T}{F_g}$$

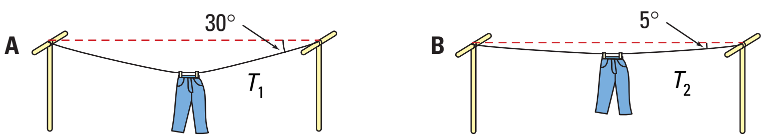
$$T = F_g \tan\frac{\theta}{2}$$

For a given amount of mass, the weight remains constant. The weight is the vertical component of the force compressing the wooden post. For the mass to be supported, the weight (vertical component) and the tension in the thread (horizontal component) must add "tip to tail" to form a closed triangle with the resultant force in the post. Notice that the weight, for a given amount of mass, does not change; therefore, as the angle is increased, the tension force must get progressively larger to keep the system in equilibrium. The tension force, T, can be found using simple trigonometry.

3. Organize your data to compare breaking weight to interior angle.
4. Draw conclusions about the two-dimensional nature of force.

Think It Through

- Which clothesline will be under the greatest tension, assuming that both pairs of pants are identical? Why? [Hint: Review your results from the Quick Lab.]



- If the tension in the ropes remains the same, what angle, θ, between the two ropes would result in the greatest force in the direction of motion?

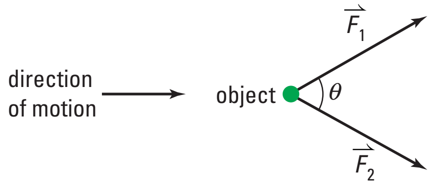


Figure 4.16 Which way does the net force act?

Thus far, you have performed force calculation for cases in which the direction of the net force was obvious. However, in many cases, the direction of the net force is not clear. Before you solve the problem, you must first find the magnitude and direction of the net force. Fortunately, the methods for adding and subtracting vectors involved in motion can be applied to any vector quantity.

Young children provide wonderful examples of the vector nature of forces. If you have ever had two children pulling each of your arms in different but not opposite directions, then you have witnessed the vector nature of forces. One child pulls you in one direction, the other pulls you in another direction, and you end up moving in a third direction that is actually determined by the vector sum of the original two forces.

MODEL PROBLEMS

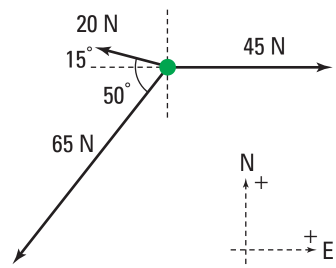
Forces in Two Dimensions

1. **Three children are each pulling on their older sibling, who has a mass of 65 kg. The forces exerted by each child are listed here. Use a scale diagram to determine the resultant acceleration of the older sibling.**

$\vec{F}_1 = 45\text{ N[E]}$
$\vec{F}_2 = 65\text{ N[S}40^\circ\text{W]}$
$\vec{F}_3 = 20\text{ N[N}75^\circ\text{W]}$

Frame the Problem

- The force of gravity on the older sibling is balanced by the normal force of the ground. Therefore, you can neglect vertical forces because there is no motion in the vertical plane.
- Draw a free body diagram representing horizontal forces on the older sibling.
- The *net force* in the horizontal plane will determine the magnitude and direction of the *acceleration* of the older sibling,
- *Newton's second law* applies to this problem.



Identify the Goal

The acceleration, $\vec{a}$, of the older sibling

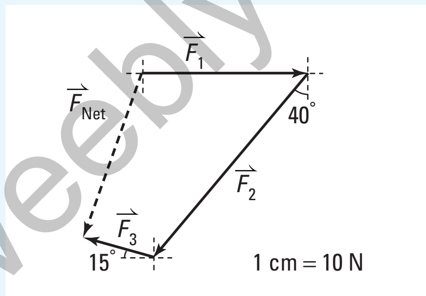
Variables and Constants

Involved in the problem		Known	Unknown
$\vec{F}_1$	$\vec{a}$	$\vec{F}_1 = 45$ N[E]	$\vec{a}$
$\vec{F}_2$	θ	$\vec{F}_2 = 65$ N[S40°W]	θ
$\vec{F}_3$		$\vec{F}_3 = 20$ N[N75°W]	

Strategy

Draw a scale diagram, adding the vectors "tip to tail."
If you need review, turn to Table 3.1 on page 91.

Calculations



Measure the length of the resultant force vector.

$$|\vec{F}_{net}| = 4.8 \text{ cm}$$

Use the scale factor to determine the magnitude of the force.

$$|\vec{F}_{net}| = (4.8 \cancel{\text{cm}})\left(\frac{10 \text{ N}}{\cancel{\text{cm}}}\right)$$

$$|\vec{F}_{net}| = 48 \text{ N}$$

Use a protractor to measure the angle.

$$\theta = [\text{S}20°\text{W}]$$

Use Newton's second law in terms of acceleration.

$$\vec{a} = \frac{\vec{F}}{m}$$

$$\vec{a} = \frac{48 \text{ N}[\text{S}20°\text{W}]}{65 \text{ kg}}$$

$$\vec{a} = 0.7385 \frac{\frac{\cancel{\text{kg}} \cdot \text{m}}{\text{s}^2}[\text{S}20°\text{W}]}{\cancel{\text{kg}}}$$

$$\vec{a} = 0.7385 \frac{\text{m}}{\text{s}^2}[\text{S}20°\text{W}]$$

The older sibling will have an acceleration of 0.74[S20°W].

Validate

The acceleration value is reasonable. Units cancelled to give $\frac{\text{m}}{\text{s}^2}$ which is correct for acceleration.

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2. Solve the same problem using the method of components rather than a scale diagram.

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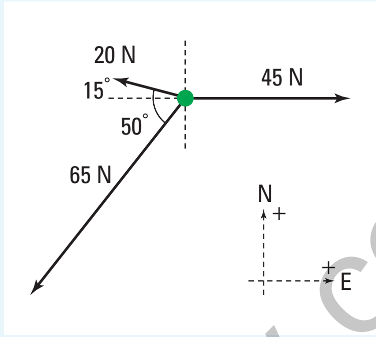
Frame the Problem

- The force of gravity on the older sibling is balanced by the normal force of the ground. Therefore, you can neglect vertical forces because there is no motion in the vertical plane.
- Draw a free body diagram representing horizontal forces on the older sibling.
- The *net force* in the horizontal plane will determine the magnitude and direction of the *acceleration* of the older sibling,
- *Newton's second law* applies to this problem.

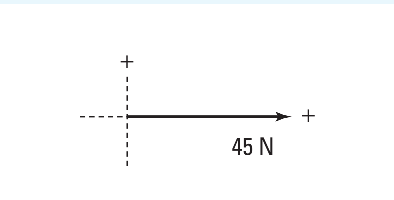


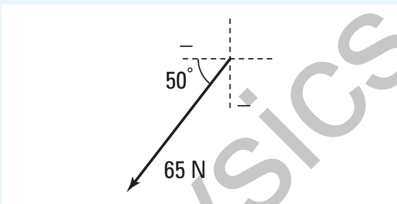
Identify the Goal

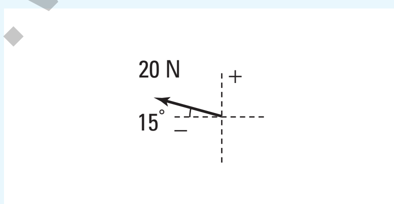
The acceleration, $\vec{a}$, of the older sibling

Strategy and Calculations

Draw each vector with its tail at the origin of an x–y-coordinate system where $+y$ coincides with north and $+x$ coincides with east.







Find the angle with the nearest x-axis.

East coincides with the x-axis so the angle is 0°

In the angle [S40°W], the 40° angle is with the $-y$-axis. The angle with the $-x$-axis is $90° - 40° = 50°$

In the angle [N75°W] the 75° angle is with the $+y$-axis. The angle with the $-x$-axis is $90° - 75° = 15°$

Find the x-component of each force vectors.

$F_{1x} = |\vec{F}_1| \cos 0°$

$F_{1x} = (45\text{ N})(1.000)$

$F_{1x} = 45\text{ N}$

$F_{2x} = -|\vec{F}_2| \cos 50°$

$F_{2x} = -(65\text{ N})(0.6428)$

$F_{2x} = -41.78\text{ N}$

The angle is in the third quadrant so x is negative.

$F_{3x} = -|\vec{F}_3| \cos 15°$

$F_{3x} = -(20\text{ N})(0.9659)$

$F_{3x} = -19.32\text{ N}$

The angle is in the second quadrant so x is negative

Find the y-components of each force vector.

$F_{1y} = |\vec{F}_1| \sin 0°$

$F_{1y} = (45\text{ N})(0.0)$

$F_{1y} = 0.0\text{ N}$

$F_{2y} = -|\vec{F}_2| \sin 50°$

$F_{2y} = -(65\text{ N})(0.7660)$

$F_{2y} = -47.79\text{ N}$

The angle is in the third quadrant so y is negative.

$F_{3y} = |\vec{F}_3| \sin 15°$

$F_{3y} = (20\text{ N})(0.2588)$

$F_{3y} = 5.176\text{ N}$

Make a table in which to list the x- and y-components. Add them to find the components of the resultant vector.

Vector	x-component	y-component
$\vec{F}_1$	45 N	0.0 N
$\vec{F}_2$	–41.78 N	–47.79 N
$\vec{F}_3$	–19.32 N	5.176 N
$\vec{F}_{net}$	–16.1 N	–42.614 N

Use the Pythagorean Theorem to find the magnitude of the net force.

$$|\vec{F}_{net}|^2 = (F_{x\ net})^2 + (F_{y\ net})^2$$
$$|\vec{F}_{net}|^2 = (-16.1\ \text{N})^2 + (-42.614\ \text{N})^2$$
$$|\vec{F}_{net}|^2 = 259.21\ \text{N}^2 + 1815.9\ \text{N}^2$$
$$|\vec{F}_{net}|^2 = 2075.163\ \text{N}^2$$
$$|\vec{F}_{net}| = 45.55\ \text{N}$$

Use trigonometry to find the angle θ.

Since both the x- and y-components are negative, the angle is in the third quadrant.

$$\tan\theta = \frac{-41.614\ \text{N}}{-16.1\ \text{N}}$$
$$\tan\theta = 2.619$$
$$\theta = \tan^{-1} 2.619$$
$$\theta = 69.1^\circ$$

The net force on the older sibling is 46 N at an angle of 69° from the x-axis in the third quadrant. This result is equivalent to 46 N[W69°S] or 46 N[S21°W].

Apply Newton's second law in terms of acceleration to find the older sibling's acceleration.

$$\vec{a} = \frac{\vec{F}}{m}$$
$$\vec{a} = \frac{45.55\ \text{N[S21°W]}}{65\ \text{kg}}$$
$$\vec{a} = 0.70077 \frac{\frac{\cancel{\text{kg}} \cdot \text{m}}{\text{s}^2}}{\cancel{\text{kg}}}[\text{S21°W}]$$
$$\vec{a} = 0.70077 \frac{\text{m}}{\text{s}^2}[\text{S21°W}]$$

The acceleration of the older sibling is 0.70 $\frac{\text{m}}{\text{s}^2}$[S21°W].

Validate

Using components gives nearly the same answer as the scale diagram method. You would expect the method of components to yield more accurate results. Also, the units cancelled to give m/s^2 which is correct for acceleration.

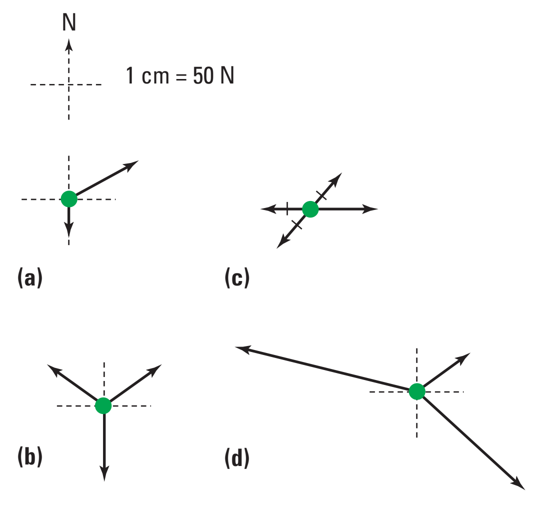
continued ►

continued from previous page

PRACTICE PROBLEMS

15. A swimmer is propelled directly north by a force of 35.0 N. Moving water exerts a second force of 20 N[E]. Use both a scale diagram and a mathematical solution to determine the net force acting on the swimmer.

16. Find the resultant force acting on each object pictured. Obtain values by measuring the vectors.



17. A train car is pulled along the tracks by a force of 1500 N from a pickup truck driving beside the tracks. The rope connecting the truck and the train car makes an angle of 15° to the direction of travel.

(a) Find the component of the pulling force in the direction of travel.

(b) Find the component of the pulling force perpendicular to the direction of travel.

18. A student pushes a 25 kg lawn mower with a force of 150 N. The handle makes an angle of 35° to the horizontal.

(a) Find the vertical and horizontal components of the applied force.

(b) Calculate the normal force supporting the lawn mower while it is being pushed.

(c) Calculate the net force propelling the mower if a frictional force of 85 N exists.

(d) Calculate the horizontal acceleration of the lawn mower. (Remember: Only part of the F_{applied} is parallel to the direction of horizontal acceleration.)

TRY THIS...

Perform each of the following.

- Stretch an elastic band between your hands.
- Gently push a toy across the lab bench.
- Push with all your might on a concrete wall.

Describe what you felt in each situation. Describe the forces that you applied and the forces that you felt applied to you. Draw free body diagrams for each object. Draw free body diagrams of one of your hands for each scenario. Make a general statement about action forces (the forces you applied) and reaction forces (the ones you felt).

Newton's Third Law

For Newton's first and second laws, you focussed on individual objects and all of the forces acting on one specific object. The net force determined the change, or lack of change in the motion of that object. In Newton's third law, you will consider the interactions between two objects. You will not even consider all of the forces acting on the two objects but instead concentrate on only the force involved in the interaction between those two objects.

Newton realized that every time an object exerted a force on a second object, that object exerted a force back on the first.

NEWTON'S THIRD LAW

For every action force on object B due to object A, there is a reaction force, equal in magnitude but opposite in direction, due to object B acting back on object A.

$$\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$$

Newton's third law states that forces always act in pairs. An object cannot experience a force without also exerting an equal and opposite force. There are always *two forces* acting and *two objects* involved. To develop an understanding of Newton's third law, consider something as simple as walking across the room.

If someone asked you what force caused you to start moving across the room after standing still, you might say, "I push on the floor with my feet." Think about that statement. You *push* on the floor. According to Newton's second law, when you exert a force on an object, that object should move. So, by pushing on the floor, you should cause the floor to move. However, many other objects, such as the walls, the subfloor, and other structures are also pushing on the floor, making the sum of all of the forces equal to zero. Therefore, according to Newton's first law, the floor does not move. You cannot explain why you can walk across the room without calling on Newton's third law. According to Newton's third law, when you exert a frictional force on the floor, it exerts an equal and opposite frictional force on you. In reality, the floor pushes on you, propelling you across the floor as shown in Figure 4.17.

Think It Through

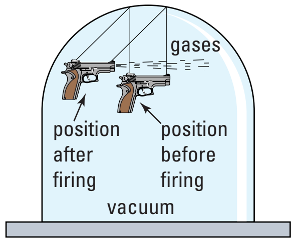
- Draw force diagrams for each of the situations illustrated here.

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following web site: **www.school.mcgrawhill.ca/resources/** and follow the **Physics 11** links for a laboratory activity on Newton's third law.

PHYSICS FILE

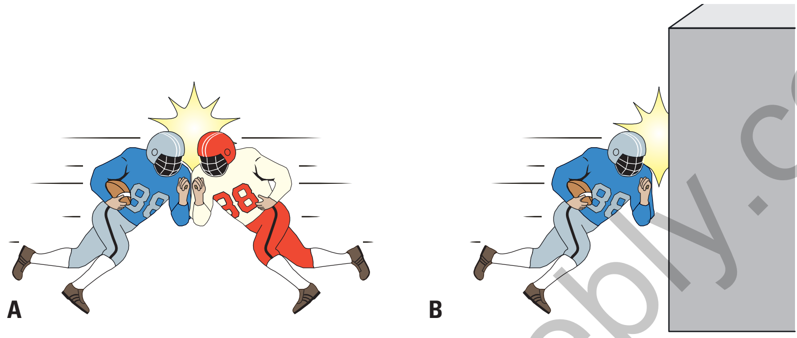
An American physicist, Robert Goddard, published a paper in 1919 that suggested rockets could be used to attain altitudes higher than the atmosphere. Editors of the New York Times ridiculed Goddard, claiming a rocket would not work outside of the atmosphere.



Goddard used the demonstration pictured to show the editors their error.

Figure 4.17 Newton's third law explains how the floor pushes you across the room.

- Look at the illustration of (A) two identical football players colliding and (B) one of the football players travelling with the exact same speed colliding with a wall. Use Newton's third law and compare the forces exerted on each player in both situations. Explain your answer.



Classical mechanics is a powerful tool for analyzing and predicting the behaviour of macroscopic objects. Remember, this term applied to objects large enough to see, such as a chair, a scooter, an ironing board, or a clothesline. Solving problems relating to such objects may require the application of one, two, or even all three of the laws to reach a solution. The laws are valid in all inertial reference frames.

Figure 4.18 Understanding Newton's second law of force and motion.

Concept Organizer

External forces
$\vec{F}_{applied}$
$\vec{F}_g$
$\vec{F}_s$
$\vec{T}$

→ **Newton's 2nd Law** $\vec{F}_{net} = m\vec{a}$

→ **Is $\vec{a} = 0$?**

yes → **Equilibrium**

no → **Non-equilibrium** → **Kinematics equations of motion**

An object's state of motion or rest is determined by vector addition of all external forces acting the object. If the forces sum to zero the object will be in a state of equilibrium – either at rest or in uniform motion. If the forces do not sum to zero, the object will be accelerating.

4.3 Section Review

1. K/U State Newton's first law and give two examples.

2. K/U State Newton's second law and give two examples.

3. K/U State Newton's third law and give two examples.

4. K/U By how much will an object's acceleration change if
   (a) the force is doubled?
   (b) the mass of the object is halved?
   (c) the mass is doubled and the force is halved?

5. K/U State the equal-and-opposite force pairs in each of the following situations:
   (a) kicking a soccer ball
   (b) a pencil resting on a desk
   (c) stretching an elastic band

6. K/U A block of pure gold is perfectly balanced by a 2.0 kg lead mass. Describe what would happen to this setup if it was placed on the Moon.

7. K/U Consider a football player throwing a football. The chart represents action-reaction force pairs from the situation.

Type of force (action-reaction pairs)	Objects involved		
	Player	Ball	Earth
gravitational	✓		✓
normal	✓		✓
friction	✓		✓
normal	✓	✓	
gravitational		✓	✓

   Construct similar charts for each of the following situations.
   (a) A hockey player strikes a puck resting on the ice.
   (b) A person pours water from a bucket toward the ground.

8. K/U Determine the net force in each of the following situations:
   (a) A race car travels at 185 km/h[W].
   (b) Two tug-of-war teams are at a standoff, each pulling with 1200 N of force.
   (c) The Voyager 1 space probe moves at 25 000 km/h in deep space beyond our solar system.

9. K/U Apply Newton's third law to each situation in order to determine the reaction force, magnitude, and direction.
   (a) A soccer ball is kicked with 85 N[W].
   (b) A bulldozer pushes a concrete slab directly south with 45 000 N of force.
   (c) A 450 N physics student stands on the floor.

10. C How would you describe the vector nature of Newton's second law to a friend? Provide at least one example.

UNIT PROJECT PREP

Cartoons are famous for situations in which characters "forget" that forces, such as gravity, exist. When the character "remembers," the consequences are predictably disastrous.

- Can you create a situation where a character forgets that a force or reaction force exists and suffers the consequences?
- How can you use exaggeration to give the illusion of defying Newton's laws? For example, a person running leaps over a two-storey house, or a child moves a refrigerator with one finger.
- Can you reverse an action and its reaction?

4.4 Fundamental Forces of Nature

SECTION EXPECTATIONS

- Identify the four fundamental forces of nature.
- Describe scientific models for the fundamental forces.

KEY TERMS

- exchange particle
- strong nuclear force
- electromagnetic force
- weak nuclear force
- force of gravity
- Grand Unification Theory
- Big Bang
- super force
- Big Crunch

Throughout this chapter, you have been learning how to describe the motion of objects under the influence of forces. You have focussed on the motion resulting from the forces and not on the forces themselves. To some extent, you explored the force of gravity, a non-contact force, and friction, a contact force. You may have wondered about two questions. First, what really happens when two objects come into "contact" with each other? And second, how do non-contact forces extend their influence through apparently empty space? These questions are not trivial, and demand a deeper look at the nature of force in general. In fact, scientists have identified four fundamental forces of nature — electromagnetic, strong nuclear, weak nuclear, and gravitational forces. Physicists have classified all forces that exist as one of these four fundamental forces.

Four Fundamental Forces

What do physicists know about the four forces today and how have they learned about these properties? One important source of information is quantum theory and the study of elementary particles, those particles that make up the familiar proton, neutron, and electron. Current theory holds that material objects interact with each other, exerting forces on each other through **exchange particles**. Specific elementary particles, much less massive than a proton, travel from one object to another "carrying" the force. In this way, each force is "carried" or *mediated* by the exchange of a particle. The properties of these exchange particles then determines the characteristics of the four forces.

Strong Nuclear Force

The **strong nuclear force** is the strongest of the fundamental forces. It is able to overcome the repulsion of positively charged protons, keeping them tightly packed in the nucleus of an atom. The exchange particles of the force are called pions, with other heavy particles also being involved. The strong nuclear force has a very short range, not much longer than the diameter of a proton itself.

Electromagnetic Force

Electric forces and magnetic forces were considered to be separate forces until the 1860s when James Clerk Maxwell was able to demonstrate that they were different manifestations of the same force — the **electromagnetic force**. The electromagnetic force is mediated by a massless particle known as a photon. The massless nature of the photon makes the effective range infinite, even though the strength of the force decreases rapidly as the distance between the objects increases. As described earlier in this chapter, so-called contact forces actually belong to the electromagnetic force category. Two objects may appear to come into contact on a macroscopic scale, but, in fact, it is the repulsion of each material's electrons that are interacting. Therefore, most "everyday" forces (other than gravity) are really examples of the electromagnetic force.

Weak Nuclear Force

Understanding the function of the **weak nuclear force** has been particularly challenging. The weak nuclear force is very weak, 10 000 times weaker than the strong nuclear force. This force acts over the shortest range of any of the fundamental forces. Despite these meagre statistics, the weak nuclear force plays a major role in the structure of the universe. It is an exchange force mediated by the exchange of three different particles called vector bosons. The weak nuclear force is responsible for radioactive decay. Specifically, the weak force changes the flavour (type) of an elementary particle called a quark. When this process occurs, a neutron in the nucleus transforms into a proton.

Gravitational Force

The **force of gravity** is the most familiar to all forces. You have experienced it from the moment you tried to take your first step. Nevertheless, it is the least understood of the four fundamental forces. Newton's model of gravity allows us to carry out the complex calculations required to get humans to the Moon. Einstein's model of gravity actually removes the concept that gravity is a force at all, suggesting instead that it is the result of large masses bending the fabric of space-time.

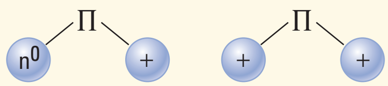
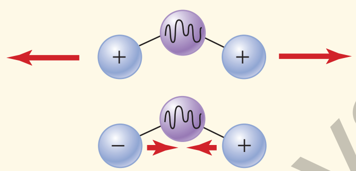
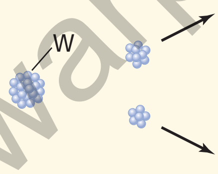
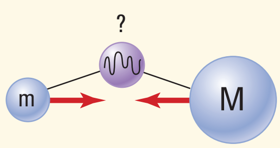
Both models serve their respective purpose, but fail to paint a clear picture as to what gravity really is. Gravity is theorized to be an exchange force with a massless mediating particle called a graviton. The massless nature of the graviton allows gravity to have infinite range similar to the electromagnetic force. However, the graviton is the only exchange particle never to have been detected. Gravity is by far the weakest of the four fundamental forces

Grand Unification Theory

Having four separate and quite different classes of forces is unsettling to many physicists. Since James Clerk Maxwell was able to find a theory that unified the electric and magnetic forces, physicists have searched for a **Grand Unification Theory** to show that all of the observed forces are four manifestations of one single force of nature. Albert Einstein spent the last 20 years of his life searching for a unification theory and failed. Nevertheless, scientists have not given up. With advances in technology, they have been able to dig deeper into the depths of the atom and have gathered a wealth of data. In 1967, three physicists introduced a theory that seemed to successfully unite the weak nuclear force and the electromagnetic force. The search is still on.

Table 4.6 summarizes the properties of the four fundamental forces of nature. The table includes the exchange particles that have been found (using particle accelerators), as well as those that are suspected to exist.

Table 4.6 Fundamental Forces Summary

Fundamental Force	Function	Relative strength	Range	Exchange particle(s)
strong nuclear	 It holds the nucleus of each atom together.	1	10^{-15} m (diameter of a proton)	π (pions), others
electromagnetic	 Like charges repel, unlike charges attract.	1/137	infinite	photon (massless)
weak nuclear	 It is involved in radioactive decay.	10^{-5}	10^{-17} m (1% of the diameter of a proton)	W^+, W^-, Z_0 (vector bosons)
gravity	 Matter attracts matter.	6×10^{-39}	infinite	graviton? (massless)

While elementary particle physicists were looking inside of the atom, even inside protons and electrons, cosmologists were looking out across the universe and back in time to learn more about the four forces of nature.

PHYSICS FILE

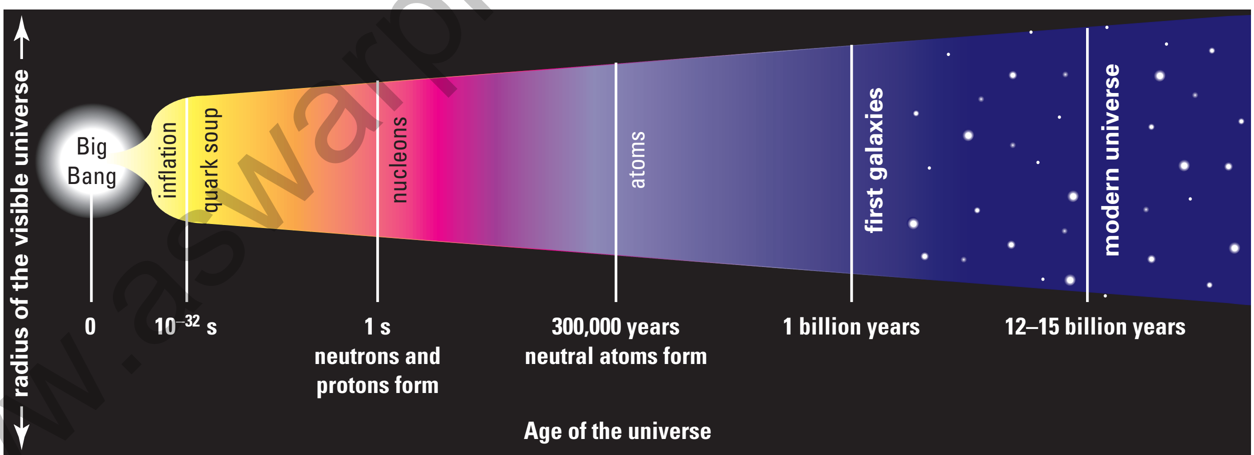
Since many stars are millions of light years away, the light that astronomers are looking at now, left those stars millions of years ago. Astronomers and cosmologists are literally looking at events that occurred millions or even billions of years back in the past.

The Big Bang

Innovative experiments and technological advances continually add to the accumulating data that currently form the basis used to understand the universe. Albert Einstein gave us the now well-tested and widely accepted theory of general relativity, which establishes the relationships among matter, energy, time, and space. Einstein assumed, without discussion, that the universe was static (that is, it remains the same size). A Russian theorist, Aleksander Friedmann, predicted that Einstein's model of the universe would be incredibly unstable. According to the theory, the universe would either collapse in on itself or expand outward to infinity, depending on a relatively small difference in the total mass of the universe.

At the same time, physicists were collecting data that showed that galaxies were moving apart. The data supported the expanding universe idea. If the universe is expanding, then it must have had a beginning or starting point from which the expansion started. As it turns out, Einstein's theory could be adapted to fit an expanding universe. An English physicist, Fred Hoyle, completely discounted the expanding universe theory and nicknamed it the **Big Bang** in an attempt to discredit it. Well, the catchy name stuck, and the theory has held up in the face of masses of data collected over the past 70 years.

Figure 4.19 The Big Bang theory of the origin of our universe pictured as a function of time



Pondering the origins of the universe is fodder for theologians, mystics, philosophers, and scientists. In science, the slow methodical approach is adopted. Only information obtained by experimentation or observation is accepted. Understanding the characteristics of the four fundamental forces of nature is a direct result of this process. Approximately 10 to 20 billion years ago, all of the matter and energy that can be observed in the universe was concentrated in an area smaller than the point of a needle. The minute universe explosively began to expand and cool at an incredible rate. During the first few nanoseconds of the explosion, at the incomprehensibly high temperatures near 10^{32} K, the strengths of the four forces were the same. This unified force is nicknamed the **super force**.

Within about 10^{-4} s, the universe cooled to a temperature of only 100 millions times the temperature of the Sun's core and the four fundamental forces of nature had acquired their present-day characteristics. The Big Bang model of the universe predicts the existence and characteristics of the four fundamental forces. The model also predicts how the formation of matter continued as the energy cooled out into elementary particles, then atomic nuclei, finally forming the host of elements that exist on today's periodic table. Observation and experimentation from several fields of physics have provided the evidence that is helping to unravel the mysteries of our universe.

Astronomy

Giant ground-based telescopes and the Hubble telescope allow astronomers to view distant galaxies billions of light-years away (Figure 4.20), and to see what the universe was like when it was very young.

Particle Physics

Particle accelerators probe into the world of high-energy physics, re-creating environments similar to moments after the Big Bang. Figure 4.21 shows the amazing patterns they find.

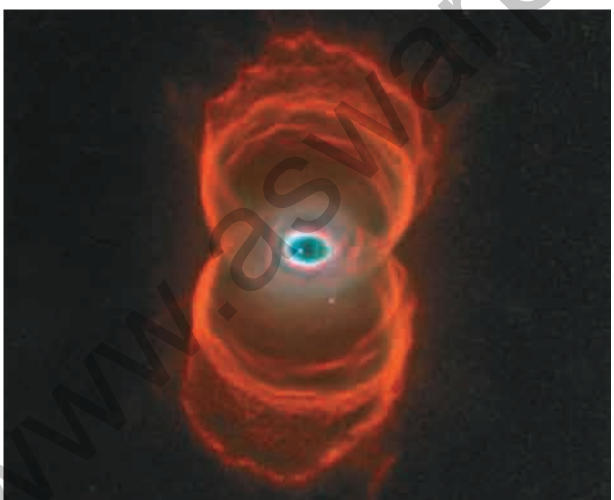


Figure 4.20 The light from some stars has been travelling toward Earth for billions of years.

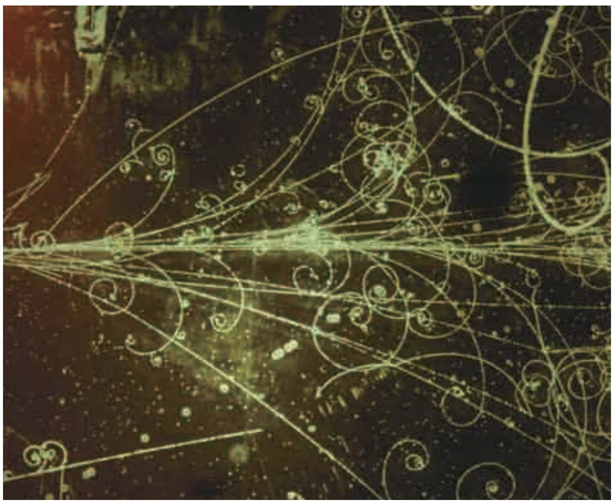


Figure 4.21 Particles of different mass and charge produce different trajectories. You cannot see the particles but you can see their tracks.

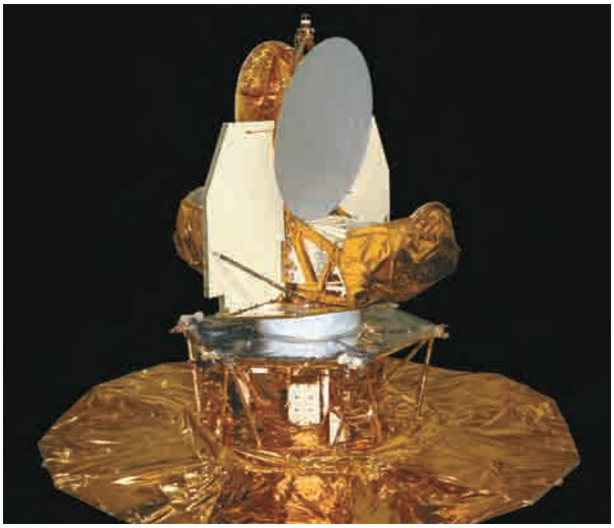


Figure 4.22 This second-generation satellite named MAP, short for Microwave Anisotropy Probe, will continue the analysis of its predecessor COBE (Cosmic Background Explorer). It will be parked at the Second Lagrange point where Earth's gravitational attraction will be exactly matched by the Sun's pull.

REPORT CARD FOR MAJOR THEORIES

Concept	Grade	Comments
The universe evolved from a hotter, denser state	A+	Compelling evidence drawn from many corners of astronomy and physics
The universe expands as the general theory of relativity predicts	A–	Passes the tests so far, but few of the tests have been tight
Dark matter made of exotic particles dominates galaxies	B+	Many lines of indirect evidence, but the particles have yet to be found

Figure 4.23 The Big Bang origin theory of our universe actually refers to several competing explanations as to how the universe came to its present form. This table compares some of the competing ideas and highlights the major feature of each.

Quantum Mechanics

Quantum mechanics, a branch of modern physics that deals with matter and energy on atomic scales, predicts that the four forces of nature were unified until approximately 1×10^{-43} s after the Big Bang.

Satellites

Sophisticated technology is allowing astronomers to peer back to the moment when time began by looking at the background radiation left over from the Big Bang (Figure 4.22). The picture generated from the background radiation data provides the largest-scale view of the universe that is possible.

Theoretical Physics

Working within the framework of the Big Bang theory, several component theories are attempting to answer some intriguing questions, as Figure 4.23 shows.

Big Bang cosmology, or the Standard Cosmological Model as it is also known, is evolving as new theories add to and change certain aspects of it, but it may always leave some questions unanswered. For instance, what was the universe like before the Big Bang? What does the distant future hold for the universe once the last stars exhaust their fuel? What was the nature of the super force? (The super force is the name given to the state when all four fundamental forces, electromagnetic, weak nuclear, strong nuclear,

PHYSICS FILE

The background microwave radiation generated during the Big Bang bathes us on Earth even today. If you have ever used a television set that operates with an antenna rather than cable or satellite, part of the snow observed when a channel is not being received is due to the Big Bang background radiation.

PHYSICS FILE

"The universe is made mostly of dark matter and dark energy," says Prof. Saul Perlmutter, leader of the Supernova Cosmology Project at Berkeley, California, "and we don't know what either of them is." Dark matter may consist of brown dwarf "sub-stars," pure quark "clumps," or something even more exotic. Scientists have long speculated that dark matter may cause a Big Crunch. More recently, dark energy findings suggest that, instead of slowing down, the expansion of the universe may be *accelerating*. This staggering possibility is based on observations that older, more distant supernovas are moving apart more slowly than expected. Since these supernovas come from a much earlier age of the universe, cosmologists now believe that the universe is not only expanding, but doing so at increasing velocities. Dark energy is the only entity that could cause this, almost as if the universe were fizzing like a bottle of baking soda that has been mixed with vinegar.

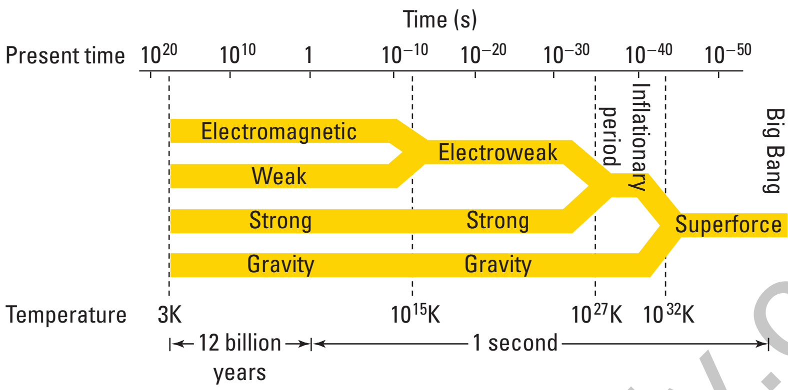


Figure 4.24 Current theory time line of the creation of our universe

and gravity, were united.) How could anything exist with the power to expand our universe to what it is today? Understanding the characteristics of each fundamental force that exists today is the first step in a long road to understanding the unification of the forces.

Figure 4.24 provides a time line detailing when each of the four forces is believed to have obtained its current properties.

Although it is incredibly weak and the least understood of the fundamental forces, gravity has the honour of determining the ultimate fate of the universe — if enough mass exists in the universe, gravity could ultimately stop and reverse the expansion of our universe, leading to what is sometimes referred to as the **Big Crunch**.

4.4 Section Review

1. K/U What evidence first suggested the concept of the Big Bang?
2. K/U List and briefly describe three fields in physics that have aided in providing knowledge about the origin of the universe.
3. K/U Describe each of the four fundamental forces as they exist today.
4. C Prepare a short presentation that you could use to teach a Grade 5 class about the four fundamental forces.
5. K/U It has been suggested that "the weakest of all forces will eventually win out, causing the end of the universe as we know it." Describe what this statement means.
6. K/U According to current theory, how do each of the four fundamental forces exert their influence through empty space?
7. C Summarize the contributions of astronomy, particle physics, quantum mechanics, and mathematical theoretical physicists to our current understanding of the universe.

CHAPTER 4 Review

REFLECTING ON CHAPTER 4

- Inertia is the natural tendency of an object to remain at rest or in uniform motion.
- The amount of inertia depends on the amount of mass of an object.
- The force of gravity acting on an object near a celestial object, such as Earth, is called weight. An object's weight is given by $\vec{F}_g = m\vec{g}$.
- The normal force acts perpendicular to the plane of the surfaces in contact.
- The force of friction is the product of the *coefficient* of friction between the contact surfaces and the *normal force* pressing the objects together ($F_f = \mu F_N$). The force of friction always acts in a direction to oppose motion. The coefficient of friction, μ, is dependent on the types of materials in contact.
- Application of the standard model of friction assumes that
  (a) the force of friction is independent of area of contact
  (b) the force of friction is proportional to the normal force
  (c) the force of friction is independent of the velocity of motion
- Free body diagrams represent all forces *acting on* one object (and only those forces).
- Forces that the object exerts on other objects are *not* shown in a free body diagram.
- The object is represented as a single dot and an arrow is used to represent each force *acting on* the object.
- The direction of each force arrow represents the direction of the force and the arrow's relative length provides information about the magnitude of the force.
- **Newton's 1st law:** An object will stay at rest or in straight-line motion at a constant speed unless acted on by an external force.
- **Newton's 2nd law:** An object will accelerate in the direction of the unbalanced net force. The magnitude of the acceleration will be proportional to the magnitude of the force and inversely proportional to the mass, $\vec{a} = \frac{\vec{F}}{m}$.
- **Newton's 3rd law:** For every action force on object B, there is an equal in magnitude but opposite in direction reaction force acting back on object A. Thus, forces always act in equal and opposite pairs.
- Our current model of the universe categorizes all known forces as one of four distinct types: **strong nuclear**, **weak nuclear**, **electromagnetic**, and **gravitation**. The Standard Cosmological Model suggests that each of these forces took on their physical characteristics moments after the Big Bang.

Knowledge and Understanding

1. Describe three examples of inertia.
2. A small stuffed animal hangs from the rear view mirror of a car turning a corner. Sketch the position of the stuffed animal relative to the mirror during the turn as seen by a passenger. Explain the reason for the perceived movement of the stuffed animal.
3. Astronauts working outside of the space shuttle in Earth orbit are able to move large satellites. One astronaut referred to the satellites not as heavy, but as massive. Explain the astronaut's comment.
4. You are a passenger in a car that is driving on the highway at 100 km/h. Explain, in terms of inertia, what happens to you if the driver brakes suddenly?
5. Consider the motion of an object. State Aristotle's, Buridan's, and Galileo's understanding of what is now termed inertia.
6. If gold were sold by weight, at which of the two locations would you prefer to buy it: At a location on the equator at sea level, or at the North Pole at sea level? If it were sold by mass, where would you prefer to buy it? Explain.

7. Describe how the normal force acting between a block and a board changes when the board-block combination are (a) horizontal and (b) at an angle to the horizontal.
8. State Newton's three laws and provide two examples for each.
9. Scientists have classified all forces that exist as one of four fundamental forces. List and describe the four fundamental forces.

Inquiry

10. Design and carry out an experiment to compare the values of the maximum acceleration of a bus or subway train when speeding up and slowing down. Is the magnitude of the acceleration greater when speeding up or when slowing down?
11. Sketch a graph that shows the velocity of a sky diver through three phases:
    - **(a)** from the time she jumps from the plane to the time when she opens her parachute
    - **(b)** from the time when she opens her parachute to the time when she reaches terminal velocity
    - **(c)** from the time when she reaches terminal velocity, with her parachute fully deployed, until the time when she lands

    Use the graph to make conclusions about the forces acting on the sky diver during each of the three phases of her fall.
12. A sky diver uses a GPS system to measure his velocity every second during a free fall. The recorded velocities at the end of each of the first 5 seconds are 9.5 m/s, 18 m/s, 25 m/s, 30 m/s, and 32 m/s. Plot a velocity-time graph of this free fall, assuming his velocity is 0 m/s at time 0 s. Is the graph linear? What does the shape of the graph imply about the sky diver's acceleration and the forces acting on him during these 5 seconds?
13. In Investigation 4-B on page 165, you varied the force on a dynamics cart and observed the change in the cart's acceleration. Design an experiment to test what happens to the acceleration of the cart when its mass is varied, instead of the force.
14. If it is winter time, design and carry out an experiment to test the success of different kinds of wax in reducing friction on snow skis.

Communications

15. Use a labeled diagram to show the principal forces acting on a car that is slowly braking as it moves towards a stop light. The length of the force vectors should represent their magnitude. Make reference to this diagram to explain why accidents occur when the road is covered with ice.
16. Summarize Newton's three laws of motion in a table with three columns, headed Law, Example, and Catch phrase. In the third column, create a personalized version of each law, such as "You get what you give."
17. Describe three benefits of using free-body diagrams in engineering problems involving the design of bridges.

Making Connections

18. Make a concept map or flow chart showing how Newton's contributions to mechanics enabled scientific discovery and technological application to advance in the centuries following.
19. The work of Newton was so revolutionary for European society that it inspired several contemporary poets to compose poems reflecting on his work. From your perspective, living in the 21st century, create a free-verse poem describing the impact of the scientific revolution of Galileo, Newton, and others in changing our view of nature, society, and technology.
20. List all the sports you can think of that involve an object being propelled at high velocity. Choose one of these sports and describe how the sport has been changed, because of technological advances in the equipment or safety concerns in the use of the equipment.
21. Propose a course of action to a government committee looking into building a high-speed rail link between Montreal, Ottawa, and Toronto. The proposal should consider economic, environmental, political, and safety issues.

Problems for Understanding

22. A piano is to be slid across the floor. It has a mass of 450 kg.

(a) Calculate the normal force supporting the piano.

(b) If the coefficient of static friction between the floor and the piano is 0.35, calculate the minimum amount of force needed to get the piano to move.

(c) Once the piano is moving, a horizontal force of 1.1×10^3 N is necessary to keep it moving at a constant speed. Determine the coefficient of kinetic friction.

23. Draw a free-body diagram to show the magnitude of the forces acting in the following situations:

(a) A person on a scooter uses one of her feet to accelerate forward.

(b) The person glides briefly at a constant speed.

(c) She slows down as she continues to glide.

24. As it moves through the water a 400 kg boat experiences a resistance force of 2 500 N from the air and 3 200 N force of resistance from the water. If the motor provides a forward force of 6 000 N:

(a) Determine the net force.

(b) Calculate the acceleration of the boat.

25. A croquet ball with a mass of 300 g is thrown with an initial velocity of 6.0 m/s[right]. A force of friction of 0.45 N causes the ball to come to a stop. How long did it take the ball to roll to a stop?

26. A cyclist is travelling at 21 km/h when she sees a stop sign ahead. She applies the brakes and comes to a stop in 15 m. The mass of the cyclist and the bike is 73 kg.

(a) Calculate the acceleration of the cyclist.

(b) Determine the coefficient of friction between the road and the bike tires.

27. A water-skier is being pulled behind a boat. The skier leaves the wake behind the boat and moves so that the rope makes an angle of 48° with the back of the boat. Calculate the horizontal and vertical components if the tension in the rope is 620 N.

28. A toboggan with a mass of 15 kg is being pulled with an applied force of 45 N at an angle of 40° to the horizontal. What is the acceleration if the force of friction opposing the motion is 28 N?

29. A grocery cart is being pushed with a force of 450 N at an angle of 30.0° to the horizontal. If the mass of the cart and the groceries is 42 kg,

(a) Calculate the force of friction if the coefficient of friction is 0.60.

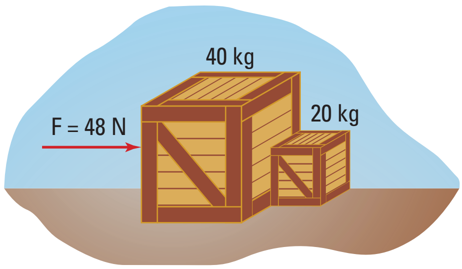
(b) Determine the acceleration of the cart.

30. Calculate the net force if the following three forces are all being applied at the same time: 40 N[S], 60 N[N], and 30 N[N35°E].

31. Two boxes are side by side on a frictionless surface. A horizontal force is applied to move both boxes.

(a) Calculate the acceleration of both boxes.

(b) Determine the force that the 4.0×10^1 kg box applies to the 2.0×10^1 kg box.



Numerical Answers to Practice Problems

1. 23 N **2. (a)** 66.722 kg **(b)** 656.03 N **(c)** 605.81 N
3. $W_{Earth} = 2.05 \times 10^3$ N, $W_{Moon} = 3.43 \times 10^2$ N
4. 3.25×10^{-2} m/s^2 **5. (a)** 5.89 N **(b)** 3.50 N; 0.595 **(c)** μ_k
6. (a) 1.23×10^3 N **(b)** 527 N **(c)** 264 N **7.** 1.95×10^2 N **8.** 0.34
9. 0.55 m/s^2[E] **10.** 0.53 m/s^2[E] **11.** 1.6 m[N] **12. (a)** 5.6 m/s^2
(b) 2.0×10^2 m[E] **13.** 1.7 kg **14.** 0.23 **15.** 40 N[N30°E]
16. (a) 43 N[E] **(b)** 7.4 N[N] **(c)** 15 N[E] **(d)** 15 N[W28°S]
17. (a) 1.4×10^3 N **(b)** 3.9×10^2 N **18. (a)** $F_x = 120$ N, $F_y = -86$ N
(b) 3.3×10^2 N **(c)** 38 N in direction 2.3° below the horizontal **(d)** 1.5 m/s^2

Create Your Own Reality

The zoetrope—an early device for creating "motion pictures."

Background

In this unit, you have studied both how to describe different kinds of motion and how physicists provide explanations of why objects move the way they do. In developing your understanding, you highlighted that objects move in relation to a frame of reference. The manipulation of this relationship between an object and its frame of reference allows film-makers to create different "realities."

Challenge

In groups of three or four, you are to research, write a storyline for, and produce a short animated film sequence, video, or special effects show that demonstrates an aspect of how film-makers use physics to create a virtual reality. Think about how filmmakers make use of the following. In Chapter 2, you examined how an object that is speeding up will have an increasing displacement between each consecutive time frame. In Chapter 3, you explored how objects appear to be moving differently relative to different frames of reference. In Chapter 4, you considered how natural forces cause an object to change speed or direction, although you do not see any physical force being applied. You can also draw on Units 3 and 4 for researching the physics involved in creating optical illusions and virtual realities. Unit 5 will stimulate your thinking about "magic tricks."

Here are the components you are required to include in the project.

A Entertainment Technology
Decide on which era of the entertainment industry you wish to study. You could decide to make one of the early film technologies such as a magic lantern to present your finished product. Or, you may wish to explore software for creating three-dimensional, computer-generated objects.

B The Physics of Motion
Decide what aspect of physics you are going to demonstrate. How do you create the illusion of an object changing speed or direction? How can frames of reference be manipulated to portray a rocket flying off into space when in reality the whole film is created inside a studio? How do special sound or light effects help create a desired virtual reality?

C Plot and Setting
Decide on a situation and short story as a context for your cartoon or film. Your special effects or virtual reality will have more impact if it is based on a believable story.

Web Link

www.school.mcgrawhill.ca/resources/

For more information about computer animation, special effects, and virtual reality, go to the above Internet site. Follow the links for **Science Resources** and **Physics 11** to find out where to go next.

ASSESSMENT

After you complete this project:

- **assess the success of your project based on how similar the final project is to your proposal**
- **assess your project based on how clearly the physical concepts are conveyed**
- **assess your project using the rubric designed in class**

Design Criteria

A. Brainstorm ideas and conduct preliminary research to enhance them.

B. For further ideas, consider some of the following:

- Interview the technical staff of a theatre group about how they create special effects.
- Visit a theme park and note carefully how virtual realities are created. For example, how do they use movable chairs to simulate a thrilling auto race?
- View a digital videodisc (DVD) that contains additional segments that explain how special effects were created. Make notes on the physics involved. Bear in mind that your own effects will be much simpler than those in big-budget movies.

C. Write a proposal for a *manageable* amount of work. Include a flow chart with time lines for tasks for each member of the group.

- If your project is to build an early piece of technology, you will develop relatively few frames. If you are using computer simulations, your animation or video will be longer.
- Part of the evaluation of your project will be the evaluation of your ability to develop a proposal for a reasonable amount of work.

D. Prepare a written presentation of your project, including

- a title page with the names of your group members
- a summary of several pages that lists the technology you used, the aspect of physics that you dealt with, and the reality that you created in your animation sequence, video, or special effects show
- a log of your work, including your proposal, outline of initial research, storyboard, a description of any problems encountered and how you solved them, and a list of references and resources.

Three-dimensional modelling used by engineers is one example of an application of virtual reality.

Action Plan

1. Construct the technology based on self-made or ready-made plans, and become familiar with the operation of the technology.
2. Develop a storyboard (a shot-by-shot sequence of your storyline).
3. Outline the physics that you are using to guide the development of your storyline.
4. Complete production: complete storyboard artwork, block scene-by-scene staging, and film the video or rehearse the live show.
5. Present the completed project.

Evaluate

1. As a class, design a rubric to evaluate the projects, including proposal and presentation.
2. Use your rubric to evaluate your project.

UNIT 1 Review

Knowledge and Understanding

True and False

In your notebook, indicate whether each statement is true or false. Correct each false statement.

1. Average velocity equals distance over elapsed time.
2. On a velocity-time graph the slope equals the acceleration.
3. One walks 10 km north and then 10 km south. His displacement is 20 km.
4. An object falling freely experiences non-uniform acceleration.
5. The order of adding vectors does not matter in determining the resultant.
6. Vectors representing different kinds of quantities can be added and subtracted together.
7. The downstream velocity of a river that flows north has no effect on a boat's westward velocity.
8. An object must experience a force to keep it in motion.
9. Free body diagrams show all forces acting on an object.
10. At any one location, all objects, no matter how massive, fall with the same acceleration if air resistance is ignored.
11. Newtonian Physics is used to solve all force and motion interactions on both the microscopic and macroscopic level.

Multiple Choice:

In your notebook, write the letter of the best answer for each of the following questions.

12. The speed of a vehicle travelling at 90 km/h is equal to:
    (a) 324 m/s **(c)** 129.6 m/s **(e)** none of these
    (b) 0.4 m/s **(d)** 25 m/s
13. A woman walks 15 km[N], 4 km[W], 2 km[S] and 4 km[E]. The resultant displacement is
    (a) 17 km **(c)** 25 km[N] **(e)** 13 km[N]
    (b) 17 km[N] **(d)** 8 km[N]
14. If action and reaction forces are always equal and opposite then why do objects move at all?
    (a) one object has more mass than the other object
    (b) the forces act on different objects
    (c) the reaction forces take over since the action forces acted first
    (d) the reaction force is slower to react because of inertia
    (e) the action and reaction forces are not exactly equal
15. A cable on an elevator exerts a 6 KN upward force. The downward force of gravity on the elevator is also 4 KN. The elevator could be
    (a) moving upward with constant speed.
    (b) moving downward with decreasing speed.
    (c) moving upward with decreasing speed.
    (d) moving downward with increasing speed.
    (e) moving upward with increasing speed.
16. An airplane is moving at constant velocity in a straight level flight. What is the <u>net</u> force acting on the plane?
    (a) zero
    (b) upward
    (c) downward
    (d) in the direction of motion
    (e) opposite to the direction of motion

Short Answer

In your notebook, write a sentence or short paragraph to answer each of the following questions.

17. What could happen in each of the following situations?
    (a) A vehicle tries to come to a stop at a traffic light on an icy street.
    (b) A passenger in a car does not have their seat belt on when the driver must make a quick stop.
    (c) A student has placed their textbooks in the back window of a car. While driving they have to make a sudden stop to avoid driving through a stop sign.
18. Draw a properly labelled graph that illustrates uniformly decreasing acceleration.
19. Distinguish between the average velocity and the instantaneous velocity.
20. Which of the four fundamental forces is the weakest?

21. What is the normal force?

22. What is the difference between static and kinetic frictional forces?

23. (a) What does the slope of the tangent to the curve on a position-time graph represent?
   (b) What does the slope of the tangent to the curve on a velocity-time graph represent?
   (c) What does the area under the curve on a velocity-time graph represent?

Inquiry

24. Design a simple experiment involving the dropping of a coin to test Galileo's ideas of inertia on a train or subway moving with constant velocity. State your hypothesis, and write out a simple procedure. What variables will you need to control? What variable will you measure? If possible, carry out the experiment. What do you conclude?

25. When you stand on your bathroom scales you measure your weight. But what will your scales show if you stand on them in an elevator at the moment when it begins to accelerate up? Down? Design and carry out an experiment to test your hypothesis.

26. You and four of your friends live at five different locations in a large city. You want to find a central meeting place that minimizes the total travel of all five of you. Can you think of a way of solving this problem using elastic bands? If you have found a solution, try it out using a map of the locations of your residences. Can you explain the physics behind how this works?

Communication

27. A jet ski moving at 30 km/h on water can make a 90° turn in a very short distance, while a supertanker moving with the same velocity needs a distance of up to 20 kilometers to turn through the same angle. Explain this phenomenon in terms of Newton's First Law.

28. Create a concept map or graphic organizer that links the "derived" SI units for force, velocity, and acceleration, to the "basic" SI units for distance, mass, and time.

29. Design a section of a new roller coaster and create a schematic diagram of a roller coaster car, with people in it, at several locations on this section. For each location, draw a free body diagram of the forces acting on the car. Based on this, make some safety recommendations for the structural engineer to consider.

30. Create a computer program (i.e., spreadsheet, programming language, etc.) to solve for the magnitude and direction of the resultant force acting on a point, given the magnitudes and directions of the individual forces acting on that point.

Making Connections

31. Propose a course of action to a government committee looking into building a high-speed rail link between Montreal, Ottawa, and Toronto. The proposal should consider economic, environmental, political, and safety issues.

32. How has tire manufacturing technology impacted transportation?

Problems for Understanding

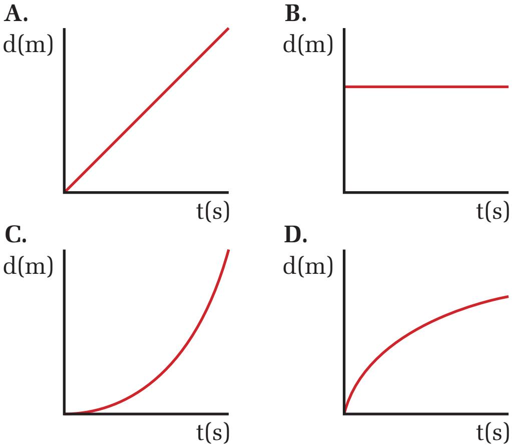
Show complete solutions for all problems that involve equations and numbers.

33. A delivery truck travels 15 km north, then 13 km east and finally heads south for 18 km. Determine the truck's displacement.

34. A car is traveling 5.0×10^1 km/h[N]. It turns a corner and heads down a side street at 4.0×10^1 km/h[E]. Determine the car's change in velocity.

35. A tourist is travelling south to Toronto late at night and has her car set on cruise control. On the highway she sees a sign that says "Toronto 165 km" and notices that it is 10:30 p.m. At 11:00 p.m. she sees a second sign that says "Toronto 110 km".
   (a) How much time passed from when the tourist saw the first sign to when she saw the second sign?
   (b) What is her displacement for the time interval?
   (c) Calculate the velocity of the tourist.

36. Use the position-time graphs below to answer the following questions:



Which graph best describes each situation:

(i) A car is stopped at a stoplight.
(ii) The light turns green, so the car gradually increases in speed.
(iii) A car is travelling on a highway at a constant speed.
(iv) A car slows down as they approach a school zone.

37. A student is late for school. She runs out the door and starts down the street at 8.0 km/h. Three minutes later, her Mom notices that she left her physics homework on the table and immediately runs after her at 12.0 km/h.

(a) How far does she get in 3 minutes
(b) How long does it take her mom to catch her (in minutes)?
(c) How far away from home does her mom catch her?

38. On a highway a car is travelling at 28 m/s[N] when it increases its speed to pass another car. Calculate the acceleration of the car if it reaches a speed of 33 m/s in 2.0 s.

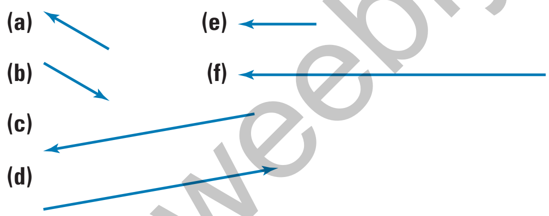
39. How far does a car travel if it accelerates from 22 m/s[W] to 28 m/s[W] at a rate of 3.0 m/s^2?

40. How long does it take a race car, accelerating from a velocity of 6.0 m/s at 4.0 m/s^2 to travel a distance of 216 m?

41. A sprinter is running the 100 m dash. For the first 1.75 s of the race she accelerates from rest to a speed of 5.80 m/s. For the rest of the 100 m she continues at a constant speed. What time did the sprinter achieve for the race?

42. Two vectors X and Y are shown:

Choose from the choices below to answer the following questions:



(i) Which most accurately represents the sum of the vectors X and Y?
(ii) Which most accurately represents the difference of the vectors X and Y, (X − Y)?
(iii) Which most accurately represents the product $(\frac{1}{2}X)$?

43. A person in a kayak paddles across a calm lake at 2.5 m/s[S] for 3.0×10^1 minutes. He then heads east at 2.0 m/s for 2.0×10^1 min.

(a) Calculate the displacement of the kayak from its starting point.
(b) Determine the average velocity for the trip.

44. Jerry watches a stick float downstream in a river and notes that it moves 12 m[E] in 2.0×10^1 s. His friend Ben is starting on the south side of the river and is going to swim across. In still water Ben knows that he can swim with a speed of 1.7 m/s. What is Ben's velocity relative to the shore? If the river is 1.5 km wide, how long will it take Ben to cross the river? How far downstream will he land?

45. A passenger climbs aboard a northbound bus and walks toward the back at a rate of 1.8 m/s. The bus starts off up the street at 9.2 m/s. What velocity will the passenger appear to be walking relative to

(a) a person standing on the sidewalk.
(b) a person who is walking 2.1 m/s south along the sidewalk.
(c) a person who is walking 2.1 m/s north along the sidewalk.

46. A speedboat is towing a water skier. At the beginning of the ride the skier is following straight along behind the boat which is traveling 68 km/h due north. The skier cuts out to the right side so that he is heading at an angle of 48° to the direction of the boat. Calculate the skier's change in velocity if his speed while cutting to the side is 76 km/h.

47. A sailboat is using its motor to travel with a velocity of 42 km/h[E 40.0°S] when a wind from the north starts blowing at 5.0 km/h, what will be the velocity of the sailboat relative to the shore?

48. A pilot wants to land at a small lake that is [N30.0°W] of the airport that she is starting from. The wind has a velocity of 25.0 m/s[W] and the air speed of the plane is 1.90×10^2 m/s. What direction will the plane have to fly to get to its destination? What will be the velocity of the plane relative to the ground?

49. A pitcher throws a baseball with a velocity of 26 m/s[S]. It strikes a player's bat and the velocity changes to 3.0×10^1 m/s[N]. If the player's bat was in contact with the ball for 3.0×10^{-3} s, determine the acceleration of the ball.

50. A cyclist is travelling at 12 m/s[E] when she turns a corner and continues at a velocity of 12 m/s[N]. If the cyclist took 2.5 s to complete the turn, calculate her acceleration.

51. A basketball player is running down the court at 3.0 m/s[N]. It takes him 2.0 s to change his velocity to receive a pass. His acceleration is 1.4 m/s^2[E 5.0° S]. Calculate the new velocity of the player.

52. A toboggan is being pulled with an applied force that is at an angle of 30° to the horizontal.
   - **(a)** Draw a free-body diagram to illustrate all the forces acting on the toboggan.
   - **(b)** Predict the motion of the toboggan if the horizontal component of the applied force is greater than the frictional force.
   - **(c)** Predict the motion of the toboggan if the horizontal component of the applied force is equal to the frictional force.
   - **(d)** Predict the motion of the toboggan if the horizontal component of the applied force is less than the frictional force.

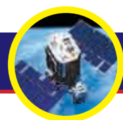
53. A grocery cart has a mass of 32.0 kg. An applied force of 4.00×10^2 N[E] is used to move the cart. The cart starts from rest and the force is applied for 5.0 s.
   - **(a)** Calculate the force of friction acting on the grocery cart if the coefficient of friction between the cart and the asphalt is 0.87.
   - **(b)** Calculate the acceleration of the grocery cart.
   - **(c)** How far does the cart move in 5.0 s?

54. A wagon is used to help deliver papers. There is a force applied at an angle of 25° to the horizontal that causes the wagon to move a distance of 15 m[N] in 10.0 s from rest. There is a force of friction of 3.1 N acting on the 27 kg wagon.
   - **(a)** What is the acceleration of the wagon?
   - **(b)** What is the net force acting on the wagon?
   - **(c)** Calculate the applied force.

55. A tug-of-war has started over a popular toy. One child pulls with a force of 2.0×10^1 N[W], a second child pulls with a force of 15 N[N] and a third child pulls with a force of 4.0×10^1 N[E30°S]. Calculate the net force on the toy.

56. A parachutist jumps from a plane and falls faster and faster through the air. At one point in time her acceleration is 8.0 m/s^2 [down]. If she has a mass of 65 kg, calculate the force of air resistance that is acting opposite to her motion.

COURSE CHALLENGE



Space-Based Power

Consider the following as you begin gathering information for your end-of-course project:

- Analyze the contents of this unit and begin recording concepts, diagrams, and formulas that might be useful.
- As you collect ideas attempt to collect information in a variety of ways, including conceptual organizers, useful web sites, experimental data, and perhaps unanswered questions to help you create your final assessment product.
- Scan magazines, newspapers, and the Internet for interesting information to enhance your project.

UNIT 2

Energy, Work, and Power

OVERALL EXPECTATIONS

DEMONSTRATE how energy and work are related.

DESIGN an experiment to test predictions about the law of conservation of energy and energy transformations.

APPLY your understanding of the principles of energy to athletic performance and athletic equipment.

UNIT CONTENTS

On November 20, 1998, the first piece of the International Space Station lifted off aboard a Russian proton rocket. This launch marked the dawn of a new era in both space science and international co-operation. The collaborative expertise of nearly 100 000 people from 16 different countries is making this immense project possible. In all, 46 separate launches will be required to haul all of the components to this construction site orbiting 400 km above Earth's surface.

Hauling these delicate objects into orbit is a technological feat in itself, requiring millions of tonnes of rocket fuel. Once in orbit, the pieces must be assembled with precision. Much of the delicate work is performed by a new-generation Canadarm called the "Special Purpose Dexterous Manipulator". Larger jobs require the 17 m Canadarm. Both "arms" are part of the Canadian Mobile Services System that is permanently attached to the Space Station.

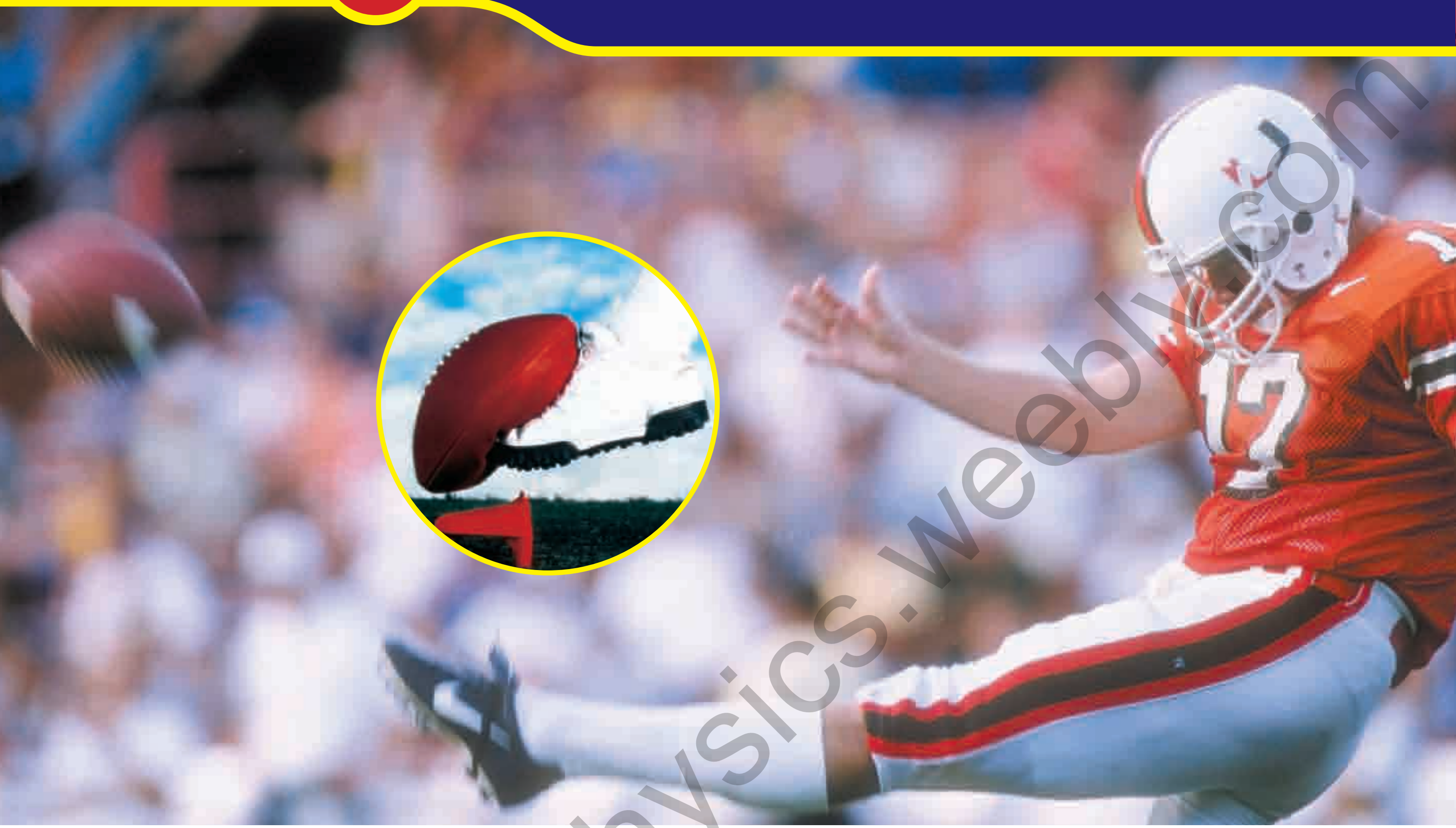
Once the station is assembled, what will keep the robotic arms functioning, the air filters operating, and the inhabitants cozy and warm? The answers to these questions lie in our ability to understand and then manipulate energy. You will begin to appreciate the real significance and accomplishment that the International Space Station represents as you learn to see the world as a physicist does. Understanding energy is the first step to understanding the technological world in which you live.

UNIT INVESTIGATION PREP

In the unit project on pages 318–319 you will analyze a sport or sports equipment. Consider:

- How do skateboarders "jump" their boards?
- What energy transformations are designed into hockey helmets for player protection?

CHAPTER 5 Work and Mechanical Energy



CHAPTER CONTENTS

A football flies through the air. The kicker's foot has just done work on the football, causing it to seemingly defy gravity as it soars high above the field. The kick returner anxiously waits as the ball falls faster and faster toward his arms. The opposing team bears down on him as rapidly as the ball descends. Catching the ball, he runs about six yards. Then you hear the clash of helmets as the opposing tackles bring him to the ground. Although you cannot actually see the energy that has been transferred to the ball and among the players, you most certainly can see and even hear its effects. By simply using your own five senses, you can witness the effects of energy and energy transformations.

Although it may not be obvious, every object you see has some form of energy. When you observe people walking, curtains blowing in the breeze, a jet plane in the distance, or hear the quiet humming of a computer fan, you are detecting evidence of energy transformations. In this chapter, you will learn to understand and describe, both conceptually and mathematically, some important types of energy transformations.

MULTI LAB

Energy Transformations

TARGET SKILLS
- Predicting
- Analyzing and interpreting
- Communicating results

Hit a Block

Suspend a mass on a string as shown in the photo. Keeping the string taut, pull the mass upward away from the block. Release the mass so it is free to swing down and strike the stationary block. Predict how varying the height of the mass will affect the motion of the block after it is hit by the mass. Repeat the procedure several times, holding the mass at different heights.

Analyze and Conclude

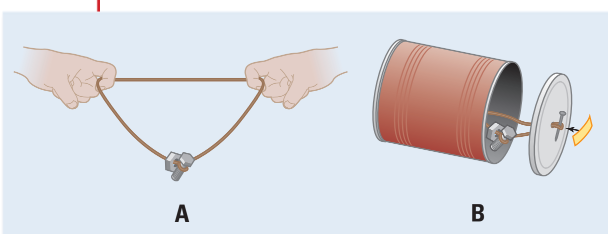
1. What force causes the mass to swing?
2. Using technical terms, write a statement that describes the relationship between the height of the block and the resulting motion of the mass.

Come-Back Can

Obtain a hammer, two nails, one elastic band, a coffee can, tape, and items to act as weights. Attach your weights to *one* side of the elastic band with a string. Punch a hole in the centre of the plastic lid and the bottom of the can. Slip the elastic band through each hole. Ensure that the weights are in the centre of the elastic band. Put a nail through the loop of the elastic band and securely tape everything in place.

Analyze and Conclude

1. On a smooth, flat surface, gently roll the can away from yourself.
2. Release the can and describe what happens.
3. Suggest an explanation for what you observed.



Wind-Up Toy

Your task is to develop a relationship between the number of turns used to wind a toy car and the distance the toy travels. Devise a method to ensure that the toy travels in a straight line.

Analyze and Conclude

1. How is energy stored in the toy when you wind it up?
2. What causes the toy to move?
3. What force causes the toy to stop?
4. Make a general statement about the number of winding turns and energy.
5. Make a general statement about the number of winding turns and the distance travelled.
6. What happened to the stored energy?

5.1 Work and Energy

SECTION EXPECTATIONS

- Describe the requirements for doing work.
- Analyze and interpret experimental data representing work done on an object.
- Identify the relationship between work done and displacement along the line of force.

KEY TERMS

- kinetic energy
- potential energy
- mechanical energy
- work
- joule

Each morning, people throughout Canada perform the same basic activities as they prepare for the day ahead. The ritual might begin by swatting the alarm clock, turning on a light, and heading for a warm shower. Following a quick breakfast of food taken from the refrigerator, they hurry on their way, travelling by family car, bus, subway, train, bicycle, or on foot. This ritual, repeated the world over, demands energy. Electrical energy sounds the alarm, lights the hallways, heats the water, and refrigerates and then cooks the food. Fossil fuels provide the energy for the engines that propel our vehicles. Energy is involved in everything that happens and, in fact, is the reason that everything *can* happen.

Figure 5.1 One thousand cars could be driven about 350 km, the distance from Ottawa to Hamilton, with the amount of energy it takes to launch a space shuttle into orbit. That requires 2.5×10^{12} J of energy.

Types of Energy

Physicists classify energy into two fundamental types — **kinetic energy** (the energy of motion) and **potential energy** (energy that is stored). The many different forms of energy, such as light energy, electrical energy, and sound energy that you will study in this and other units, all fit into one of these two categories. In this chapter, you will focus on one form of energy called **mechanical energy**.

The mechanical energy of an object is a combination of kinetic energy and potential energy. For example, the football in the photograph on page 194 has kinetic energy because it is moving. It also has potential energy because it is high in the air. The force of gravity acts on the ball, causing it to fall. As it falls, its speed increases and it gains kinetic energy. The best way to begin to understand energy is to study the relationship between energy and work.

Defining Work

If you have ever helped someone to move, you will understand that lifting heavy boxes or sliding furniture along a rough floor or carpet requires a lot of energy and is hard work. You may also feel that solving difficult physics problems requires energy and is also hard work. These two activities require very different types of work and are examples of how, in science, we need to be very precise about the terminology we use.

In physics, a force does work on an object if it causes the object to move. Work is always done *on* an object and results in a change in the object. **Work** is not energy itself, but rather it is a transfer of mechanical energy. A pitcher does work on a softball when she throws it. A bicycle rider does work on the pedals, which then cause the bicycle to move along the road. You do work on your physics textbook each day when you lift it into your locker. Each of these examples demonstrates the two essential elements of work as defined in physics. There is always a *force* acting on an object, causing the object to move a certain *distance*.

You know from experience that it takes more work to move a heavy table than to move a light chair. It also takes more work to move the table to a friend's house than to move it to the other side of the room. In fact, the amount of work depends directly on the magnitude of the *force* and the *displacement* of the object along the line of the force.

PHYSICS FILE

How much energy is released during a volcanic eruption? The 1998 eruption of Merapi in Indonesia released approximately 840 000 GJ of energy, enough to supply total world energy requirements for over two months. There are currently more than 1300 potentially active volcanoes around the globe.

WORK

Work is the product of the force and the displacement when the force and displacement vectors are parallel and pointing in the same direction.

$$W = F_{\parallel}\Delta d$$

Quantity	Symbol	SI unit
magnitude of the force (parallel to displacement)	$F_{\parallel}$	N (newton)
magnitude of the displacement	Δd	m (metre)
work done	W	J (joule)

Unit Analysis

(force)(displacement) = N · m = J

Note: Both force and displacement are vector quantities, but their product, work, is a scalar quantity. For this reason, vector notations will not be used. Instead, a subscript on the symbol for force will indicate that the force is parallel to the displacement.

Figure 5.2 The joule was chosen as the unit of work in honour of a nineteenth-century physicist, James Prescott Joule.

The derived unit of work, or newton metre (N · m), is called a **joule** (J). One joule of work is accomplished by exerting exactly one newton of force on an object, causing it to move exactly one metre.

The definition for work applies to an individual force, not the net force, acting on an object. As shown in Figure 5.3, two forces are acting on the box. Both forces — the applied force and the force of friction — are doing work. You can calculate the work done by the applied force or the work done by the frictional force.

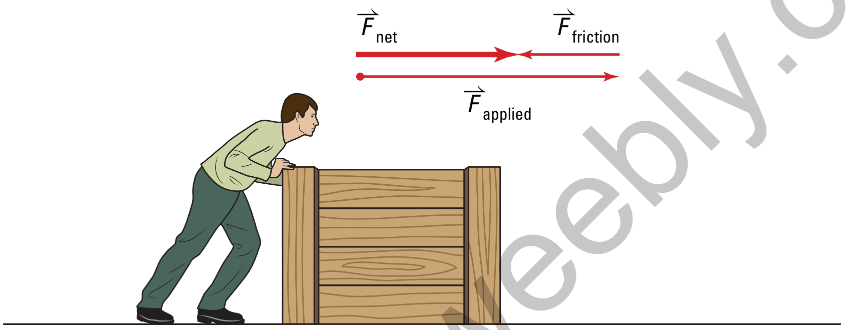


Figure 5.3 When you were determining the motion of objects in Chapter 4, you used the net force acting on the object. The net force is really the vector sum of all of the forces acting on the object. When calculating work, you determine the work done by one specific force, not the net force.

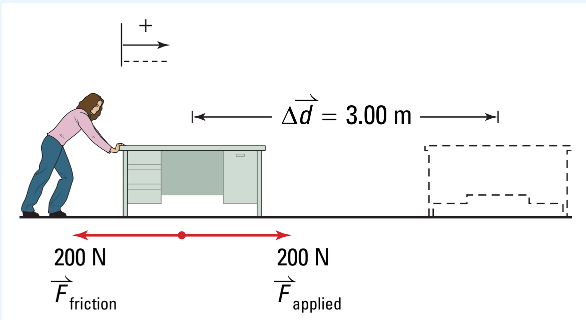
MODEL PROBLEM

Determining the Amount of Work Done

A physics student is rearranging her room. She decides to move her desk across the room, a total distance of 3.00 m. She moves the desk at a constant velocity by exerting a horizontal force of 2.00×10^2 N. Calculate the amount of work the student did on the desk in moving it across the room.

Frame the Problem

- The student *applies a force* to the desk.
- The *applied force* causes the desk to move.
- The *constant velocity* of the desk means that the *acceleration is zero*; thus, the net force on the desk is zero. Therefore, a *frictional force* must be balancing the applied force.
- Since the *force applied* by the student acts in the *same direction* as the *displacement* of the desk, the student is *doing work* on the desk.



Identify the Goal

Amount of work, W, done by the girl on the desk while moving it across the room

Variables and Constants

Involved in the problem	Known	Unknown
Δd	$\Delta d = 3.00$ m	W
F_{applied} (in the direction of the motion)	$F_{\text{applied}} = 2.00 \times 10^2$ N	
W		

PROBLEM TIP

When asked to calculate work done, be sure to identify the force specified by the problem. Then, consider only that force when setting up the calculation. Other forces may be doing work on the object, but you should consider only the work done by the force identified.

Strategy	Calculations
Use the formula for work done by a force acting in the same direction as the motion.	$W = F_{\parallel}\Delta d$
All of the needed variables are given, so substitute into the formula.	$W = (2.00 \times 10^2\ \text{N})(3.00\ \text{m})$
Multiply.	$W = 6.00 \times 10^2\ \text{N} \cdot \text{m}$
An N · m is equivalent to a J, therefore,	$W = 6.00 \times 10^2\ \text{J}$

The student did 6.00×10^2 J of work while moving the desk.

Validate

The applied force was used, because that is the force identified by the problem. The frictional force also did work, but the problem statement did not include work done by friction. Work has units of energy or joules, which is correct.

PRACTICE PROBLEMS

1. A weight lifter, Paul Anderson, used a circular platform attached to a harness to lift a class of 30 children and their teacher. While the children and teacher sat on the platform, Paul lifted them. The total weight of the platform plus people was 1.1×10^4 N. When he lifted them a distance of 52 cm, at a constant velocity, how much work did he do? How high would you have to lift one child, weighing 135 N, in order to do the same amount of work that Paul did?

2. A 75 kg boulder rolled off a cliff and fell to the ground below. If the force of gravity did 6.0×10^4 J of work on the boulder, how far did it fall?

3. A student in physics lab pushed a 0.100 kg cart on an air track over a distance of 10.0 cm, doing 0.0230 J of work. Calculate the acceleration of the cart. (Hint: Since the cart was on an air track, you can assume that there was no friction.)

When Work Done Is Zero

Physicists define work very precisely. Work done on an object is calculated by multiplying the *force* times the *displacement* of the object when the two vectors are *parallel*. This very precise definition of work can be illustrated by considering three cases where intuition suggests that work has been done, but in reality, it has not.

Language Link

"The *condition* of the house has not changed." In this sentence, the term "condition" is used to represent a measurable and obvious change in the total energy of the house. A change in condition would mean that the house gained some form of kinetic or potential energy from the work done by pushing on it. How does kicking a stationary soccer ball change the condition of the ball?

Case 1: Applying a Force That Does Not Cause Motion

Consider the energy that you could expend trying to move a house. Although you are pushing on the house with a great deal of force, it does not move. Therefore, the work done on the house, according to the equation for work, is zero (see Figure 5.4). In this case, your muscles feel as though they did work; however, they did no work on the house. The work equation describes work done by a force that moves the object on which the force is applied. Recall that work is a transfer of energy to an object. In this example, the *condition* of the house has not changed; therefore, no work could have been done on the house.

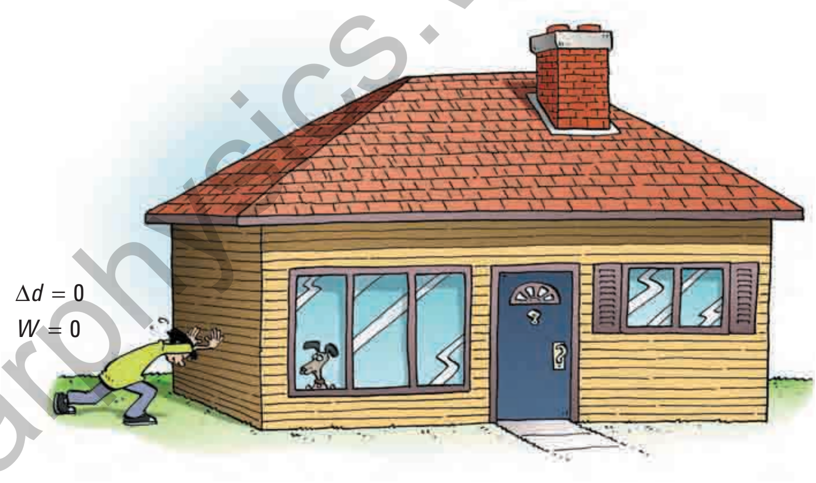


Figure 5.4 $W = F_{\parallel}\Delta d \quad W = F_{\parallel} \times 0 \quad W = 0$

Case 2: Uniform Motion in the Absence of a Force

Recall from Chapter 4 that Newton's first law of motion predicts that an object in motion will continue in motion unless acted on by an *external* force. A hockey puck sliding on a frictionless surface at constant speed is moving and yet the work done is still zero (see Figure 5.5). Work was done to start the puck moving, but because the surface is frictionless, a force is not required to keep it moving; therefore, no work is done on the puck to keep it moving.

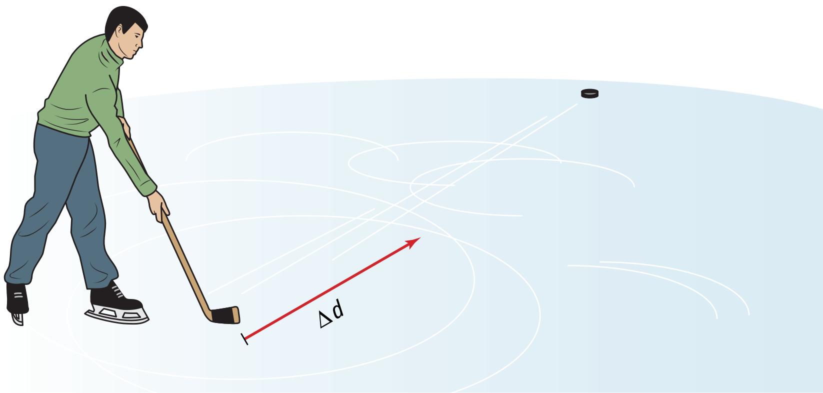


Figure 5.5 $W = F_{\parallel}\Delta d$ $W = 0 \times \Delta d$ $W = 0$

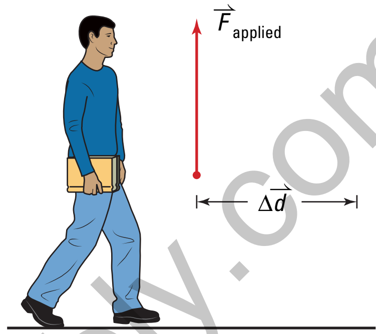
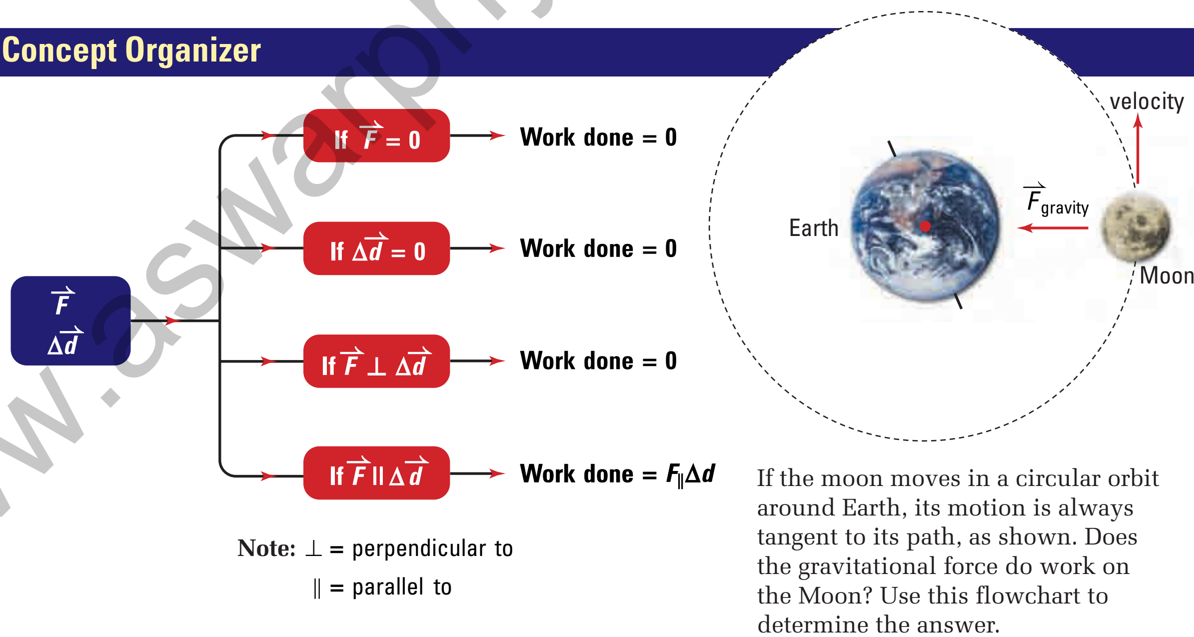


Figure 5.6 You are exerting an upward force (against gravity) on your book to prevent it from falling. However, since this force is perpendicular to the motion of the book, it does no work on the book.

Case 3: Applying a Force That Is Perpendicular to the Motion

Assume that you are carrying your physics textbook down the hall, at constant velocity, on your way to class. Your hand applies a force directly upward to your textbook as you move along the hallway. When considering the work done on the textbook by your hand, you can see that the upward force is perpendicular (i.e., at 90˚) to the displacement. In this case, the work done by your hand on the textbook is zero (see Figure 5.6). It is important to note that your hand does do work on the textbook to accelerate it when you begin to move, but once you and the textbook are moving at a constant velocity, you are no longer doing work on the book.

Concept Organizer



If the moon moves in a circular orbit around Earth, its motion is always tangent to its path, as shown. Does the gravitational force do work on the Moon? Use this flowchart to determine the answer.

Figure 5.7 Making decisions about work done

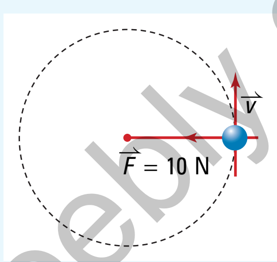
MODEL PROBLEM

Work Done by Swinging a Mass on a String

A child ties a ball to the end of a 1.0 m string and swings the ball in a circle. If the string exerts a 10 N force on the ball, how much work does the string do on the ball during a swing of one complete circle?

Frame the Problem

- The string *applies a force* to the ball.
- The ball is *moving*.
- The direction of the motion of the ball is *perpendicular* to the direction of the force.



Identify the Goal

Amount of work, W, done by the string on the ball

Variables and Constants

Involved in the problem	Known	Unknown
Δd	$\Delta d = 2\pi\ (1.0\ \text{m})$ (circumference of a circle of radius 1.0 m)	W
F_{applied}	$F_{\text{applied}} = 10\ \text{N}$ (perpendicular to the direction of the motion)	$F_{\parallel}$
W		
$F_{\parallel}$		

PROBLEM TIP

When solving problems involving work, consider the following questions.

- Is a force acting on the object to be moved?
- Does the force *cause* displacement of the object?
- Is the force acting in the same direction as the displacement?

If the answer to each question is yes, then you can safely apply the equation for work done. If the answer to any of the questions is no, compare the problem to the cases discussed on pages 200 to 201. The work done might be zero.

Strategy

The force that the string applies on the ball is not in the direction of the motion; therefore, it cannot do work on the ball. No information is given about any possible force that is parallel to the direction of the motion. However, the problem did not ask for work done by any force other than that exerted by the string.

Calculations

The string does no work on the ball as it swings around on the end of the string.

$W = 0\ \text{J}$

Validate

The orientations of the force and displacement vectors fit the conditions described in Case 3. It is not possible for the force to do work. Therefore the work must be zero.

PRACTICE PROBLEMS

4. With a 3.00×10^2 N force, a mover pushes a heavy box down a hall. If the work done on the box by the mover is 1.90×10^3 J, find the length of the hallway.

5. A large piano is moved 12.0 m across a room. Find the average horizontal force that must be exerted on the piano if the amount of work done by this force is 2.70×10^3 J.

6. A crane lifts a 487 kg beam vertically at a constant velocity. If the crane does 5.20×10^4 J of work on the beam, find the vertical distance that it lifted the beam.

7. A teacher carries his briefcase 20.0 m down the hall to the staff room. The teacher's hand exerts a 30.0 N force upward as he moves down the hall at constant velocity.
   (a) Calculate the work done by the teacher's hand on the briefcase.
   (b) Explain the results obtained in part (a).

8. A 2.00×10^2 N force acts horizontally on a bowling ball over a displacement of 1.50 m. Calculate the work done on the bowling ball by this force.

9. The *Voyager* space probe has left our solar system and is travelling through deep space, which can be considered to be void of all matter. Assume that gravitational effects may be considered negligible when *Voyager* is far from our solar system.
   (a) How much work is done on the probe if it covers 1.00×10^6 km travelling at 3.00×10^4 m/s?
   (b) Explain the results obtained in part (a).

10. An energetic group of students attempts to remove an old tree stump for use as firewood during a party. The students apply an average upward force of 650 N. The 865 kg tree stump does not move after 15.0 min of continuous effort, and the group gives up.
    (a) How much work did the students do on the tree stump?
    (b) Explain the results obtained in part (a).

Work Done by Changing Forces

We have restricted our discussion so far to forces that remain constant throughout the motion. However, the definition of work as given by $W = F_{\parallel}\Delta d$ applies to all cases, including situations where the force changes. Mathematically, solving problems with changing forces goes beyond the scope of this course. However, you can use a graph to approximate a solution without using complex mathematics. A force-versus-position graph allows you to determine the work done, whether or not the force remains constant. Examine Figure 5.8, in which the graph shows a constant force of 10 N acting over a displacement of 4.0 m. The area under the force-versus-position line is given by the shaded rectangle.

$$\begin{aligned}\text{Area under the curve} &= \text{area of the shaded rectangle}\\ &= \text{length} \times \text{width}\\ &= (10\text{ N})(4.0\text{ m})\\ &= 40\text{ N}\cdot\text{m}\\ &= 40\text{ J}\end{aligned}$$

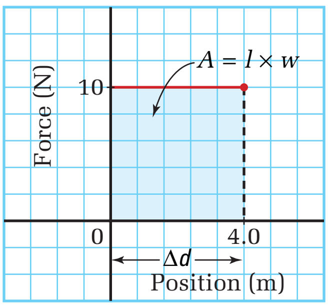


Figure 5.8 The length of the shaded box is $F_{\parallel} = 10$ N. The width is $\Delta d = 4.0$ m. Therefore, the area is $F_{\parallel} \times \Delta d = 40$ N · m. The area under the curve is the same as the work done by the force.

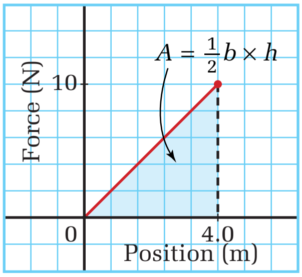


Figure 5.9 When the force increases linearly, the average force can be calculated by using the equation

$$F_{\text{ave}} = \tfrac{1}{2}(F_{\text{initial}} + F_{\text{final}})$$

The area under the curve is in the shape of a triangle. Thus, the work done can be calculated by calculating the area of the triangle.

This result is identical to the one obtained by applying the equation for the work done: $W = F_{\parallel}\Delta d$.

$$\begin{aligned} W &= F_{\parallel}\Delta d \\ &= (10\ \text{N})(4.0\ \text{m}) \\ &= 40\ \text{N}\cdot\text{m} \\ &= 40\ \text{J} \end{aligned}$$

A force-versus-position graph can be used to determine work done even when the applied force does not remain constant. Consider the force-versus-position graph in Figure 5.9. It shows a force that starts at zero and increases steadily to 10 N over a displacement of 4.0 m. In this case, the area under the curve forms a triangle. Even though the force does not remain constant, it is still possible to calculate the work done by finding the area of the triangle.

$$\begin{aligned} \text{Work done} &= \text{area under the force-versus-position curve} \\ &= \text{area of the triangle} \\ &= \tfrac{1}{2}\text{base} \times \text{height} \\ &= (0.5)(4.0\ \text{m})(10\ \text{N}) \\ &= 20\ \text{N}\cdot\text{m} \\ &= 20\ \text{J} \end{aligned}$$

$$\begin{aligned} \text{Work done} &= \text{average force multiplied by the displacement} \\ &= \tfrac{1}{2}(0\ \text{N} + 10\ \text{N})(4.0\ \text{m}) \\ &= (0.5)(10\ \text{N})(4.0\ \text{m}) \\ &= 20\ \text{N}\cdot\text{m} \\ &= 20\ \text{J} \end{aligned}$$

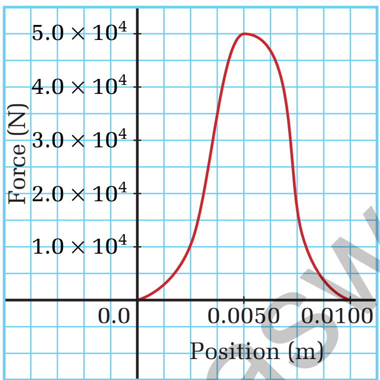


Figure 5.10 Even when a force-versus-position curve is irregular, the area under the curve gives the work done. This curve represents the force of a golf club on the ball when the club strikes the ball.

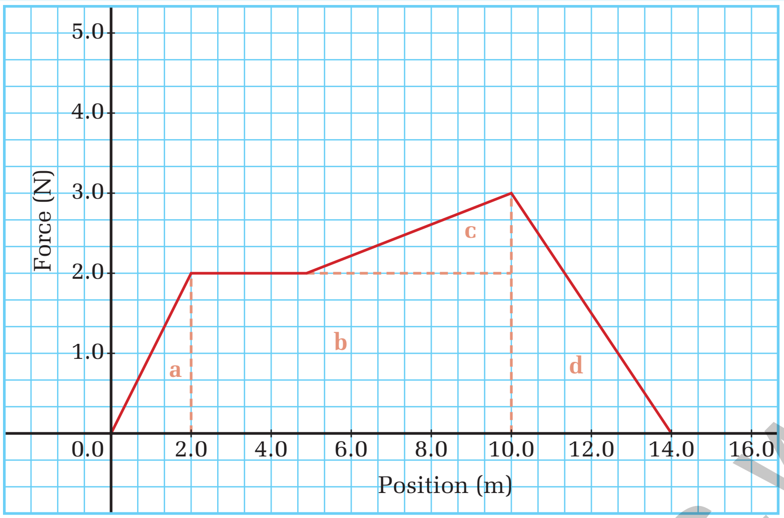
Notice that calculating the area of the triangle yields the same results as the equation for work, if the average force is used. In many situations, however, the applied force changes in a way that makes it difficult to obtain an average force. Solving problems that involve such a changing applied force can be solved using calculus. Since this advanced mathematical technique is not a requirement of this course, you can estimate solutions to problems involving changing forces by estimating the area under a curve, such as the one shown in Figure 5.10.

The force-versus-position curve in Figure 5.10 represents the force exerted on a golf ball by the club when the golfer tees off. Notice how the force changes, reaching a maximum and then falling back to zero. To calculate the area under the curve and, therefore, the work done on the ball by the club, you must count the squares and estimate the area in the partial squares. This method yields a result that is a close approximation to the numerical answer that could be obtained using calculus.

MODEL PROBLEM

Estimating Work from a Graph

Determine the amount of work done by the changing force represented in the force-versus-position plot shown here.



Frame the Problem

- A *changing force* is acting on an object.
- Since the force is not constant, the formula for work does not apply.
- The *area under a force-position curve* is equal to the work done when the units of force and displacement on the graph are used correctly.
- You can divide the area into segments that have simple geometric shapes. Then, use the formulas for the shapes to find the areas. The sum of the areas for each shape gives the total area and, thus, the work done.

Identify the Goal

The work, W, done by the forces represented on the force-versus-position plot

Variables and Constants

Involved in the problem	Known	Unknown
Scale for force and displacement on graph	Scale for force and displacement on graph	A_a
A_a A_b		A_b
A_c A_d		A_c
W		A_d
		W

continued ►

continued from previous page

Strategy	Calculations	
Divide the area under the curve into simple triangles and rectangles, as shown on the plot.		
Calculate A_b, the area of the rectangle b.	Area = base × height base = 10.0 m − 2.0 m = 8.0 m height = 2.0 N − 0.0 N = 2 N	$A = b \times h$ $A_b = (8.0\ \text{m})(2.0\ \text{N})$ $A_b = 16.0\ \text{N} \cdot \text{m}$ $A_b = 16\ \text{J}$
Calculate A_a, the area of triangle a.	Area = $\frac{1}{2}$base × height base = 2.0 m − 0.0 m = 2.0 m height = 2.0 N − 0.0 N = 2 N	$A = \frac{1}{2} b \times h$ $A_a = \frac{1}{2}(2.0\ \text{m})(2.0\ \text{N})$ $A_a = 2.0\ \text{N} \cdot \text{m}$ $A_a = 2.0\ \text{J}$
Calculate A_c, the area of triangle c.	Area = $\frac{1}{2}$base × height base = 10.0 m − 5.0 m = 5.0 m height = 3.0 N − 2.0 N = 1.0 N	$A = \frac{1}{2} b \times h$ $A_c = \frac{1}{2}(5.0\ \text{m})(1.0\ \text{N})$ $A_c = 5.0\ \text{N} \cdot \text{m}$ $A_c = 5.0\ \text{J}$
Calculate A_d, the area of triangle d.	Area = $\frac{1}{2}$base × height base = 14.0 m − 10.0 m = 4.0 m height = 3.0 N − 0.0 N = 3.0 N	$A = \frac{1}{2} b \times h$ $A_d = \frac{1}{2}(4.0\ \text{m})(3.0\ \text{N})$ $A_d = 6.0\ \text{N} \cdot \text{m}$ $A_d = 6.0\ \text{J}$
Find A_T, the total area.	$A_T = A_a + A_b + A_c + A_d$ $= 2.0\ \text{J} + 16.0\ \text{J} + 5.0\ \text{J} + 6.0\ \text{J}$ $= 29.0\ \text{J}$	
Work is equal to the total area under the curve.	$W = 29\ \text{J}$	

The force represented by the graph did 29 J of work.

Validate

By looking at the graph, you can estimate that the average force is close to 2 N. Therefore, a rough estimate of the work would be

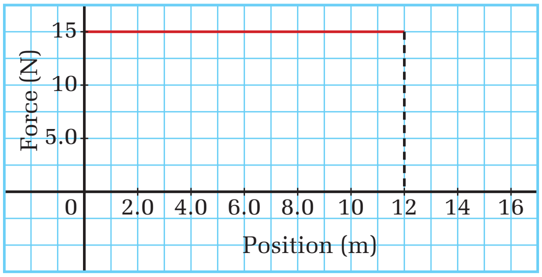
$$\text{Work} \approx 2\ \text{N} \times 14\ \text{m} = 28\ \text{J}$$

This is close enough to give you confidence in the value of 29 J.

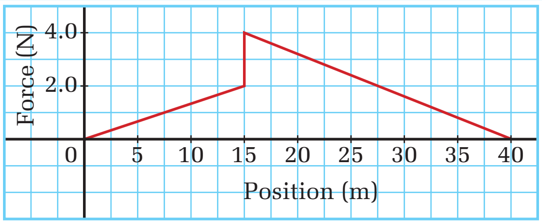
PRACTICE PROBLEMS

11. Determine the amount of work done by the forces represented in the four force-versus-position plots that follow.

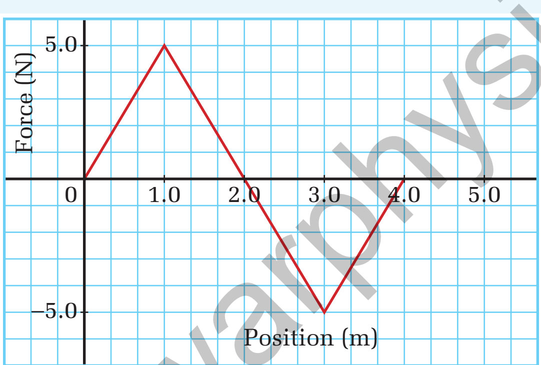
A



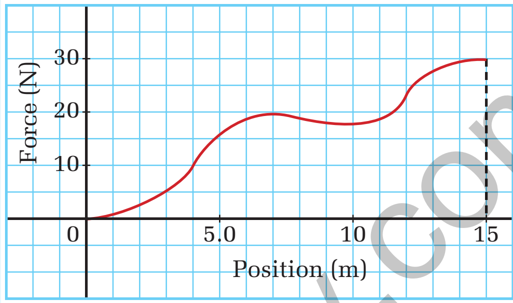
B



C



D



12. Draw a force-versus-position plot that represents a constant force of 60 N exerted on a Frisbee™ over a distance of 80.0 cm. Show the work done on the Frisbee™ by appropriately shading the graph.

13. Stretch a rubber band and estimate the amount of force you are using to stretch it. (Hint: A 100 g mass weighs approximately 1N.) Notice how the force you must exert increases as you stretch the rubber band. Draw a force-versus-position graph of the force you used to stretch the rubber band for a displacement of 15 cm. Use the graph to estimate the amount of work you did on the rubber band.

Constant Force at an Angle

Everyday experience rarely provides situations in which forces act precisely parallel or perpendicular to the motion of an object. For example, in Figure 5.11 on the next page, the applied force exerted by the child pulling the wagon is at an angle relative to the direction of the wagon's displacement. In cases such as this, only part of the force vector or a component of the force does work on the wagon.

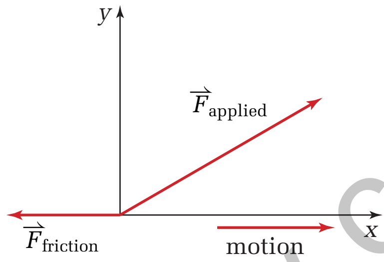


Figure 5.11 To calculate the work done on the wagon, use only the component of the force that is in the direction of the displacement.

To determine the work done by the child on the wagon, you must first find the component of the force that is parallel to the direction of motion of the wagon. The first step in performing this calculation is choosing a coordinate system with one axis along the direction of motion of the wagon. Then, use simple trigonometry to *resolve* the force into its components — one that is parallel to the direction of motion and one that is perpendicular to the

QUICK LAB

Cart Bungee

TARGET SKILLS

- Predicting
- Identifying variables
- Performing and recording

Connect one elastic band between a cart and a force sensor on an inclined slope. Set up a motion sensor to track the position of the cart. Have the computer generate a force-versus-position graph as you release the cart and it moves down the incline until the elastic band stops it. Use the computer software to calculate the area under the force-versus-position curve.

Analyze and Conclude

1. What does the area under the curve on your graph represent?
2. Predict how changing the number of elastic bands will affect the area under the curve.
3. Predict how changing the mass of the cart will affect the area under the curve.
4. What other variables could you change? Predict how they would affect the area under the curve.
5. If you have the opportunity, test your predictions.

direction of motion. As shown in Figure 5.12, the parallel component of the force vector is $F_x = |\vec{F}| \cos \theta$. Note that the angle, θ, is always the angle between the force vector and the displacement vector.

To summarize, when the applied force, $\vec{F}$, acts at an angle to the displacement of the object, use the component of the force parallel to the direction of the motion, $F_x = |\vec{F}| \cos \theta$, to calculate the work done. In these cases, the equation for work is derived as follows.

- This equation applies to cases where the force and displacement vectors are in the same direction and, thus, vector notations are not used. $W = F_{\|}\Delta d$
- This equation applies to cases where the x-component is parallel to the direction of the motion, and thus, vector notations are not used. $W = F_x \Delta d$
- The component of the original force, $\vec{F}$, that is parallel to the displacement $F_x = |\vec{F}| \cos \theta$
- Substitute the expression for F_x into the expression for work. $\therefore W = |\vec{F}| \cos \theta \, \Delta d$

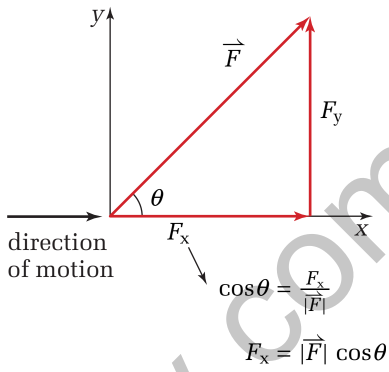


Figure 5.12 To find the horizontal component of the force, start with the definition of the cosine of an angle. Then solve for F_x.

WORK

Work done when the force and displacement are *not* parallel and pointing in the same direction

$$W = F\Delta d \cos \theta$$

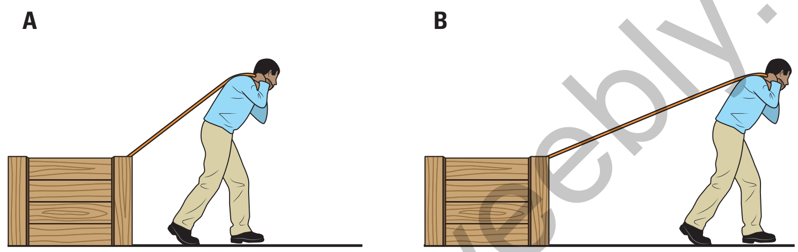
θ is the angle between the force and displacement vectors.

Note: Since work is a scalar quantity and only the magnitudes of the force and displacement affect the value of the work done, vector notations have been omitted.

The example of the child pulling the wagon demonstrates some subtle aspects of the definition of work. Consider the question "Does the force of gravity do work on the wagon?" To answer this, follow the reasoning process outlined in Figure 5.7, the Concept Organizer, on page 201. You can see that the force of gravity is not zero, but that it is perpendicular to the displacement. Therefore, we may conclude that the work done by gravity on the wagon in this case is zero. Note that $F \cos \theta = F \cos 90^\circ = F \times 0 = 0$.

Think It Through

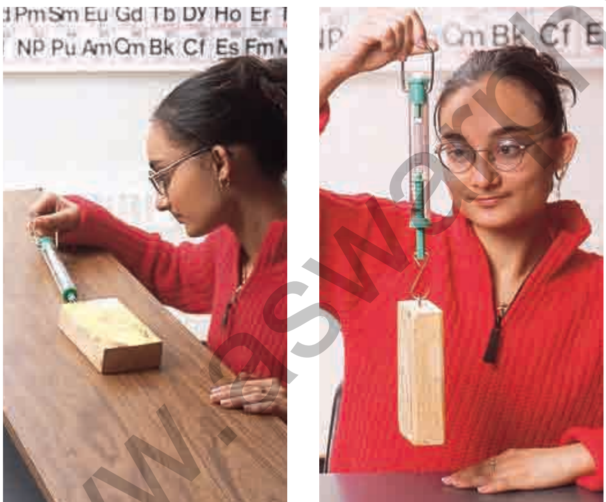
- A child is pulling a wagon up a ramp. The applied force is parallel to the ramp. Is gravity doing any work on the wagon? Explain your reasoning.
- Examine the figure below. Assume that, in both case A and case B, the mass of the crate, the frictional force, and the constant velocity of the crate are the same. In which case, A or B, is the worker exerting a greater force on the crate by pulling on the rope? Explain your reasoning.



QUICK LAB

Elevator Versus a Ramp

TARGET SKILLS
- Predicting
- Performing and recording



What forces are acting on the mass? How will these forces affect its motion?

Set up an inclined plane. Carefully measure both its length and height. Using a Newton spring scale or a force sensor, carefully pull a cart up the incline at a constant velocity. Observe and record the force required. Now lift the cart at a constant velocity through the same height as the incline. Again, record the force required. Predict which method will require more work to accomplish. Calculate the work done in each case.

Analyze and Conclude

1. Compare the work done in each case. How accurate was your prediction?
2. Discuss the experimental variables that most directly affect the work done.
3. Repeat the experiment using a large, rough mass that will slide up the incline rather than roll as the cart did. Predict which method of pulling the large mass will require more work. Was your prediction correct? Why or why not?

Positive and Negative Work

Does the force of friction do work on the mass in Figure 5.13? It is parallel to the displacement, but it is acting in the opposite direction. This means that the angle between the displacement and the force of friction is 180°. Applying the revised equation for work, we find the following results.

Apply the equation for work to this case	$W = F\Delta d \cos 180°$
Because $\cos 180° = (-1)$	$W = F\Delta d(-1)$
Therefore	$W = -F\Delta d$

The work done by the frictional force is non-zero and negative. *Negative work* done by an external force *reduces* the energy of a mass. The energy does not disappear, but is, instead, lost to the surroundings in the form of heat or thermal energy. If the person stopped pulling the mass, its motion would quickly stop, as the frictional force would reduce the energy of motion to zero.

Positive work adds energy to an object; *negative* work removes energy from an object. In many situations, such as the one shown in Figure 5.14, two different forces are doing work on the same object. One force is doing positive work and the other is doing negative work.

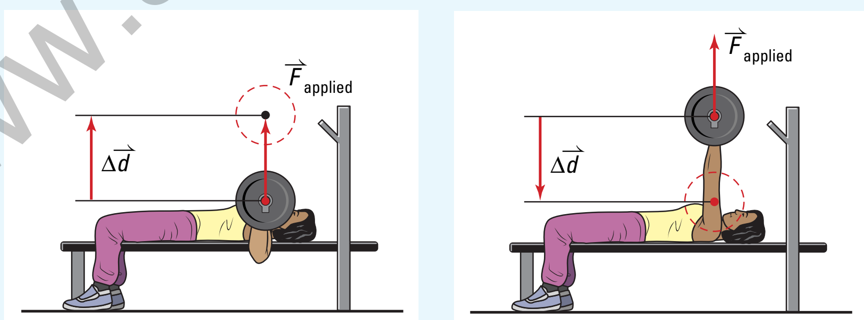
Figure 5.13 In what direction is the force of friction acting?

Figure 5.14 The hammer does positive work on the nail — the applied force and the displacement are in the same direction as the nail moves into the wood. The force of friction does negative work on the nail — the force of friction is opposite to the displacement as the nail moves into the wood. The nail also does negative work on the hammer — the applied force is opposite to the direction of the displacement. The hammer stops moving.

MODEL PROBLEM

Doing Positive and Negative Work

Consider a weight lifter bench-pressing a barbell weighing 6.50×10^2 N through a height of 0.55 m. There are two distinct motions: (1) when the barbell is lifted up and (2) when the barbell is lowered back down. Calculate the work done on the barbell during each of the two motions.



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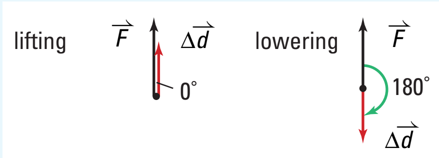
Frame the Problem

- The weight lifter *lifts* and *lowers* the barbell at a *constant velocity*. Therefore, the force *she exerts* is equal to the *weight* of the barbell.
- Use the formula for work when the direction of the force is at an angle with the direction of the displacement.
- Positive work adds energy to the object. Negative work removes energy from the object.
- The angle between the force acting on the barbell and its displacement is
  0° while lifting
  180° while lowering



Identify the Goal

Work, W, done while lifting the barbell

Work, W, done while lowering the barbell

Variables and Constants

Involved in the problem	Known	Unknown
F	$F = 6.50 \times 10^2$[up]	W
Δd	$\Delta d = 0.55$ m[up] while lifting	
θ	$\Delta d = 0.55$ m[down] while lowering	
W	$\theta = 0°$ while lifting	
	$\theta = 180°$ while lowering	

Strategy / Calculations

Use the formula for work when the force is not the same direction as the displacement.

$$W = F\Delta d \cos\theta$$

	Lifting	Lowering
Substitute in the values.	$W = (6.5 \times 10^2\ \text{N})(0.55\ \text{m})\cos 0°$	$W = (6.5 \times 10^2\ \text{N})(0.55\ \text{m})\cos 180°$
Multiply.	$W = 3.65 \times 10^2\ \text{N} \cdot \text{m}\ (+1)$ $W = 3.7 \times 10^2$ J	$W = 3.65 \times 10^2\ \text{N} \cdot \text{m}\ (-1)$ $W = -3.7 \times 10^2$ J

The weight lifter did 3.7×10^2 J of work to lift the barbell and -3.7×10^2 J of work to lower it.

Validate

The barbell gained energy when it was raised. The energy that the barbell gained would become very obvious if it was dropped from the elevated position — it would accelerate downward, onto the weight lifter!

The weight lifter does negative work on the bar to lower it. She is removing the energy that she previously had added to the bar by lifting it. If the weight lifter did not do negative work on the bar, it would accelerate downward.

PRACTICE PROBLEMS

14. A large statue, with a mass of 180 kg, is lifted through a height of 2.33 m onto a display pedestal. It is later lifted from the pedestal back to the ground for cleaning.

(a) Calculate the work done by the applied force on the statue when it is being lifted onto the pedestal.

(b) Calculate the work done by the applied force on the statue when it is lowered down from the display pedestal.

(c) State all of the forces that are doing work on the statue during each motion.

15. A mechanic exerts a force of 45.0 N to raise the hood of a car 2.80 m. After checking the engine, the mechanic lowers the hood. Find the amount of work done by the mechanic on the hood during each of the two motions.

16. A father is pushing a baby carriage down the street. Find the total amount of work done by the father on the baby carriage if he applies a 172.0 N force at an angle of 47° with the horizontal, while pushing the carriage 16.0 m along the level sidewalk.

17. While shopping for her weekly groceries, a woman does 2690 J of work to push her shopping cart 23.0 m down an aisle. Find the magnitude of the force she exerts if she pushes the cart at an angle of 32° with the horizontal.

18. A farmer pushes a wheelbarrow with an applied force of 124 N. If the farmer does 7314 J of work on the wheelbarrow while pushing it a horizontal distance of 77.0 m, find the angle between the direction of the force and the horizontal.

5.1 Section Review

1. K/U In each of the following cases, state whether you are doing work on your textbook. Explain your reasoning.

(a) You are walking down the hall in your school, carrying your textbook.

(b) Your textbook is in your backpack on your back. You walk down a flight of stairs.

(c) You are holding your textbook while riding up an escalator.

2. K/U Your lab partner does the same amount of work on two different objects, A and B. After she stops doing work, object A moves away at a greater velocity than object B. Give two possible reasons for the difference in the velocities of A and B.

3. C Describe two different scenarios in which you are exerting a force on a box but you are doing no work on the box.

4. K/U State all of the conditions necessary for doing positive work on an object.

5. I A student used a force meter to pull a heavy block a total distance of 4.5 m along a floor. Part of the floor was wood, another part was carpeted, and a third part was tiled. In each case, the force required to pull the block was different. The table below lists the distance and the force recorded for the three parts of the trip.

Floor surface	Distance pulled	Force measured
wooden floor	1.5 m	3.5 N
carpet	2.5 m	6.0 N
tiled floor	0.5 m	4.5 N

(a) Use these data to construct a force-versus-distance graph for the motion.

(b) Calculate the total work performed on the heavy block throughout the 4.5 m.

5.2 Kinetic Energy and the Work-Energy Theorem

SECTION EXPECTATIONS

- Analyze the factors that determine an object's kinetic energy.
- Communicate the relationships between work done to an object and the object's change in kinetic energy.
- Use equations to analyze quantitative relationships between motion and kinetic energy.

KEY TERMS

- work-kinetic energy theorem
- work-energy theorem

Simon Whitfield won a gold medal in the triathlon at the Sydney Olympics. Chemical reactions in his muscles caused them to shorten. This shortening of his muscles did work on the bones of his skeleton by exerting a force that caused them to move. The resulting motion of his bones allowed him to run faster than all of his competitors. How can you mathematically describe the motion resulting from the work his muscles did? In this section, you will investigate the relationship between doing work on an object and the resulting motion of the object.

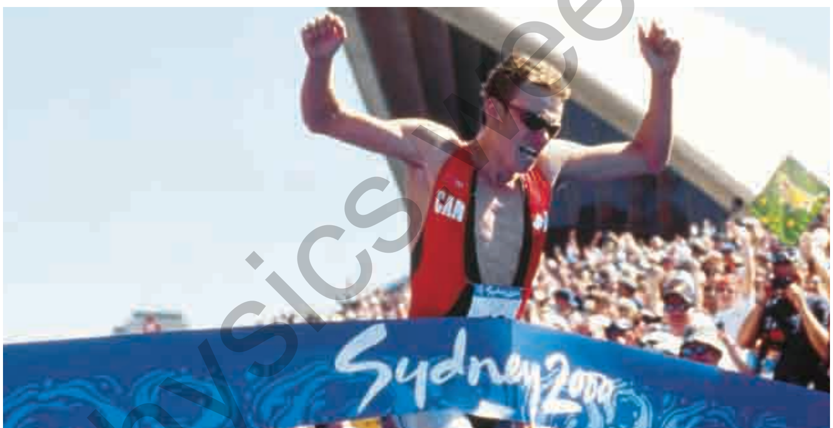


Figure 5.15 Olympic triathlon winner Simon Whitfield crossing the finish line ahead of all of the other competitors.

Kinetic Energy

A baseball moves when you throw it. A stalled car moves when you push it. The subsequent motion of each object is a result of the work done on it. The energy of motion is called kinetic energy. By doing some simple "thought experiments" you can begin to develop a method to quantify kinetic energy. First, imagine a bowling ball and a golf ball rolling toward you with the same velocity. Which ball would you try hardest to avoid? The bowling ball would, of course, do more "work" on you, such as crushing your toe. Since both balls have the same velocity, the mass must be contributing to the kinetic energy of the balls. Now, imagine two golf balls flying toward you, one coming slowly and one rapidly. Which one would you try hardest to avoid? The faster one, of course. Using the same reasoning, an object's velocity must contribute to its kinetic energy. Could kinetic energy be a mathematical combination of an object's mass and velocity?

Dutch mathematician and physicist Christian Huygens (1629–1695) looked for a quantity involving mass and velocity that was characteristic of an object's motion. Huygens experimented with collisions of rigid balls (similar to billiard balls). He discovered that if he calculated the product of the mass and the square of the velocity (i.e. mv^2) for each ball and then added those products together, the totals were the same before and after the collisions. German mathematician Gottfried Wilhelm Leibniz (1646–1716), Huygens' student, called the quantity *vis viva* for "living force." It was many years later, after numerous, detailed observations and calculations, that physicists realized that the correct expression for the kinetic energy of an object, resulting from the work done on it, is actually *one half* of the quantity that Leibniz came up with.

Figure 5.16 When billiard balls collide, the work each ball does on another gives the other ball kinetic energy only.

KINETIC ENERGY

Kinetic energy is one half the product of an object's mass and the square of its velocity.

$$E_k = \frac{1}{2}mv^2$$

Quantity	Symbol	SI unit
kinetic energy	E_k	J (joule)
mass	m	kg (kilogram)
velocity	v	$\frac{\text{m}}{\text{s}}$ (metres per second)

Unit Analysis

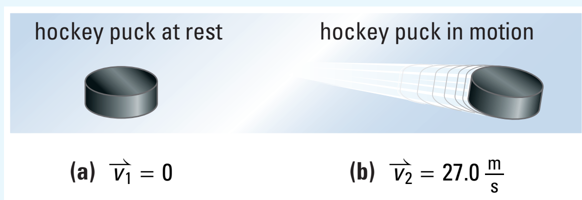
$(\text{mass})(\text{velocity})^2 = \text{kg}\left(\frac{\text{m}}{\text{s}}\right)^2 = \text{kg}\frac{\text{m}^2}{\text{s}^2} = \text{kg}\frac{\text{m}}{\text{s}^2}\text{m} = \text{N} \cdot \text{m} = \text{J}$

Note: When velocity is squared, it is no longer a vector. Therefore, vector notation is not used in the expression for kinetic energy.

MODEL PROBLEM

Calculating Kinetic Energy

A 0.200 kg hockey puck, initially at rest, is accelerated to 27.0 m/s. Calculate the kinetic energy of the hockey puck (a) at rest and (b) in motion.



Frame the Problem

- A hockey puck was *at rest* and was then *accelerated*.
- A moving object has *kinetic energy*.
- The amount of *kinetic energy* possessed by an object is related to its *mass* and *velocity*.

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Identify the Goal

The kinetic energy, E_k, of the hockey puck
at rest
at a velocity of $27.0\ \frac{m}{s}$

PROBLEM TIP

It is very important to carry units through all calculations, as they will provide both a check to see that your work is correct and a hint as to what to do next.

Variables and Constants

Involved in the problem	Known	Implied	Unknown
m	$m = 0.200$ kg	$v_1 = 0.0\ \frac{m}{s}$ (at rest)	E_k
v_1 (at rest)	$v_2 = 27.0\ \frac{m}{s}$ (moving)		
v_2 (moving)			
E_k			

Strategy / Calculations

Strategy	Calculations: At rest	Calculations: Moving
Use the equation for kinetic energy.	$E_k = \frac{1}{2}mv^2$	
All of the needed values are known, so substitute into the formula.	$E_k = \frac{1}{2}(0.200\ \text{kg})\left(0\ \frac{m}{s}\right)^2$	$E_k = \frac{1}{2}(0.200\ \text{kg})\left(27.0\ \frac{m}{s}\right)^2$
Multiply.	$E_k = 0\ \text{kg}\ \frac{m^2}{s^2}$	$E_k = 72.9\ \text{kg}\ \frac{m^2}{s^2}$
$1\ \text{kg}\ \frac{m}{s^2}$ is equivalent to 1 N.	$E_k = 0\ \text{kg}\ \frac{m}{s^2}\ \text{m}$ $E_k = 0\ \text{N} \cdot \text{m}$	$E_k = 72.9\ \text{kg}\ \frac{m}{s^2}\ \text{m}$ $E_k = 72.9\ \text{N} \cdot \text{m}$
1 N·m is equivalent to 1 J.	$E_k = 0$ J	$E_k = 72.9$ J

The puck had zero kinetic energy while at rest, and 72.9 J of kinetic energy when moving.

Validate

A moving object has kinetic energy, while an object at rest has none. The units are expressed in joules, which is correct for energy.

PRACTICE PROBLEMS

19. A 0.100 kg tennis ball is travelling at 145 km/h. What is its kinetic energy?

20. A bowling ball, travelling at 0.95 m/s, has 4.5 J of kinetic energy. What is its mass?

21. A 69.0 kg skier reaches the bottom of a ski hill with a velocity of 7.25 m/s. Find the kinetic energy of the skier at the bottom of the hill.

Table 5.1 Examples of Mechanical Kinetic Energies

Item	Information		
	Mass	Velocity	Kinetic energy
Meteor Crater meteor	3.0×10^4 kg	$9.3 \times 10^6 \ \frac{\text{m}}{\text{s}}$	1.3×10^{18} J
International Space Station	4.44×10^5 kg	$2.74 \times 10^5 \ \frac{\text{km}}{\text{h}}$	1.29×10^{15} J
aircraft carrier	9.86×10^7 kg	$40 \ \frac{\text{km}}{\text{h}}$	6.1×10^9 J
tractor trailer	1.8×10^4 kg	$50 \ \frac{\text{km}}{\text{h}}$	1.7×10^6 J
hockey player	120 kg	$12 \ \frac{\text{m}}{\text{s}}$	8.6×10^3 J
pitched baseball	2.50×10^2 g	$1.00 \times 10^2 \ \frac{\text{km}}{\text{h}}$	9.65 J
person	75 kg	$0.5 \ \frac{\text{m}}{\text{s}}$	9 J
housefly	2.0 mg	$7.2 \ \frac{\text{km}}{\text{h}}$	4.0×10^{-3} J
electron in computer monitor	9.11×10^{-31} kg	$2.0 \times 10^8 \ \frac{\text{m}}{\text{s}}$	1.8×10^{-14} J

*Note that all velocities were converted to m/s and all mass values to kg before calculating the E_k.

Think It Through

- As a car leaves a small town and enters a highway, the driver presses on the accelerator until the speed doubles. By what factor did the car's kinetic energy increase when its speed doubled?
- If two cars were travelling at the same speed but one car had twice the mass of the other, was the kinetic energy of the larger car double, triple, or quadruple the kinetic energy of the smaller car?
- Examine all of the moving objects in the photographs in Figure 5.17, "Visualizing kinetic energy," on the following page, and answer the following questions.
  1. Which moving object probably has the greatest velocity? Explain why you chose that object.
  2. Work is being done on which of the objects in the photos? What is the force doing the work in each case?
  3. Which objects are probably losing kinetic energy?
  4. Which objects are probably gaining kinetic energy?
  5. Which object has the greatest amount of kinetic energy?

Figure 5.17 Visualizing kinetic energy

Work and Kinetic Energy

The special relationship between doing work on an object and the resulting kinetic energy of the object is called the **work-kinetic energy theorem**. Everyday experience supports this theorem. If you saw a hockey puck at rest on the ice and a moment later saw it hurtling through the air, you would conclude that someone did work on the puck, by exerting a large force over a short distance, to make it move. This correct conclusion illustrates how doing work on an object gives the object increased velocity or kinetic energy.

Figure 5.18 Find out how the work done on the hockey puck is related to the puck's kinetic energy.

To develop a mathematical expression that relates work to the energy of motion, assume that all of the work done on a system gives the system kinetic energy only. Start with the definition of work and then apply Newton's second law. To avoid dealing with advanced mathematics, assume that a constant force gives the system a constant acceleration so that you can use the equations of motion from Unit 1. Since work and kinetic energy are scalar quantities, vector notation will be omitted from the derivation. This is valid as long as the directions of the force and displacement are parallel and the object is moving in a straight line.

PHYSICS FILE

Deriving or generating a mathematical equation to describe what you observe in the world is one of the things that theoretical physicists do. The challenge is to make appropriate substitutions from information that you already know and develop a useful relationship.

- Assume that the force is constant and write the equation for work. $W = F_{\parallel}\Delta d$
- Recall Newton's second law, $\vec{F} = m\vec{a}$. Assume the force and the acceleration are parallel to the direction of the displacement and motion is in one direction. Then omit vector symbols and use $F = ma$. $F = ma$
- Substitute ma for F in the equation for work. $W = ma\Delta d$
- Recall, from Chapter 2, the definition of acceleration for uniformly accelerated motion. $a = \dfrac{v_2 - v_1}{\Delta t}$
- Rewrite the equation for work in terms of initial and final velocities by substituting the definition for acceleration into a. $W = m\dfrac{(v_2 - v_1)}{\Delta t}\Delta d$
- Also, from Chapter 2, recall the equation for displacement for uniformly accelerated motion. $\Delta d = \dfrac{(v_1 + v_2)}{2}\Delta t$
- Divide both sides of the equation by Δt to obtain an equation for $\frac{\Delta d}{\Delta t}$. $\dfrac{\Delta d}{\Delta t} = \dfrac{(v_1 + v_2)}{2}$
- Rewrite the equation for work by substituting the value for $\frac{\Delta d}{\Delta t}$. $W = m\dfrac{(v_2 - v_1)(v_1 + v_2)}{2}$
- Expand the brackets (FOIL). $W = \frac{1}{2}m(\cancel{v_1v_2} + v_2^2 - v_1^2 - \cancel{v_1v_2})$
- Simplify by combining like terms. $W = \frac{1}{2}m(v_2^2 - v_1^2)$
- Expand. Notice that the result is in the form of initial and final kinetic energies. $W = \frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$
- Conclude that work done on an object results in a change in the kinetic energy of the object.

$$W = E_{k2} - E_{k1}$$
$$W = \Delta E_k$$

Math Link

Try to derive the work-kinetic energy theorem using the work equation, $W = F_{\parallel}\Delta d$, and the equation of motion, $v_2^2 = v_1^2 + 2a\Delta d$, from Chapter 2. You may prefer this derivation rather than the one illustrated. (Hint: Solve the motion equation for acceleration.)

The delta symbol, Δ, denotes change. The expressions

$$W = \Delta E_k$$
$$W = E_{k2} - E_{k1}$$

are mathematical representations of the work-kinetic energy theorem which describes how doing work on an object can change the object's kinetic energy (energy of motion).

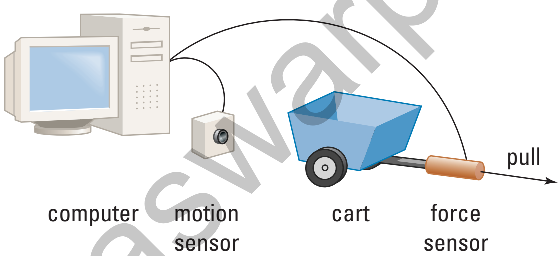
The work-kinetic energy theorem is part of the broader **work-energy theorem**. The work-energy theorem includes the concept that work can change an object's potential energy, thermal energy, or other forms of energy.

Think It Through

- Raj cannot understand why his answer to a problem is wrong. He was trying to calculate the amount of work done by a hockey stick on a hockey puck. The puck was moving slowly when the stick hit it, making it move faster. First, Raj found the difference of the final and initial velocities, and squared the value. He then multiplied his value by the mass of the puck. Finally, he divided by two. Explain to Raj why his answer was wrong. Tell him how to solve the problem correctly.

QUICK LAB
Pulling a Cart

TARGET SKILLS
- Performing and recording
- Analyzing and interpreting
- Communicating results



A baseball bat does a lot of work on a baseball in a very short period of time. If all goes as the batter plans, the result may be a long fly ball. The work-kinetic energy theorem can predict and quantify the work done on the baseball and its resulting motion. In this investigation, you will test the work-kinetic energy theorem using a slightly more controlled environment than a baseball diamond. Set up the force and motion sensors using one interface, as shown in the illustration. (Alternatively, use a Newton scale and ticker tape.) Pull on the cart with the force meter and collect data that will allow you to

- generate a force-versus-position graph
- determine the final velocity of the cart

Analyze and Conclude

1. Determine the total work that you did on the cart.
2. Using your value for work, predict the final speed of the cart.
3. Determine the actual final speed of the cart.
4. Discuss whether your data support the work-kinetic energy theorem.
5. Give possible reasons for any observed discrepancies.

CAREERS IN PHYSICS

Science of the Sole

When the world's athletes take a run at the gold in the Olympics, few people know that a Canadian physicist is running in spirit right beside them. Dr. Benno Nigg, a professor at the University of Calgary and founder and chairperson of its Human Performance Laboratory, is a leading expert in biomechanics. Biomechanics is the science of how living things move. With biomechanics, scientists can determine how dinosaurs really walked, tens of millions of years ago. Biomechanics can also shed light on how humans walk, or, more importantly for athletes, how humans run.

It may sound strange, but there is a lot of physics in the design of running shoes. Dr. Nigg's work demands a precise application of forces, energy, and thermal physics. For example, the hardness of the shoe affects which kinds of muscle fibres are activated. This, in turn, will have an effect on the runner's fatigue. So an in-depth understanding of how the mechanical energy of the impact of the shoe is transmitted to the runner is vital. These discoveries are even now being used by athletics-wear companies to design the next generation of running shoe.

Dr. Nigg's interest in this kind of physics has taken him far. He has won awards from around the world, and is a member of the Olympic Order and the International Olympic Committee Medical Commission. He has consulted for all of the largest sportswear and equipment companies. If you look at the qualifications for researchers and technicians at any of these companies, you will see very quickly that almost every position requires a knowledge of biomechanics. This is truly a career that can bring an interest in sports and an interest in science together.

Dr. Nigg will tell you that, when he first entered the field, his main qualifications were a broad educational background and a deep interest in physics. He says these enabled him to go anywhere: "When you study physics, you open doors."

Dr. Benno Nigg

Going Further

According to Dr. Nigg, the best way to learn about biomechanics and the careers available is to get hands-on experience. Many students don't realize that very often university and corporate laboratories offer summer programs specifically aimed at high school students. Call a local university or an athletics-equipment manufacturer and see what they have to offer.

Web Link

www.school.mcgrawhill.ca/resources/

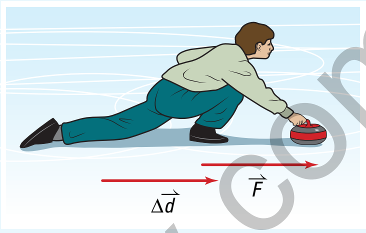
The Internet has a number of excellent resources that can help to explain some of the more difficult concepts and considerations involved in determining how runners run and what we can do to help them run faster. For example, Dr. Nigg's *Biomechanigg* page illustrates a number of these concepts. Go to the web site shown above and click on **Science Resources** and then on **Physics 11** to find out where to go next. Try to create your own method for measuring the forces involved in walking and running.

Applying the Work-Kinetic Energy Theorem

1. A physics student does work on a 2.5 kg curling stone by exerting 4.0×10^1 N of force horizontally over a distance of 1.5 m.

(a) Calculate the work done by the student on the curling stone.

(b) Assuming that the stone started from rest, calculate the velocity of the stone at the point of release. (Consider the ice surface to be effectively frictionless.)



Frame the Problem

- The curling stone was *initially at rest*; therefore, it had *no kinetic energy*.
- The student did *work* on the stone, giving it *kinetic energy*.
- The *force* exerted by the student was in the *same direction* as the *displacement* of the stone; thus, the equation for work applies.
- Since an ice surface has so little friction, we can *ignore* any effects of *friction*.
- The ice surface is level; therefore, there was no change in the height of the stone.
- The *work-kinetic energy theorem* applies to the problem.

Identify the Goal

Work done by the student on the stone
Velocity of the stone at release

Variables and Constants

Involved in the problem		Known	Implied	Unknown
F	v_{initial}	$F = 4.0 \times 10^1$ N	$v_{\text{initial}} = 0\ \frac{\text{m}}{\text{s}}$	W
Δd	$E_{\text{k(final)}}$	$\Delta d = 1.5$ m	$E_{\text{k(initial)}} = 0$ J	$E_{\text{k(final)}}$
W	v_{final}	$m = 2.5$ kg		v_{final}
$E_{\text{k(initial)}}$	m			

Strategy / Calculations

Strategy	Calculations
The formula for work done by a force parallel to the displacement applies.	$W = F_{\parallel}\Delta d$
The values are known, so substitute.	$W = (4.0 \times 10^1\ \text{N})(1.5\ \text{m})$
Multiply.	$W = 6.0 \times 10^1\ \text{N} \cdot \text{m}$
An N·m is equivalent to a J.	$W = 6.0 \times 10^1\ \text{J}$

The student did 6.0×10^1 J of work on the curling stone.

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Strategy

Knowing the work, you can use the work-kinetic energy theorem to find final kinetic energy.

Calculations

$$W = E_{k(final)} - E_{k(initial)}$$

Substitute first

$$W = E_{k(final)} - E_{k(initial)}$$
$$6.0 \times 10^1\ \text{J} = E_{k(final)} - 0\ \text{J}$$
$$6.0 \times 10^1\ \text{J} + 0\ \text{J} = E_{k(final)}$$
$$E_{k(final)} = 6.0 \times 10^1\ \text{J}$$

Solve for $E_{k(final)}$ first

$$W = E_{k(final)} - E_{k(initial)}$$
$$W + E_{k(initial)} = E_{k(final)}$$
$$6.0 \times 10^1\ \text{J} + 0\ \text{J} = E_{k(final)}$$
$$E_{k(final)} = 6.0 \times 10^1\ \text{J}$$

Knowing the final kinetic energy, you can use the formula for kinetic energy to find the final velocity.

$$E_k = \frac{1}{2}mv^2$$

Substitute first

Divide both sides of the equation by the terms beside v^2.

$$6.0 \times 10^1\ \text{J} = \frac{1}{2}(2.5\ \text{kg})v^2$$
$$\frac{6.0 \times 10^1\ \text{J}}{\frac{1}{2}(2.5\ \text{kg})} = \frac{\cancel{\frac{1}{2}(2.5\ \text{kg})}}{\cancel{\frac{1}{2}(2.5\ \text{kg})}}v^2$$
$$48\frac{\cancel{\text{kg}}\,\text{m}^2}{\cancel{\text{kg}}\,\text{s}^2} = v^2$$

Take the square root of both sides of the equation.

$$\sqrt{48\frac{\text{m}^2}{\text{s}^2}} = v$$

Simplify.

$$v = \pm 6.928\ \frac{\text{m}}{\text{s}}$$

Solve for v_{final} first

$$E = \frac{1}{2}mv^2$$
$$\frac{E}{\frac{1}{2}m} = v^2$$
$$\frac{2E}{m} = v^2$$
$$\sqrt{\frac{2E}{m}} = v$$
$$\sqrt{\frac{2(6.0 \times 10^1\ \text{J})}{2.5\ \text{kg}}} = v$$
$$\sqrt{48\frac{\text{kg m}^2}{\text{kg s}^2}} = v$$
$$v = \pm 6.928\ \frac{\text{m}}{\text{s}}$$

The velocity of the stone, on release, was 6.9 m/s.

Validate

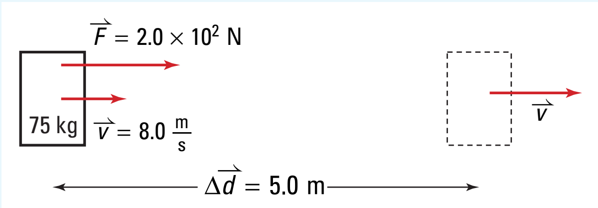
The student did work on the stationary stone, transferring energy to the stone. The stone's kinetic energy increased and, therefore, so did its velocity, as a result of the work done on it.

Notice that *directional information* (±) is *lost* when the *square root* is taken. You must determine which answer (positive or negative) is correct by choosing the one that logically agrees with the situation. In this case, the direction of the applied force was considered positive; therefore, any motion resulting from the application of this force will also be positive.

2. **A 75 kg skateboarder (including the board), initially moving at 8.0 m/s, exerts an average force of 2.0×10^2 N by pushing on the ground, over a distance of 5.0 m. Find the new kinetic energy of the skateboarder if the trip is completely horizontal.**

Frame the Problem

Make a sketch of the force and motion vectors.



- The skateboarder has an *initial velocity* and, therefore, an *initial kinetic energy*.
- He exerts a force by pushing along the ground. As a result, the *ground exerts a force* on him in the *direction of his motion*.
- The ground *does work* on the skateboarder, thus changing his *kinetic energy*.
- Assuming that the friction is negligible, *all of the work* goes into *kinetic energy*. Therefore, the *work-kinetic energy theorem* applies to the problem.

Identify the Goal

The final kinetic energy, E_{k2}, of the skateboarder

A skateboarder does work by pushing on the ground. The work gives the skateboarder kinetic energy.

Variables and Constants

Involved in the problem		Known	Unknown
E_{k1}	W	$v = 8.0 \frac{m}{s}$	E_{k1}
E_{k2}	F	$m = 75$ kg	E_{k2}
v	Δd	$\Delta d = 5.0$ m	W
m		$F = 2.0 \times 10^2$ N	

Strategy

A tree diagram showing relationships among the variables is often helpful when several steps are involved in obtaining a solution.

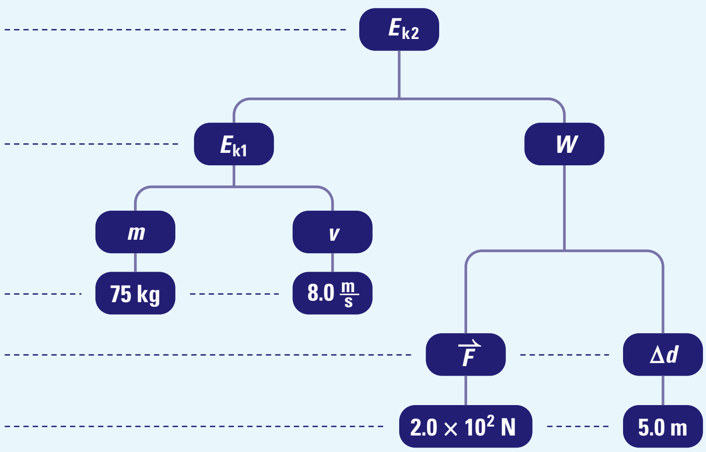
You can calculate final kinetic energy if you can find the initial kinetic energy and the work done.

You can calculate the initial kinetic energy if you know the mass and the initial velocity.

The mass and initial velocity are known.

You can calculate the work done if you can find the force and the displacement.

The force and displacement are known.



The problem is essentially solved. All that remains is the math.

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Strategy	Calculations	
Find the initial kinetic energy by using the formula.	$E_k = \frac{1}{2}mv^2$	
Substitute.	$E_{k1} = \frac{1}{2}(75\ \text{kg})(8.0\ \frac{\text{m}}{\text{s}})^2$	
Multiply.	$E_{k1} = 2.4 \times 10^3\ \text{kg}\ \frac{\text{m}^2}{\text{s}^2}$	
Simplify.	$E_{k1} = 2.4 \times 10^3\ \text{kg}\ \frac{\text{m}}{\text{s}^2}\ \text{m}$	
1 N·m is equivalent to 1 J.	$E_{k1} = 2.4 \times 10^3\ \text{N} \cdot \text{m}$ $E_{k1} = 2.4 \times 10^3\ \text{J}$	
Find work by using the formula.	$W = F_{\parallel}\Delta d$	
Substitute.	$W = (2.0 \times 10^2\ \text{N})(5.0\ \text{m})$	
Multiply.	$W = 1.0 \times 10^3\ \text{N} \cdot \text{m}$	
1 N·m is equivalent to 1 J.	$W = 1.0 \times 10^3\ \text{J}$	
Find the final kinetic energy by using the work-kinetic energy theorem.	$W = E_{k2} - E_{k1}$	
	Substitute first	**Solve for E_{k2} first**
Add E_{k1} or its value to both sides of the equation.	$1.0 \times 10^3\ \text{J} = E_{k2} - 2.4 \times 10^3\ \text{J}$ $1.0 \times 10^3\ \text{J} + 2.4 \times 10^3\ \text{J} = E_{k2}$	$W + E_{k1} = E_{k2}$ $1.0 \times 10^3\ \text{J} + 2.4 \times 10^3\ \text{J} = E_{k2}$
Simplify.	$E_{k2} = 3.4 \times 10^3\ \text{J}$	$E_{k2} = 3.4 \times 10^3\ \text{J}$

The skateboarder's final kinetic energy was 3.4×10^3 J.

Validate

The ground did positive work on the skateboarder, exerting a force in the direction of the motion. Intuitively, this work should increase the velocity and by definition, the kinetic energy, which it did.

PRACTICE PROBLEMS

22. A 6.30 kg rock is pushed horizontally across a 20.0 m frozen pond with a force of 30.0 N. Find the velocity of the rock once it has travelled 13.9 m. (Assume there is no friction.)

23. The mass of an electron is 9.1×10^{-31} kg. At what speed does the electron travel if it possesses 7.6×10^{-18} J of kinetic energy?

24. A small cart with a mass of 500 g is accelerated, uniformly, from rest to a velocity of 1.2 m/s along a level, frictionless track. Find the kinetic energy of the cart once it has reached a velocity of 1.2 m/s. Calculate the force that was exerted on the cart over a distance of 0.1 m in order to cause this change in kinetic energy.

25. A child's toy race car travels across the floor with a constant velocity of 2.10 m/s. If the car possesses 14.0 J of kinetic energy, find the mass of the car.

26. A 1250 kg car is travelling 25 km/h when the driver puts on the brakes. The car comes to a stop after going another 10 m. What was the average frictional force that caused the car to stop? If the same car was travelling at 50 km/h when the driver put on the brakes and the car experienced the same average stopping force, how far would it go before coming to a complete stop? Repeat the calculation for 100 km/h. Make a graph of stopping distance versus speed. Write a statement that describes the relationship between speed and stopping distance.

5.2 Section Review

1. K/U State the work-kinetic energy theorem and list three common examples that effectively support the theorem.

2. C Discuss how the following supports the work-kinetic energy theorem. A cue ball is at rest on a pool table, and then moves after being struck by a pool cue.

3. K/U A pitcher does work, *W*, on a baseball when he pitches it. How much more work would he have to do to pitch the ball three times as fast?

4. K/U Two identical cars are moving down a highway. Car X is travelling twice as fast as car Y. Both drivers see deer on the road ahead and apply the brakes. The forces of friction that are stopping the cars are the same. What is the ratio of the stopping distance of car X compared to car Y?

5. K/U Two cars, A and B, are moving. B's mass is half that of A and B is moving with twice the velocity of A. Is B's kinetic energy four times as great, twice as great, the same, or half as great as A's kinetic energy?

6. I How much force do the tires of a bicycle apply to the pavement when they are braking and/or skidding to a stop? Design and perform an experiment that will help you determine the average braking force indirectly. (It would be very difficult to measure the braking force of skidding tires directly.) Use the work-kinetic energy theorem. It implies that the initial kinetic energy of the bicycle and rider, before the brakes are applied, will be equal to the work done by the brakes and tires in stopping the bicycle.
   (a) What equipment, materials, and tools will you need to determine the initial kinetic energy of the bicycle and rider before applying the brakes? What will you need to determine the stopping distance?
   (b) Develop a procedure that lists all the steps you will follow.
   (c) Repeat the experiment several times with the same rider. Next, repeat it with different riders. What do you conclude?

UNIT INVESTIGATION PREP

Sporting activities and equipment involve a series of energy transformations governed by the work-kinetic energy theorem.

- Identify specific energy transformations related to your project topic.
- Analyze the energy transformations both qualitatively and quantitatively by making appropriate assumptions.

5.3

Potential Energy and the Work-Energy Theorem

SECTION EXPECTATIONS

- Describe the characteristics common to all forms of potential energy.
- Communicate the relationships between work done to an object and the object's change in gravitational potential energy.
- Use equations to analyze situations that change an object's gravitational potential energy.

KEY TERM

- gravitational potential energy

When you do work on an object, will the object always gain kinetic energy? Are there situations where you do work on an object but leave the object at rest? The work done by the student in the photograph is a clear demonstration that an object may remain motionless after work is done on it. In this section, you will consider how doing work on an object can result in a change in potential energy, rather than in kinetic energy. Potential energy is sometimes described as the energy stored by an object due to its *position* or *condition*.

Figure 5.19 When you lift groceries onto a shelf, you have exerted a force on the groceries. However, when they are on the shelf, they have no kinetic energy. What form of energy have the groceries gained?

Potential Energy

Consider the work you do on your physics textbook when you lift it from the floor and place it on the top shelf of your locker. You have exerted a force over a distance. Therefore, you have done work on the textbook and yet it is not speeding off out of sight. The work you did on your textbook is now stored in the book by virtue of its position. Your book has gained potential energy. By doing work against the force of gravity, you have given your book a special form of potential energy called **gravitational potential energy**.

Gravitational potential energy is only one of several forms of potential energy. For example, chemical potential energy is stored in the food you eat. Doing work on an elastic band by stretching it stores elastic potential energy in the elastic band. A battery contains both chemical and electrical potential energy.

Gravitational Potential Energy

For hundreds of years, people have been using the gravitational potential energy stored in water. Many years ago, people built water wheels like the one shown in Figure 5.20. Today, we create huge reservoirs and dams that convert the potential energy of water into electricity.

Figure 5.20 Gravitational potential energy is stored in the water. When the water begins to fall, it gains kinetic energy. As it falls, it turns the wheel, giving the wheel kinetic energy.

To determine the factors that contribute to gravitational potential energy, try another "thought experiment." Ask yourself the following questions.

- If a golf ball and a Ping Pong™ ball were dropped from the same distance, which one might you try to catch and which one would you avoid?
- If one golf ball was dropped a distance of 10 cm and another a distance of 10 m, which one would hit the ground harder?
- Which golf ball would hit the surface with the greatest impact, one dropped a distance of 1.0 m on Earth or 1.0 m on the Moon?

Everyday experience tells you that mass and height (vertical distance between the two positions) contribute to an object's gravitational potential energy. Your knowledge of gravity also helps you to understand that *g*, the acceleration due to gravity, affects gravitational potential energy as well.

An important characteristic of all forms of potential energy is that there is no absolute zero position or condition. We measure only changes in potential energy, not absolute potential energy. Physicists must always assign a reference position and compare the potential energy of an object to that position. Gravitational potential energy depends on the difference in height between two positions. Therefore, the zero or reference level can be assigned to any convenient position. We typically choose the reference position as the solid surface toward which an object is falling or might fall.

PHYSICS FILE

The constant *g*, the acceleration due to gravity, affects objects even when they are not moving. When something is preventing an object from falling, such as your desk holding up your book, *g* influences its weight. The weight of an object is its mass times *g*. If nothing were preventing it from falling, your book, or any other object, would accelerate at $9.81 m/s^2$, the value of *g*. The value of *g* varies with the size and mass of the planet, moon, or star. On the Moon, for example, your book would weigh less and, if falling, would accelerate at a lower rate ($1.62 m/s^2$).

PHYSICS FILE

The equation for gravitational potential energy in the box on the right is an example of what physicists call a "special case." The numerical value of *g*, 9.81m/s^2, applies only to cases near Earth's surface. The value would be different out in space or on a different planet. Therefore, because the equation contains *g*, the equation itself applies only to cases close to Earth's surface. For example, you could not use the equation to find the gravitational potential energy of an astronaut in the International Space Station.

GRAVITATIONAL POTENTIAL ENERGY

Gravitational potential energy is the product of mass, the acceleration due to gravity, and the change in height.

$$E_g = mg\Delta h$$

Quantity	Symbol	SI unit
gravitational potential energy	E_g	J (joule)
mass	m	kg (kilogram)
acceleration due to gravity	g	$\frac{\text{m}}{\text{s}^2}$ (metres per second squared)
change in height (from reference position)	Δh	m (metre)

Unit Analysis

(mass)(acceleration)(height) = $\text{kg}\frac{\text{m}}{\text{s}^2}\text{m} = \text{N} \cdot \text{m} = \text{J}$

MODEL PROBLEM

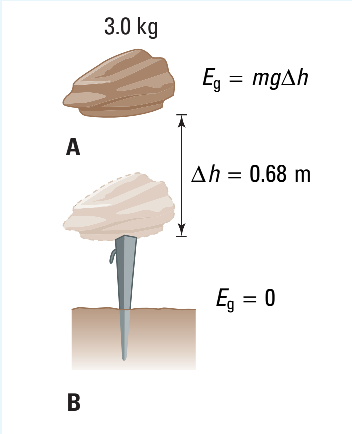
Calculating Gravitational Potential Energy

You are about to drop a 3.0 kg rock onto a tent peg. Calculate the gravitational potential energy of the rock after you lift it to a height of 0.68 m above the tent peg.

Frame the Problem

Make a sketch of the situation.

- You do *work* against gravity when you *lift* the rock.
- All of the work gives *gravitational potential energy* to the rock.
- The expression for *gravitational potential energy* applies.



Identify the Goal

The gravitational potential energy, E_g, of the rock

Variables and Constants

Involved in the problem	Known	Implied	Unknown
E_g	$m = 3.0\ \text{kg}$	$g = 9.81\ \frac{\text{m}}{\text{s}^2}$	E_g
m	$\Delta h = 0.68\ \text{m}$		
Δh			
g			

Strategy	Calculations
Use the formula for gravitational potential energy.	$E_g = mg\Delta h$
Substitute.	$E_g = (3.0\ \text{kg})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)(0.68\ \text{m})$
Multiply.	$E_g = 2.0 \times 10^1\ \text{kg}\ \frac{\text{m}}{\text{s}^2}\ \text{m}$
	$E_g = 2.0 \times 10^1\ \text{N} \cdot \text{m}$
$1\ \text{N} \cdot \text{m}$ is equivalent to 1 J.	$E_g = 2.0 \times 10^1\ \text{J}$

The rock has 2.0×10^1 J of gravitational potential energy.

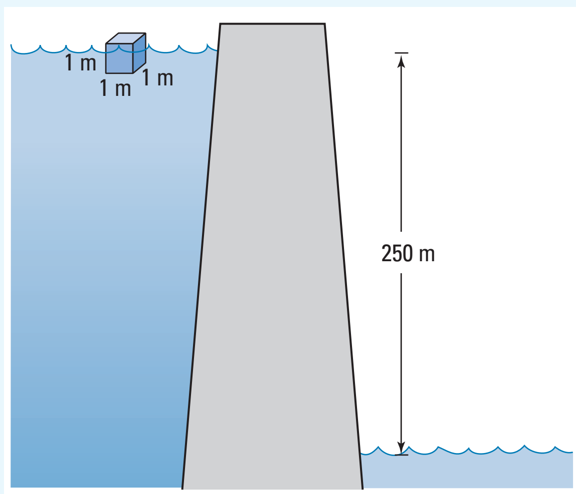
Validate

Doing work on the rock resulted in a change of position of the rock relative to the tent peg. The work done is now stored by the rock as gravitational potential energy.

PRACTICE PROBLEMS

27. A framed picture that is to be hung on the wall is lifted vertically through a distance of 2.0 m. If the picture has a mass of 4.45 kg, calculate its gravitational potential energy with respect to the ground.

28. The water level in a reservoir is 250 m above the water in front of the dam. What is the potential energy of each cubic metre of surface water behind the dam? (Take the density of water to be 1.00 kg/L.)



29. How high would you have to raise a 0.300 kg baseball in order to give it 12.0 J of gravitational potential energy?

Work and Gravitational Potential Energy

To develop a mathematical relationship between work and gravitational potential energy, start with the equation for work.

- Work is the product of the force that is parallel to the direction of the motion and the distance that the force caused the object to move. $W = F_{\parallel}\Delta d$

- Recall from Chapter 4 that the force of gravity on a mass near Earth's surface is given by $\vec{F} = m\vec{g}$, where $g = 9.81\ \text{m/s}^2$. Since the force of gravity and the acceleration due to gravity are always downward, and since work is a scalar quantity, we will omit vector notations. $F = mg$

- Substitute mg for F into the expression for work. $\therefore W = mg\Delta d$

- Substitute Δh for height in place of Δd to emphasize that the displacement vector is vertical. $W = mg\Delta h$

- This is the equation for work done to lift an object to height Δh, relative to its original position. $W = mg\Delta h$

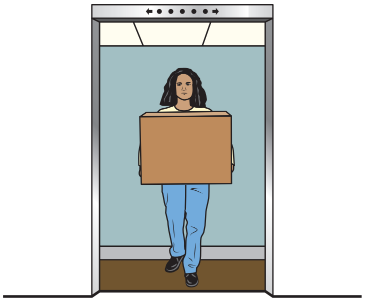
- The work, W, done on the object has become gravitational potential energy stored in the object by virtue of its position. $E_g = mg\Delta h$

Depending on your choice of a reference level, an object may have some gravitational potential energy before you do work on it. For example, choose the floor as your reference. If your book was on the desk, it would have an amount of gravitational potential energy, $mg\Delta h_1$, in relation to the floor, where Δh_1 is the height of the desk. Then you do work against gravity to lift it to the shelf, where it has gravitational potential energy $mg\Delta h_2$, where Δh_2 is the height of the shelf. The work you did *changed* the book's gravitational potential. You can describe this change mathematically as

$$W = mg\Delta h_2 - mg\Delta h_1$$
$$W = E_{g2} - E_{g1}$$
$$W = \Delta E_g$$

The mathematical expression above is a representation of the work-energy theorem in terms of gravitational potential energy.

Figure 5.21 Visualizing potential energy



Think It Through

- Object A has twice the mass of object B. If object B is 4.0 m above the floor and object A is 2.0 m above the floor, which one has the greater gravitational potential energy?
- If both objects in the question above were lowered 1.0 m, would they still have the same ratio of gravitational potential energies that they had in their original positions? Explain your reasoning.
- You carry a heavy box up a flight of stairs. Your friend carries an identical box on an elevator to reach the same floor as you. Which one, you or your friend, did the greatest amount of work on a box against gravity? Explain your reasoning.
- Examine the photographs in Figure 5.21 on the previous page, "Visualizing potential energy," then answer the following questions.
  1. Name all of the objects in the photographs that clearly illustrate gravitational potential energy that might soon be converted into kinetic energy. Explain why you made your choices.
  2. From your list for the previous question, which object do you think has the most gravitational potential energy? Explain.
  3. List as many examples as you can of forms of potential energy other than gravitational potential energy.

MODEL PROBLEM

Applying the Work-Energy Theorem

A 65.0 kg rock climber did 1.60×10^4 J of work against gravity to reach a ledge. How high did the rock climber ascend?

Frame the Problem

- The rock climber did *work* against *gravity*.
- Work done against gravity *increased* the rock climber's *gravitational potential energy*.
- The *work-energy theorem* that applies to potential energy is appropriate for this situation.

Identify the Goal

The vertical height, Δh, that the climber ascended

Variables and Constants

Involved in the problem		Known	Implied	Unknown
W	E_{g1}	$W = 1.60 \times 10^4$ J	$g = 9.81 \frac{m}{s^2}$	E_{g2}
E_{g2}	g	$m = 65.0$ kg	$E_{g1} = 0$ J	Δh
m	Δh			

Strategy	Calculations	
Use the work-energy theorem to find the climber's gravitational potential energy from the amount of work done.	$W = E_{g2} - E_{g1}$	
	Substitute first	**Solve for E_{g2} first**
Choose the starting point as your reference for gravitational potential energy, so that E_{g1} will be zero. Solve.	$W = E_{g2} - E_{g1}$ $1.6 \times 10^4 \text{ J} = E_{g2} - 0 \text{ J}$ $E_{g2} = 1.6 \times 10^4 \text{ J}$	$W = E_{g2} - E_{g1}$ $W + E_{g1} = E_{g2}$ $1.6 \times 10^4 \text{ J} + 0 \text{ J} = E_{g2}$ $1.6 \times 10^4 \text{ J} = E_{g2}$
Use the value for gravitational potential energy to find the height.	$E_{g2} = mg\Delta h$ $1.6 \times 10^4 \text{ J} = 65 \text{ kg } 9.81 \frac{\text{m}}{\text{s}^2}\Delta h$	$E_{g2} = mg\Delta h$ $\frac{E_{g2}}{mg} = \frac{\cancel{mg}\Delta h}{\cancel{mg}}$
Divide both sides of the equation by the value in front of Δh.	$\frac{1.6 \times 10^4 \text{ J}}{65 \text{ kg } 9.81 \frac{\text{m}}{\text{s}^2}} = \frac{\cancel{65 \text{ kg } 9.81 \frac{\text{m}}{\text{s}^2}}\Delta h}{\cancel{65 \text{ kg } 9.81 \frac{\text{m}}{\text{s}^2}}}$	$\Delta h = \frac{E_{g2}}{mg}$
Simplify.	$\frac{1.6 \times 10^4 \text{ J}}{65 \text{ kg } 9.81 \frac{\text{m}}{\text{s}^2}} = \Delta h$	$\Delta h = \frac{1.6 \times 10^4 \text{ J}}{65 \text{ kg}}$
Convert J to kg $\frac{\text{m}^2}{\text{s}^2}$, so that you can cancel units.	$\Delta h = 25.09 \frac{\frac{\cancel{\text{kg}} \cdot \text{m}^{\cancel{2}}}{\cancel{\text{s}^2}}}{\cancel{\text{kg}}\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}}$ $\Delta h = 25.09$ m	$\Delta h = 25.09 \frac{\frac{\cancel{\text{kg}} \times \text{m}^{\cancel{2}}}{\cancel{\text{s}^2}}}{\frac{\cancel{\text{kg}} \times \cancel{\text{m}}}{\cancel{\text{s}^2}}}$ $\Delta h = 25.09$ m

The rock climber ascended 25.1 m.

Validate

The climber did a large amount of work, so you would expect that the climb was quite high.

The units canceled to give m, which is correct for height.

continued ►

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PRACTICE PROBLEMS

30. A student lifts her 2.20 kg pile of textbooks into her locker from where they rest on the ground. She must do 25.0 J of work in order to lift the books. Calculate the height that the student must lift the books.

31. A 46.0 kg child cycles up a large hill to a point that is a vertical distance of 5.25 m above the starting position. Find
    (a) the change in the child's gravitational potential energy
    (b) the amount of work done by the child against gravity

32. A 2.50 kg pendulum is raised vertically 65.2 cm from its rest position. Find the gravitational potential energy of the pendulum.

33. A roller-coaster train lifts its passengers up vertically through a height of 39.4 m from its starting position. Find the change in gravitational potential energy if the mass of the train and its passengers is 3.90×10^3 kg.

34. The distance between the sixth and the eleventh floors of a building is 30.0 m. The combined mass of the elevator and its contents is 1.35×10^3 kg.
    (a) Find the gravitational potential energy of the elevator when it stops at the eighth floor, relative to the sixth floor.
    (b) Find the gravitational potential energy of the elevator when it pauses at the eleventh floor, relative to the eighth floor.
    (c) Find the gravitational potential energy of the elevator when it stops at the eleventh floor, relative to the sixth floor.

5.3 Section Review

1. K/U List three forms of potential energy other than gravitational potential energy and give an example of each.

2. K/U Is gravitational potential energy always measured from one specific reference point? Explain.

3. K/U Define the term "potential" as it applies to "gravitational potential energy."

4. C Describe what happens to the gravitational potential energy of a stone dropped from a bridge into a river below. How has the amount of gravitational potential energy changed when the stone is (a) halfway down, (b) three quarters of the way down, and (c) all of the way down?

5. C Your physics textbook is sitting on a shelf above your desk. Explain what is wrong with the statement, "The gravitational potential energy of the book is 20 J."

6. C The following is the derivation of the relationship between work and gravitational potential energy.

$$W = F_{\parallel}\Delta d$$
$$W = mg\Delta d$$
$$W = mg\Delta h$$

   (a) Explain why mg could be substituted for force in this derivation but not in the derivation for the relationship between work and kinetic energy.
   (b) Explain why Δh was substituted for Δd.

7. K/U An amount of work, W, was done on one ball to raise it to a height h. In terms of W, how much work must you do on four balls, all identical to the first, to raise them to twice the height h?

5.4 Conservation of Energy

The word conservation, as it is often used, means "saving" or "taking care of" something. You frequently hear about the need for "conservation of fossil fuels" or "conservation of the wilderness." These two examples share a meaning for conservation that is different from the one used by physicists. As used in physics, conservation means that something remains *constant*. "Conservation of energy" implies that the total energy of an isolated system remains constant. The energy however, may change from one form to another, or it may be transferred from one object to another *within* the system.

SECTION EXPECTATIONS

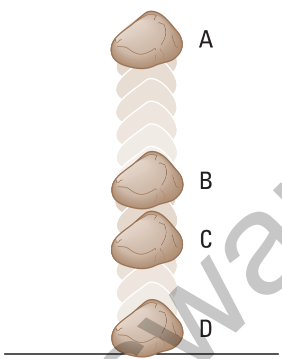
- Analyze the relationship between kinetic energy and potential energy.
- Design an experiment to investigate the conservation of mechanical energy.
- Communicate observations that would lead you to conclude that mechanical energy is not conserved.

KEY TERMS

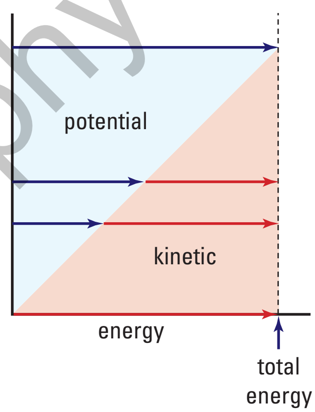
- conservative force
- non-conservative force
- law of conservation of mechanical energy
- law of conservation of energy

Conservation of Mechanical Energy

In some processes, not only total energy but total *mechanical* energy is conserved, that is, remains constant. The example of a falling rock in Figure 5.22 illustrates such a process. The rock, initially at rest, falls from a height, h, above the ground. The rock's gravitational potential energy is being transformed into kinetic energy as it falls farther and faster. Its mechanical energy, however, is being conserved.



Gravitational potential energy is being transformed into kinetic energy.



The graph shows the amount of potential and kinetic energy of the rock at different positions, up to the moment before it hits the ground.

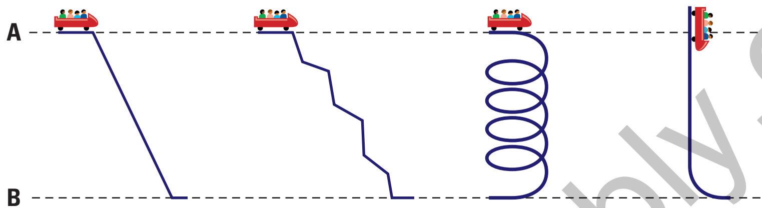
Figure 5.22 Although gravitational potential energy is being transformed into kinetic energy, the total mechanical energy of the rock remains the same as it falls.

PHYSICS FILE

In physics, a system may be defined in any way that you choose to define it. A system may be one object, such as a rock. It may be a combination of objects. Once you have chosen your system, you must not change your definition while you are making energy calculations, or the rules of physics will no longer apply.

Think It Through

- Imagine an amusement park that has rides like those illustrated here. The masses of all of the cars are identical and the same four people go on each ride. The wheels and track are effectively frictionless. Each car starts from rest at level A. What are the relative speeds of the cars when they reach level B?



- While playing catch by yourself, you throw a ball straight up as hard as you can throw it. Neglecting air friction, how does the speed of the ball, when it returns to your hand, compare to the speed with which it left your hand?

You can say, intuitively, that the kinetic energy of an object, the instant before it hits a solid surface, is the same as the gravitational potential energy at the point from which it fell from rest. However, physicists try to show such relationships mathematically. Then, they can make calculations based on the principles. Start with the general expression for kinetic energy, $E_k = \frac{1}{2}mv^2$, and show how the kinetic energy at the end of a free fall relates to the gravitational potential energy, $E_g = mg\Delta h$, at a distance Δh above the surface.

The first step in deriving this relationship is to find the velocity of an object after it falls a distance, Δh.

- Recall from Chapter 2 the equation of motion for uniform acceleration. $v_2^2 = v_1^2 + 2a\Delta d$
- The object was initially at rest. $v_1 = 0$
  $v_2^2 = 0 + 2a\Delta d$
- Substitute Δh, representing height, for Δd. $\Delta d = \Delta h$
  $v_2^2 = 0 + 2a\Delta h$
- Since the only force acting on the object is gravity, the object's acceleration is g, the acceleration due to gravity. $a = g$
- This is the square of the velocity of the object, just before hitting a surface, after falling through height Δh. $v_2^2 = 2g\Delta h$

- Substitute the previous expression for v^2 into the general expression for kinetic energy. $$E_k = \frac{1}{2}mv^2$$
- The kinetic energy of the object just before it hits the surface becomes $$E_k = \frac{1}{2}m(2g\Delta h)$$
- Notice that the kinetic energy just before the object hits the solid surface is identical to $$E_k = mg\Delta h$$
- The equation for gravitational potential energy a distance Δh above the surface is $$E_g = mg\Delta h$$

The total energy of the object is not only the same at the top and at the bottom, but throughout the entire trip. The mathematical process used above could be applied to any point throughout the fall. You could show that, for any point within the fall, the gravitational potential energy that was lost up to that point has been transformed into kinetic energy. Therefore, the sum of the kinetic and potential energies remains constant at all times throughout the fall.

Obviously, when an object hits a solid surface and stops, the mechanical energy is no longer conserved. Also, any effects of air friction were neglected in the discussion. Although the total energy of an isolated system is always conserved, mechanical energy is not necessarily conserved. Is there any specific characteristic of a process that you could use to determine whether or not mechanical energy will be conserved?

Conservative and Non-Conservative Forces

If you lift your book one metre above a table and release it, it will drop back onto the table, gaining kinetic energy as it falls. If you push your book across the table, will it automatically return to its original spot, gaining kinetic energy as it moves? Of course not. In the first case, you were doing work against the gravitational force. In the second case, you were doing work against a frictional force.

These two forces, gravity and friction, represent two important classes of forces. Before defining these classes of forces, consider another property of doing work against them. If you lift your book to a certain height, then carry it across the room, you have done the same amount of work that you would do if you simply lifted it straight up. However, if you push your book from side to side as you move it from one end of the table to the other, you have done more work than you would if you pushed it in a straight line. The amount of work you do against friction depends on the path through which you push the object.

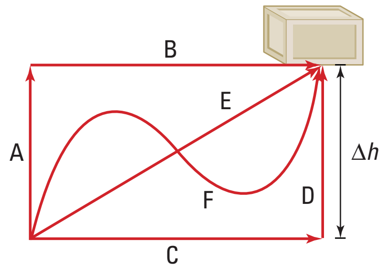


Figure 5.23 Regardless of the path taken, the work done to lift the box to height Δh is identical. Work done against a conservative force is *independent* of the path.

A **conservative force** is one that does work on an object so that the amount of work done is *independent* of the path taken. The force of gravity is an example of a conservative force because it takes the same amount of work to lift a mass to height Δh, regardless of the path. The work done, and therefore the gravitational potential energy, depend only on the height Δh.

Friction, on the other hand, is not a conservative force. The work done against a frictional force when a crate is pushed across a rough floor depends on whether the path is straight, or curved, or zigzagged. The work done *is* path-dependent, and therefore the force of friction is **non-conservative**.

Work done by conservative forces results in energy changes that are independent of the path and are therefore reversible. Work done by non-conservative forces results in energy changes that are dependent on the path, and therefore may not be reversed. We can now state the conditions under which mechanical energy is conserved. This statement is called the **law of conservation of mechanical energy**.

LAW OF CONSERVATION OF MECHANICAL ENERGY

The *total mechanical energy* of a system always remains constant if work is done by conservative forces.

$$E_T = E_g + E_k$$

where
- E_T is the total mechanical energy of the system.
- E_g is the gravitational potential energy of the system.
- E_k is the mechanical kinetic energy of the system.

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following website: ***www.school.mcgrawhill.ca/resources/*** and follow the **Physics 11** links for several laboratory activities.

Table 5.2 Examples of Conservative and Non-Conservative Forces

Conservative forces	Non-conservative forces
gravity	friction
electric	air resistance (a specific example of a frictional force)
magnetic	any applied thrust force (e.g. a rocket or a motor)
nuclear	
elastic*	

*Items such as springs and elastic bands are not "perfectly elastic"; therefore, the forces they exert are not truly conservative.

Think It Through

- A marble oscillates back and forth in a U-shaped track, repeatedly transferring gravitational potential energy to kinetic energy, and back to gravitational potential energy. Does the law of conservation of mechanical energy apply? Defend your reasoning by discussing conservative and non-conservative forces.

MODEL PROBLEM

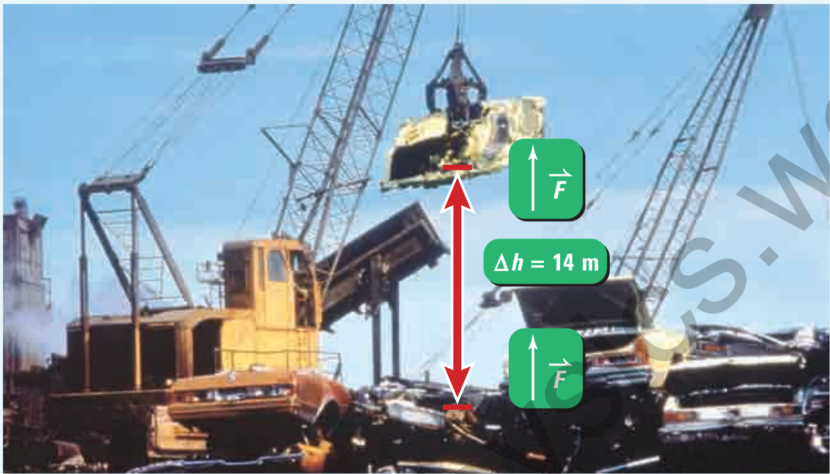
Applying the Law of Conservation of Mechanical Energy

A crane lifts a car, with a mass of 1.5×10^3 kg, at a constant velocity, to a height of 14 m from the ground. It turns and drops the car, which then falls freely back to the ground. Neglecting air friction, find

(a) the work done by the crane in lifting the car

(b) the gravitational potential energy of the car at its highest point, in relation to the ground

(c) the velocity of the car just before it strikes the ground after falling freely for 14 m



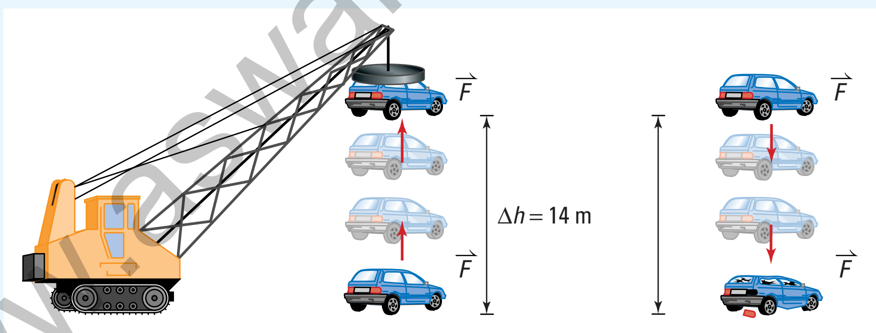
PROBLEM TIP

Strategy for Solving Energy Transformation Problems

1. Always draw a diagram of the system you are analyzing.
2. Label the initial and final positions.
3. Write an equation to represent the total energy at each position.
4. Describe and write equations to link energy totals at each point.
5. Solve for the unknowns.

Frame the Problem

Make a sketch of all of the actions in the problem.



- As the crane lifts the car, it is *doing work* on the car, against the force of gravity. Since the crane is moving the car at a constant velocity, the *forces* are *balanced*. The force exerted by the crane is equal in *magnitude* and *opposite in direction to the force of gravity*.
- The work done by the crane gives *gravitational potential energy* to the car.
- When the car is *falling*, the force of *gravity is doing work* on the car.

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- The *work done* on the car by gravity gives the car *kinetic energy*.
- Since we are neglecting air friction, the expression for *conservation of mechanical energy* applies to this problem.
- The *total mechanical energy* of the car is the same as the *work done* on the car by the crane. The work done on the car by the crane gave the car *mechanical energy*.

Identify the Goal

(a) Work, W, done by the crane

(b) Gravitational potential energy, E_g, of the car at the highest point

(c) Kinetic energy, E_k, of the car just before it hits the ground

Variables and Constants

Involved in the problem		Known	Unknown
W	v	$m = 1.5 \times 10^3$ kg	W
F_{crane}	m	$\Delta h = 14$ m	F_{crane}
Δh	F_g	**Implied**	F_g
$E_{g(top)}$	$E_{k(top)}$	$g = 9.81 \frac{m}{s^2}$	$E_{g(top)}$
$E_{g(bottom)}$	$E_{k(bottom)}$	$E_{k(top)} = 0$ J	E_T
E_T		$E_{g(bottom)} = 0$ J	$E_{k(bottom)}$
g			v

PROBLEM TIP

Often when you are solving conservation of mechanical energy problems, the mass variable can easily be eliminated, as in the following example.

$E_T = E_g$ at the top

$E_T = E_k$ just before impact

$E_{g(top)} = E_{k(bottom)}$

$\cancel{m}g\Delta h = \frac{1}{2}\cancel{m}v^2$ each m cancels

Solving for one of the other variables, Δh or v, is now easier.

Strategy	Calculations
Find the work done by the crane on the car by using the equation for work done by a force parallel to the direction of the displacement.	$W = F_{\parallel}\Delta d$
The force exerted by the crane on the car is F_{crane}. It is equal to the weight of the car, F_g.	$W = F_{crane}\,\Delta h$ $W = F_g\,\Delta h$ $W = mg\Delta h$
All of the values are known, so substitute into the equation.	$W = (1.5 \times 10^3\text{ kg})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)(14\text{ m})$
Multiply.	$W = 2.06 \times 10^5\text{ kg}\ \frac{\text{m}}{\text{s}^2}\text{m}$
$1\text{ kg}\ \frac{\text{m}}{\text{s}^2}$ is equivalent to 1 N.	$W = 2.06 \times 10^5\text{ N} \cdot \text{m}$
$1\text{ N} \cdot \text{m}$ is equivalent to 1 J.	$W = 2.06 \times 10^5$ J

(a) The crane did 2.1×10^5 J of work on the car.

Strategy

Calculations

Find the gravitational potential energy of the car at its highest point by using the expression for gravitational potential energy.

$$E_g = mg\Delta h$$

All of the values are known, so substitute into the equation.

$$E_{g(top)} = (1.5 \times 10^3\ \text{kg})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)(14\ \text{m})$$

Multiply.

$$E_{g(top)} = 2.06 \times 10^5\ \text{kg}\ \frac{\text{m}}{\text{s}^2}\text{m}$$

1 kg $\frac{\text{m}}{\text{s}^2}$ is equivalent to 1 N.

$$E_{g(top)} = 2.06 \times 10^5\ \text{N} \cdot \text{m}$$

1 N · m is equivalent to 1 J.

$$E_{g(top)} = 2.06 \times 10^5\ \text{J}$$

(b) The car had 2.1×10^5 J of gravitational potential energy at its highest point..

PROBLEM TIP

When you report an answer to any part of a problem, you must report it using the correct number of significant digits. However, when you use that answer in a subsequent part of the problem, use the value you calculated before rounding to the proper number of significant digits. Only round a number when you have completed the calculation and are reporting a solution. This will lead to a more accurate final solution.

The values needed to calculate the velocity of the car just before it hits the ground are not all known. In cases such as this, a tree diagram is often helpful in determining the values that you need

You can calculate the velocity of the car just before it hits the ground if you know the car's mass and kinetic energy just before it hits the ground.

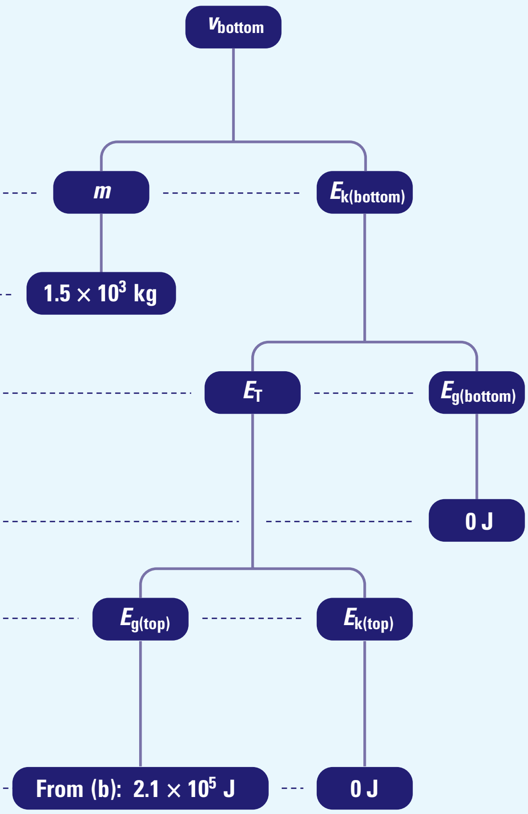
The mass is known.

You can calculate the kinetic energy of the car just before it hits the ground if you know the total mechanical energy and the gravitational potential energy of the car at that point.

The gravitational potential energy at the bottom is zero.

You can calculate the total energy of the car if you know both the gravitational potential energy and the kinetic energy at the same point.

Since the car was not in motion at the top, the kinetic energy at that point was zero. You found the gravitational potential energy at the top in the second part of the problem.



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All of the needed values are known. All that remains is to do the calculations.

Strategy	Calculations
Find E_T using the equation for conservation of mechanical energy.	$E_T = E_{g(top)} + E_{k(top)}$
All of the needed values are known, so substitute into the equation.	$E_T = 2.06 \times 10^5\ \text{J} + 0\ \text{J}$ $E_T = 2.06 \times 10^5\ \text{J}$
Knowing E_T, use the equation for conservation of mechanical energy to find $E_{k(bottom)}$.	$E_T = E_{g(bottom)} + E_{k(bottom)}$
Substitute.	$2.06 \times 10^5\ \text{J} = 0\ \text{J} + E_{k(bottom)}$ $E_{k(bottom)} = 2.06 \times 10^5\ \text{J}$

The kinetic energy of the car just before it hit the ground was 2.1×10^5 J.

Use $E_{k(bottom)}$ and the equation for kinetic energy to find v at the bottom of the fall, just before the car hit the ground.

$$E_k = \frac{1}{2}mv^2$$

	Substitute first	Solve for v first
All of the needed values are known, so you can solve the problem.	$2.06 \times 10^5\ \text{J} = \frac{1}{2}(1.5 \times 10^3\ \text{kg})v^2$	$\frac{2E_{k(bottom)}}{m} = v^2$
Isolate v^2.	$\frac{2.06 \times 10^5\ \text{J}}{\frac{1}{2}(1.5 \times 10^3\ \text{kg})} = \frac{\cancel{\frac{1}{2}(1.5 \times 10^3\ \text{kg})}\, v^2}{\cancel{\frac{1}{2}(1.5 \times 10^3\ \text{kg})}}$	$\sqrt{\frac{2E_{k(bottom)}}{m}} = v$ $\sqrt{\frac{2(2.06 \times 10^5\ \text{J})}{1.5 \times 10^3\ \text{kg}}} = v$
Take the square root of both sides of the equation.	$v^2 = 2.8 \times 10^2\ \frac{\cancel{\text{kg}}\ \text{m}^2}{\text{s}^2\ \cancel{\text{kg}}}$ $v = \sqrt{2.8 \times 10^2\ \frac{\text{m}^2}{\text{s}^2}}$ $v = \pm 16.7\ \frac{\text{m}}{\text{s}}$	$v = \sqrt{2.8 \times 10^2\ \frac{\text{N} \cdot \text{m}}{\text{kg}}}$ $v = \sqrt{2.8 \times 10^2\ \frac{\cancel{\text{kg}} \cdot \text{m}\ \text{m}}{\cancel{\text{kg}}\ \text{s}^2}}$ $v = \pm 16.7\ \frac{\text{m}}{\text{s}}$

By taking the square root, directional information was lost. Since you know that the car was falling, select the negative sign for the answer.

(c) The velocity of the car just before it hit the ground was -1.7×10^1 J.

Validate

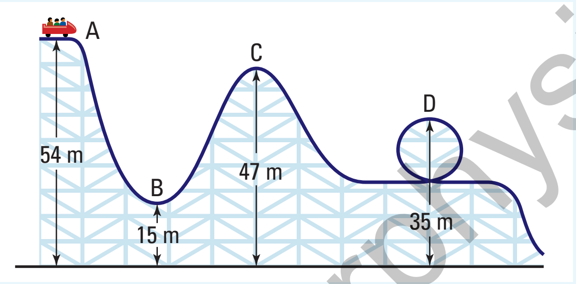
As the crane lifts the car, the energy total of the system increases until it reaches a maximum at the highest point (14 m), because work is being done on the system (car). Since the work done on the car transfers energy to the car, you would expect the gravitational potential energy of the car to be the same as the work done by the crane on the car. It is.

In every case, the units cancelled to give the correct units: joules for energy and metres per second for velocity.

PRACTICE PROBLEMS

35. You throw a ball directly upward, giving it an initial velocity of 10.0 m/s. Neglecting friction, what would be the maximum height of the ball? (Explain why you do not need to know the mass of the ball.)

36. A 4.0×10^4 kg roller coaster starts from rest at point A. Neglecting friction, calculate its potential energy relative to the ground, its kinetic energy, and its speed at points B, C, and D.

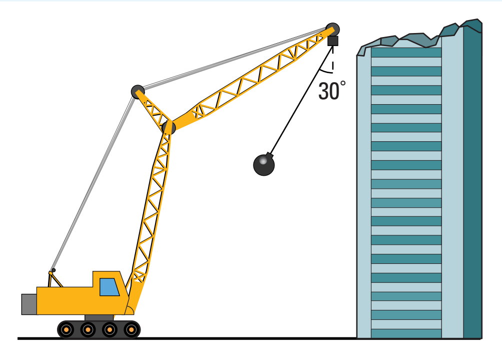


37. A wrecking ball, with a mass of 315 kg, hangs from a crane on 10.0 m of cable. If the crane swings the wrecking ball so that the angle that the cable makes with the vertical is 30.0°, what is the potential energy of the wrecking ball in relation to its lowest position? What will be the kinetic energy of the wrecking ball when it falls back to the vertical position? What will be the speed of the wrecking ball?

38. A 2.5 kg lead ball and a 55 g piece of lead shot are both dropped from a height of 25 m. Neglecting air friction, what is the kinetic energy of each object just before it hits the ground? What is the velocity of each object just before it hits the ground?

39. A 32 kg crate was pushed down a frictionless ramp. Its initial velocity at the top of the ramp was 3.2 m/s. Its velocity when it reached the bottom of the ramp was 9.7 m/s. The ramp makes an angle of 25° with the horizontal. How long is the ramp?

40. A worker on the roof of a building that is under construction dropped a 0.125 kg wrench over the edge. Another workman on the eighth floor saw the wrench go by and determined that its speed at that level was 33.1 m/s. The first floor of the building is 12.0 m high and each successive floor is 8.00 m high. Neglecting air friction, how many floors does the building have? How fast was the wrench falling just before it hit the ground? What was its kinetic energy just before it hit the ground?



ELECTRONIC LEARNING PARTNER

A video clip of a wrecking ball in action can be found on the Electronic Learning Partner.

PHYSICS & SOCIETY

TARGET SKILLS

- **Analyzing and interpreting**

Pole-Vaulting: The Art of Energy Transfer

Athlete Stacy Dragila won a gold medal for pole-vaulting at the 2000 Olympic Games in Sydney, the first games to feature women's vaulting. During her winning vaults she demonstrated a fundamental principle of physics — the conservation of energy. Dragila has speed, power, and near-perfect technique. When she vaults, she uses and transfers energy as efficiently as possible.

Before a pole-vaulter begins to sprint toward the bar, she is storing chemical energy in her muscles. If the vaulter is well trained, she will be able to use the chemical energy as efficiently as possible. This chemical energy is converted into kinetic energy as she sprints toward the bar. Near the end of the sprint, the vaulter places her pole in a socket. Kinetic energy from the sprint bends the pole and the pole gains elastic potential energy. When the pole begins to extend from its bend, it converts the elastic energy into gravitational potential energy, lifting the vaulter into the air.

Ideally, a vaulter would be able to convert all of her kinetic energy into elastic energy. But not even Dragila has perfect technique. Even if she did, some of the energy would still be converted to forms that do not perform useful work. Some kinetic energy is converted to thermal and sound energy during the sprint, and some elastic energy is absorbed by the pole as thermal energy during the lift.

Olympic gold medallist Stacy Dragila in action

The important thing to remember is that the amount of energy involved in the pole vault remains constant. The type of energy and the efficiency with which the athlete uses the energy make the difference between champions such as Dragila and other pole-vaulters.

Analyze

1. Sporting events are sometimes held at high altitudes, such as the 1968 Olympic Games in Mexico City. The thinner air poses challenges for some athletes, but pole-vaulters, and also long-jumpers and high-jumpers, tend to benefit. Why?

2. Pole-vaulting began as an inventive way to get across rivers and other barriers. The first poles were made of bamboo. Today's poles are much more sophisticated. What principles need to be considered when designing a pole?

INVESTIGATION 5-A

Conservation of Mechanical Energy

TARGET SKILLS

- Initiating and planning
- Predicting
- Performing and recording
- Analyzing and interpreting

You have learned about mechanical energy and worked problems based on the conservation of energy. Now you will design an experiment that will test the law of conservation of mechanical energy. A well-designed pendulum has such a small amount of friction that it can be neglected.

Problem

How can you verify the conservation of mechanical energy for a system in which all of the work is done by conservative forces?

Prediction

Make predictions about the type of energy transformations that will occur and when, during the cycle, they will occur.

Equipment

- parts for assembling a pendulum
- motion sensor
- metre stick or other measuring device

Procedure

Write your own procedure for testing the law of conservation of energy using a pendulum. Clearly describe the required materials and the proposed procedure.

Verify, with the teacher, that the experiment is safe before proceeding.

Make detailed predictions identifying the positions at which the mechanical energy of the pendulum will be (a) all gravitational potential, (b) all kinetic, and (c) half gravitational potential and half kinetic.

Analyze and Conclude

1. Which variables did you control in the experiment?
2. How might you improve your experiment?
3. How well did your results verify the law of conservation of energy? Was any discrepancy that you found within limits that are acceptable to you?
4. If mechanical energy was lost, explain how and why it might have been lost.

Apply and Extend

5. The transformation of energy from one form to another is never completely efficient. For example, predict what will happen to the chemical potential energy of a car's fuel as it is transferred to the kinetic energy of the motion of the car.

PHYSICS FILE

One of James Joule's scientific goals was to determine the "mechanical equivalent of heat." A story is often told that, while Joule was on his honeymoon in Switzerland, he spent his time measuring the temperature of water at the top and at the bottom of waterfalls. By determining the difference in the water temperature, he could determine how much thermal energy the water would gain by falling a certain distance.

Conservation of Total Energy

The law of conservation of mechanical energy was generated using Newton's laws of motion. Evidence also confirms the derived results and, in fact, allows the law of conservation of energy to be expanded to include work done by non-conservative forces.

Once again, consider the car in the model problem. This time do not neglect air resistance. As the car falls through the atmosphere, it collides with air molecules. The resulting friction produces heat or thermal energy, similar to the results observed when you rub your hands together. This frictional force acts through the entire distance that the car falls. Since the frictional force is in the opposite direction to the force of gravity, it does negative work on the car. Therefore, some of the gravitational potential energy is transferred into thermal energy of the surroundings. This loss of potential energy to thermal energy reduces the amount of kinetic energy gained by the car. In this case, since friction, a non-conservative force, has done work, mechanical energy is not conserved. Careful experimentation with sensitive equipment has verified that if all forms of energy within the system, including the thermal energy of air molecules and the increased thermal energy of the car, are added together, the total energy of the system remains constant. These observations led to a fundamental principle of physics, the **law of conservation of energy**.

LAW OF CONSERVATION OF ENERGY

Energy is neither created nor destroyed. It simply changes form or is transferred from one body to another. The total energy of an isolated system, including all forms of energy, always remains constant.

In summary, mechanical energy is conserved if work done by non-conservative forces is zero ($W_{nc} = 0$). In this case, total mechanical energy will remain constant and be the sum of the kinetic and potential energies. If the work done by *non-conservative forces is not zero*, then mechanical energy is *not conserved*.

ELECTRONIC LEARNING PARTNER

Your Electronic Learning Partner has an interactive simulation to show how energy conservation relates to pendulums.

WORK AND NON-CONSERVATIVE FORCES

The work done by non-conservative forces is the difference of the final mechanical energy of a system and the initial mechanical energy of a system.

$$W_{nc} = E_{final} - E_{initial}$$

where $\begin{cases} W_{nc} & \text{is the work done by non-conservative forces.} \\ E_{initial} & \text{is the initial mechanical energy of the system.} \\ E_{final} & \text{is the final mechanical energy of the system.} \end{cases}$

Concept Organizer

Newton's second law

Work
Kinetic energy
Potential energy

Work-energy theorem

Is $W_{nc} = 0$?

yes: The conservation of mechanical energy applies.
$E_T = E_g + E_k$

no: The conservation of mechanical energy does *not* apply.
$W_{nc} = E_{final} - E_{initial}$

W_{nc} is the net work done by external, non-conservative forces. For example, the work done by air resistance on a parachute is non-conservative, so mechanical energy is not conserved: Kinetic and potential energy *both* decrease.

Figure 5.24 Applying the work-energy theorem

MODEL PROBLEM

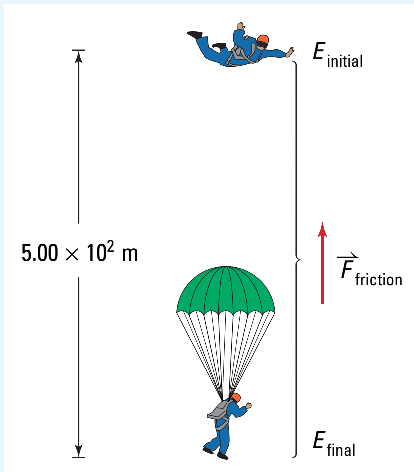
Work Done by Air Friction

A 65.0 kg skydiver steps out from a hot air balloon that is 5.00×10^2 m above the ground. After free-falling a short distance, she deploys her parachute, finally reaching the ground with a velocity of 8.00 m/s (approximately the speed with which you would hit the ground after having fallen a distance of 3.00 m).

(a) Find the gravitational potential energy of the skydiver, relative to the ground, before she jumps.

(b) Find the kinetic energy of the skydiver just before she lands on the ground.

(c) How much work did the non-conservative frictional force do?



Frame the Problem

- Make a sketch of the problem and label it.
- The hot air balloon can be considered to be at rest, so the vertical velocity of the skydiver initially is *zero*.
- As she starts to fall, the *force of air friction* does *negative* work on her, converting much of her *gravitational potential energy* into *thermal energy*.
- The rest of her *gravitational potential energy* was converted into *kinetic energy*.

continued ▶

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Identify the Goal

Initial gravitational potential energy, E_g, of the skydiver relative to the ground

Final kinetic energy, E_k, of the skydiver just before touchdown

Work done by non-conservative force, W_{nc}

Variables and Constants

Involved in the problem		Known	Unknown
$E_{initial}$	W_{nc}	$m = 65.0$ kg	$E_{initial}$
E_g	E_{final}	$g = 9.81\ \frac{\text{m}}{\text{s}^2}$	E_g
m	E_k	$\Delta h = 5.00 \times 10^2$ m	W_{nc}
g	v	$v = 8.00\ \frac{\text{m}}{\text{s}^2}$	E_{final}
Δh		E_k	

Strategy	Calculations
Use the equation for gravitational potential energy. All of the needed variables are known, so substitute into the equation.	$E_g = mg\Delta h$
Multiply.	$E_g = (65.0\ \text{kg})(9.81\ \frac{\text{m}}{\text{s}^2})(5.00 \times 10^2\ \text{m})$ $E_g = 3.188 \times 10^5\ \text{kg}\ \frac{\text{m}}{\text{s}^2}\ \text{m}$
$1\ \text{kg}\ \frac{\text{m}}{\text{s}^2}$ is equivalent to 1 N.	$E_g = 3.188 \times 10^5\ \text{N} \cdot \text{m}$
$1\ \text{N} \cdot \text{m}$ is equivalent to 1 J.	$E_g = 3.188 \times 10^5\ \text{J}$
(a) The skydiver's initial gravitational energy, before starting the descent, was 3.19×10^5 J.	
Use the skydiver's velocity just before touchdown to find the kinetic energy before touchdown. All of the needed values are known, so substitute into the equation for kinetic energy, then multiply.	$E_k = \frac{1}{2}mv^2$ $E_k = \frac{1}{2}(65.0\ \text{kg})(8.00\ \frac{\text{m}}{\text{s}})^2$ $E_k = 2.080 \times 10^3\ \text{kg}\ \frac{\text{m}^2}{\text{s}^2}$
$1\ \text{kg}\ \frac{\text{m}^2}{\text{s}^2}$ is equivalent to 1 J.	$E_k = 2.080 \times 10^3\ \text{J}$
(b) The skydiver's kinetic energy just before landing was 2.08×10^3 J.	
Use the equation for the conservation of total energy to find the work done by air friction. The final mechanical energy is entirely kinetic energy and the initial mechanical energy was entirely gravitational potential energy. These values were just calculated.	$W_{nc} = E_{final} - E_{initial}$ $W_{nc} = 2.080 \times 10^3\ \text{J} - 3.188 \times 10^5\ \text{J}$ $W_{nc} = -3.167 \times 10^5\ \text{J}$
(c) Air friction did 3.17×10^5 J of negative work on the skydiver.	

Validate

The 3.17×10^5 J of work done by air resistance is very large. This is fortunate for the skydiver, as it allows her to land softly on the ground, having lost 99.3 percent of her mechanical energy. This large loss of mechanical energy is what a parachute is designed to do.

How fast would the skydiver in the model problem be travelling just before hitting the ground if the work done by air resistance was ignored?

PRACTICE PROBLEMS

41. A 0.50 kg basketball falls from a 2.3 m shelf onto the floor, then bounces up to a height of 1.4 m before you catch it.

(a) Calculate the gravitational potential energy of the ball before it falls.

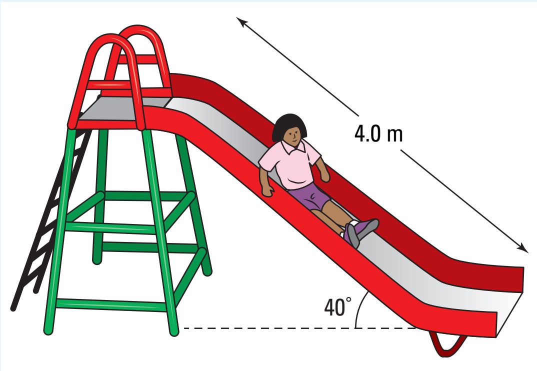
(b) Ignoring frictional effects, determine the speed of the ball as it strikes the floor, assuming that it fell from rest.

(c) How fast is the ball moving just before you catch it?

42. A 2.0 g bullet initially moving with a velocity of 87 m/s passes through a block of wood. On exiting the block of wood, the bullet's velocity is 12 m/s. How much work did the force of friction do on the bullet as it passed through the wood? If the wood block was 4.0 cm thick, what was the average force that the wood exerted on the block?

43. The Millennium Force, the tallest roller coaster in North America, is 94.5 m high at its highest point. What is the maximum possible speed of the roller coaster? The roller coaster's actual maximum speed is 41.1 m/s. What percentage of its total mechanical energy is lost to thermal energy due to friction?

44. A 15 kg child slides, from rest, down a playground slide that is 4.0 m long, as shown in the figure. The slide makes a 40° angle with the horizontal. The child's speed at the bottom is 3.2 m/s. What was the force of friction that the slide was exerting on the child?



In this chapter, you have focussed on mechanical energy. As you continue to study other forms of energy, you will discover that many of the principles that you learned here will apply to these other forms of energy. For example, in the next chapter, you will learn how to quantify the energy that is "lost" from a system when work is done by non-conservative forces such as friction. It may seem obvious to you now that friction generates heat or thermal energy. However, the nature of heat was hotly debated by scientists for many years.

5.4 Section Review

1. K/U How are conservation of mechanical energy and conservation of energy different?

2. C An extreme sport in-line skating competition often involves aerial tricks at the top of a curved ramp that has the shape of a cylinder cut in half. Describe how this activity demonstrates the concept of conservation of mechanical energy.

3. C How is the conservation of energy demonstrated if the in-line skater falls during the competition mentioned in question 2?

4. K/U A skier starts from rest at the top of a ski jump, skis down, and leaves the bottom of the jump with a velocity v. Assuming that the ski jump is frictionless, how many times higher would the jump have to be for the skier to jump with twice the velocity?

5. K/U A bullet is fired into a block of wood and penetrates to a distance Δd. An identical bullet is fired into a block of wood with a velocity three times that of the first. How much farther, in terms of Δd, does the second bullet penetrate the wood?

6. MC Some Olympic sports transform kinetic energy into gravitational potential energy of the athlete's body to aid performance. These sports include:
   - bob sledding
   - high diving off a diving board
   - pole vaulting
   - snow ski racing
   - snow ski jumping
   - trampoline jumping

   (a) In which of these sports can you increase your gravitational potential energy by using better sports equipment? (for example, a better diving board will allow you to jump higher).

   (b) Suppose you can use better materials to produce equipment with greater elastic potential energy. Which sports will be affected?

UNIT INVESTIGATION PREP

Athletic activities from walking to skydiving involve work being done by conservative and non-conservative forces.

- Identify conservative and non-conservative forces involved with your project topic.
- How are non-conservative forces used in the design of sports equipment to increase safety?

CHAPTER 5 Review

REFLECTING ON CHAPTER 5

- Work is the transfer of energy from one system to another, or from one form to another. The equation $W = F_{\parallel}\Delta d$ applies to work done by a constant force that is parallel to the direction of the motion.
- When the force is not constant, the work done can be estimated from the area under the curve of a force-versus-position graph.
- When the force is not parallel to the displacement, only the component of the force that is in the direction of the displacement does work: $W = F\Delta d \cos\theta$, where θ is the angle between the direction of the force and displacement vectors.
- Positive work on a system adds energy to the system.
- Negative work on a system removes energy from the system.
- Kinetic energy is the energy of motion.
$$E_k = \frac{1}{2}mv^2$$
- Gravitational potential energy of a system is its energy stored due to its position above a reference level. $E_g = mg\Delta h$, where Δh is the vertical distance between the system and the reference level.
- Mechanical energy of a system is conserved when work is done by conservative forces.
- Total energy is conserved even when work is done by non-conservative forces. The work done by non-conservative forces decreases the mechanical energy of the system.
$$W_{nc} = E_{final} - E_{initial}$$
- The law of conservation of energy states that the total energy of an isolated system is *always* conserved.

Knowledge/Understanding

1. What is energy?
2. How would you describe a physicist's concept of work to a non-physicist?
3. Describe a scenario where there is an applied force and motion and yet no work is done.
4. A bat hitting a baseball is difficult to analyze because the applied force is continuously changing throughout the collision. Describe how such a situation may be investigated without the use of calculus.
5. Describe the two general types of energy into which all forms of energy can be classified.
6. How much more kinetic energy would a baseball have if
   (a) its speed was doubled?
   (b) its mass was doubled?
7. Differentiate between potential energy and gravitational potential energy.

Inquiry

8. Design an experiment to test the following hypothesis: *The work required to pull a smooth wood block a distance of 1.0 m along a smooth 45° slope is three quarters of the work required to lift the block vertically a distance of 1.0 m.*
   (a) List the equipment and materials you will need to test this hypothesis.
   (b) Develop a procedure that lists all the steps you will follow in your investigation.
   (c) What independent variables are you changing? What dependent variables will you be measuring? What variables are you controlling?
   (d) Suggest some sample observations that might confirm the hypothesis.
   (e) Suggest some sample observations that might refute the hypothesis.
   (f) Carry out the investigation. Record and analyze your observations, and form a conclsion. Include the percentage deviation of your result from the predicted one.

Communication

9. In this chapter, you have learned many new concepts about work and energy. These concepts include the following terms and concrete examples: mechanical work, gravitational potential energy, kinetic energy, law of conservation of energy, energy transfer, conservative versus non-conservative forces, friction, force-distance graphs, motion sensor or photogate, force sensor or force meter, cars on inclines, building elevator, braking car, skidding bicycle, bowling balls, bow and arrow in archery, sports performance, careers, rockets and space stations, pendulums, wind-up toys, weight lifting, pushing boxes.

   Create a graphic organizer, such as a concept map, mind map, or flow chart, to show the logical connections between the concepts, events, and objects in the list.

10. Draw a force-versus-displacement plot that represents a constant force of 60 N exerted on a Frisbee™ over a distance of 80.0 cm. Show the work done on the Frisbee™ by shading the graph.

Making Connections

11. A coin is dropped from a cliff, 553 m down into the ocean. While in free fall, it eventually reaches terminal velocity (see Chapter 2). Discuss with the aid of a free-body diagram:
    - **(a)** What force does work on the coin, causing it to fall?
    - **(b)** What force does work on the coin, reducing its acceleration to zero when terminal velocity is reached?
    - **(c)** Is the coin doing work on any objects during the fall? Explain.
    - **(d)** How fast would the coin be falling if there was no force doing negative work on it?

12. Make a list of Olympic sports that involve exerting a force over a distance. For example, running involves pushing with a force over a distance. Your foot pushes backwards on the track through a distance as you move forward.

13. Choose *one* of these sports. Analyze the way a force is applied through a distance. Suggest a possible improvement so that less work (either less force or less distance) is needed to produce the same velocity or distance.

Problems for Understanding

14. Calculate the velocity a 1.0 g raindrop would reach if it fell from a height of 1.0 km. Explain why raindrops do not reach such damaging speeds.

15. A car travels at a constant velocity of 27.0 m/s for 1.00×10^2 m.
    - **(a)** Name all of the forces that act on the car.
    - **(b)** Which, if any, of these forces are doing work on the car? How much work are these forces doing?

16. In order to start her computer, a student pushes in the button to turn on the monitor. This action requires her to do 0.20 J of work. Find the average force that must be applied if she pushes the button a total distance of 0.450 cm.

17. A young girl pushes her toy box at a constant velocity with a force of 50.0 N. Calculate the work done by the girl if she moves the box 7.00 m.

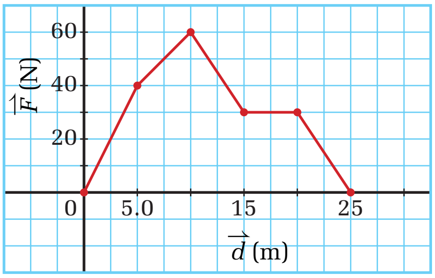
18. A total of 684 J of work are done on a couch by moving it 3.00 m at a constant velocity against a frictional force of 80.0 N. Find the net force exerted on the couch.

19. A horse pulls a wagon that was initially at rest. The horse exerts a horizontal force of 525 N, moving the wagon 18.3 m. The applied force then changes to 345 N and acts for an additional distance of 13.8 m. Calculate the total work done by the horse on the wagon during the trip.

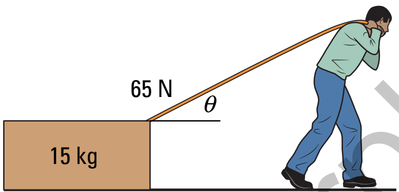
20. A man drags a small boat 6.00 m across the dock with a rope attached to the boat. Find the amount of work done if the man exerts a 112.0 N force on the rope at an angle of 23° with the horizontal.

21. A 65.0 kg rock is moved 12.0 m across a frozen lake. If it is accelerated at a constant rate of 0.561 m/s^2 and the force of friction is ignored, calculate the work done.

22. The following force-versus-position graph shows the horizontal force on a cart as it moves along a frictionless track. If the cart has a mass of 1.25 kg, find the kinetic energy and velocity of the cart at the following positions: 5.0 m, 15.0 m, and 25.0 m.



23. The diagram provided shows a man pulling a box across the floor. Assume that the force of friction can be ignored and that the acceleration of the box is 1.27 m/s^2. Find the angle to the horizontal that the man must pull.



24. A 55 kg running back travelling at 6.3 m/s moves toward a 95 kg linebacker running at 4.2 m/s. Which athlete has more kinetic energy?

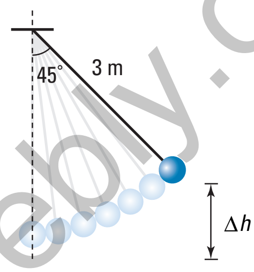
25. A 68 kg in-line skater starts from rest and accelerates at 0.21 m/s^2 for 15 s.

(a) Find her final velocity and total kinetic energy after the 15 s of travel.

(b) If she exerts a breaking frictional force of 280 N, find her stopping distance.

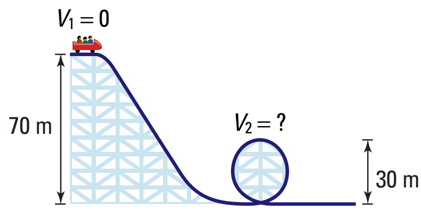
26. A girl climbs a long flight of stairs. She travels a horizontal distance of 30.0 m and a vertical distance of 14.0 m. If her change in gravitational potential energy relative to the ground is 6800 J, find the mass of the girl.

27. A 2.00 kg mass is attached to a 3.00 m string and is raised at an angle of 45° relative to the rest position, as shown. Calculate the gravitational potential energy of the pendulum relative to its rest position. If the mass is released, determine its velocity when it reaches its rest position.



28. A 5.50 kg pendulum is vertically raised 6.25 m and released. Find the maximum velocity of the pendulum and discuss, with the aid of a diagram, where the maximum velocity occurs.

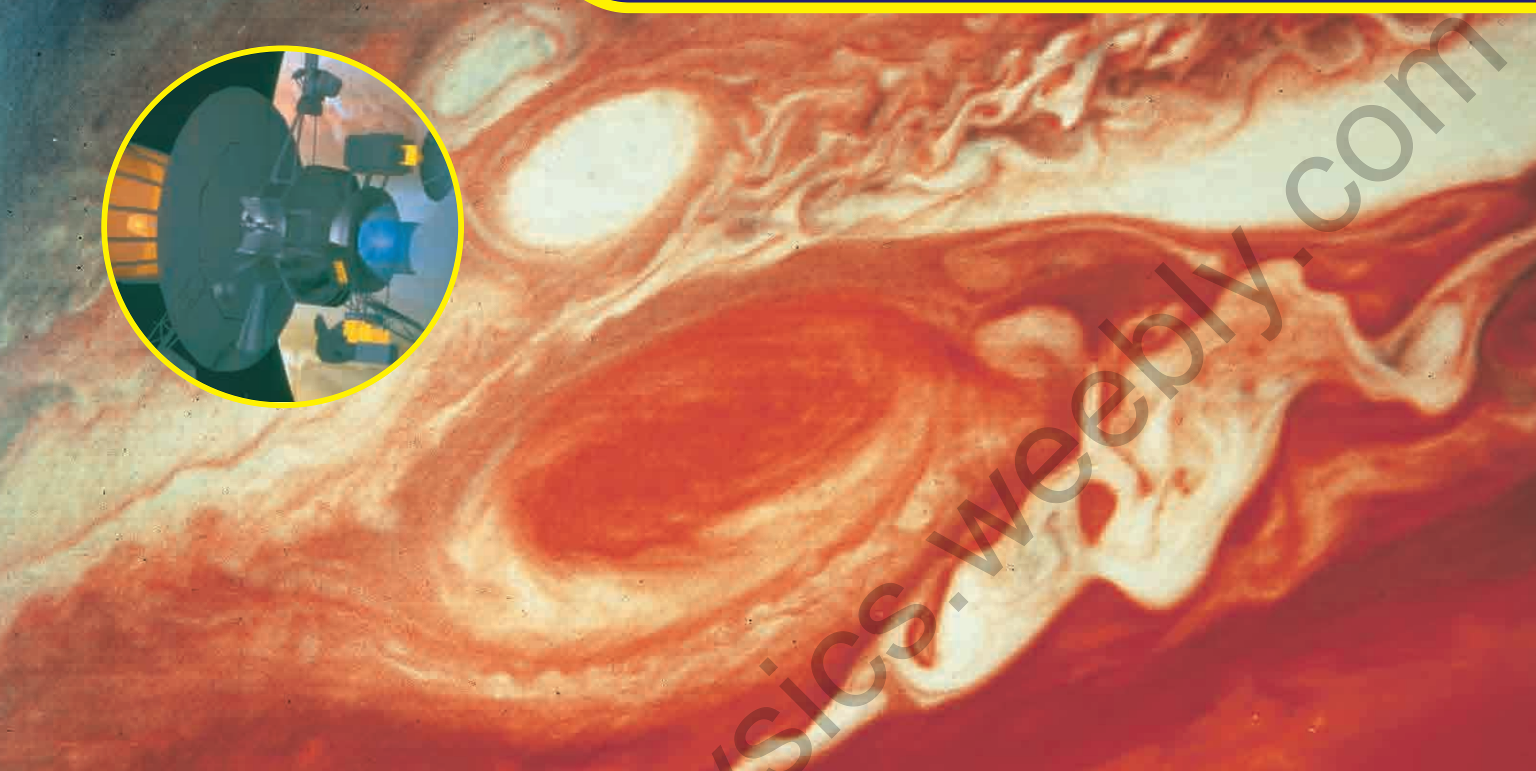
29. A roller coaster at a popular amusement park has a portion of the track that is similar to the diagram provided. Assuming that the roller coaster is frictionless, find its velocity at the top of the loop.



Numerical Answers to Practice Problems

1. 5.7×10^3 J; 42 m **2.** 82 m **3.** 2.30 m/s^2 **4.** 6.33 m **5.** 225 N **6.** 10.9 m **7. (a)** 0 J **(b)** force is perpendicular to direction of motion **8.** 3.00×10^2 J **9. (a)** 0 J **(b)** no forces are acting so no work is done (velocity is constant) **10. (a)** 0 J **(b)** the tree didn't move, so Δd is zero **11. A.** 180 J **B.** 65 J **C.** 0 J **D.** ~ 240 J **14. (a)** 4.1×10^3 J **(b)** -4.1×10^3 J **(c)** gravity and applied force **15.** raising: +126 J; lowering: −126 J **16.** 1.9×10^3 J **17.** 1.4×10^2 N **18.** 40.0° **19.** 81.1 J **20.** 1.0×10^1 kg **21.** 1810 J **22.** 11.5 m/s **23.** 4.1×10^6 m/s **24.** 0.4 J; 4 N **25.** 6.35 kg **26.** 3000 N; 40 m; 160 m; $d \propto v^2$ **27.** 87 J **28.** 2.4×10^6 J **29.** 4.1 m **30.** 1.16 m **31. (a)** 2370 J **(b)** 2370 J **32.** 16 J **33.** 1.51×10^6 J **34. (a)** 1.59×10^5 J **(b)** 2.38×10^5 J **(c)** 3.97×10^5 J **35.** 5.1 m **36. B:** $E_g = 5.9 \times 10^6$ J; $E_K = 1.5 \times 10^7$ J; $v = 28$ m/s **C.** $E_g = 1.8 \times 10^7$ J; $E_K = 2.4 \times 10^6$ J; 11 m/s **D.** $E_g = 1.4 \times 10^7$ J; $E_K = 7.2 \times 10^6$ J; 19 m/s **37.** $E_g = 4140$ J; $E_K = 4140$ J; $v = 5.12$ m/s **38.** ball: 610 J, 22 m/s; shot: 13 J, 22 m/s **39.** 1.0×10^1 m **40.** 15 floors; 49.3 m/s 152 J **41. (a)** 11 J **(b)** 6.7 m/s **(c)** 4.2 m/s **42.** −7.4 J; −180 N **43.** 43.1 m/s; 8.9% **44.** 75 N

CHAPTER 6 Energy Transformations



CHAPTER CONTENTS

The planet Jupiter poses many challenging questions to space scientists. What powers Jupiter's giant storms? Jupiter radiates twice as much energy as it receives from the Sun. What is the source of this excess energy? In search of answers, NASA's spacecraft Galileo, dropped a probe into Jupiter's swirling atmosphere. Data revealed that Jupiter undergoes a phenomenon called the Kelvin-Helmholtz contraction. The planet's own gravitational attraction is causing it to shrink. In so doing, it converts gravitational potential energy into heat. This heat drives the violent weather patterns. The probe descended a mere 0.1 percent into the dense atmosphere before being crushed by extremely high pressures and temperatures. Data collected during the descent, however, support a controversial theory that Jupiter experiences helium rain deep within its nearly bottomless atmosphere. There, atmospheric pressures, a million times greater than Earth's, cause gaseous helium to condense into a liquid.

Understanding how energy is transformed is yet another window into understanding the universe. Space scientists are learning more about a variety of subjects, from the formation of planets to the mechanisms that drive our own climate patterns.

INVESTIGATION 6-A

Developing a Theoretical Framework for Hot and Cold

Whether or not you realize it, you have been conducting informal investigations all of your life. Possibly you learned from experience the difference between hot and cold. This investigation allows you to evaluate the theories you developed from childhood experiences.

Problem

Develop a theory that can explain observed differences between hot and cold objects. The best theory should allow you to accurately predict how heated objects will behave.

Hypothesis

Form a hypothesis about what happens to an object as it is heated. What observable changes occur?

Equipment

- pencil and paper

Procedure

1. Working in a small group, generate a list of observations from memory that suggest an object is becoming hotter. To get started, make a list of the differences between hot and cold objects.
2. List three different ways that heat might be transferred.
3. Within your small group, attempt to create a theory that explains what "heat" is. Write explanations of how your theory relates to as many as possible of the observations you and your group generated in step 1. For example, your theory should be able to explain why heated objects expand. The theory does not have to be based on current scientific knowledge, but instead, must — as accurately as possible — explain and predict observed phenomena.

Analyze and Conclude

1. Test your theory's completeness. Use your theory to predict answers to each of the following questions.
   (a) Why do objects expand when heated?
   (b) What keeps a hot-air balloon aloft?
   (c) Why is heat generated when you rub your hands together?
2. Develop a question that your theory is able to explain, and then pass it to another group to see if its theory can also provide an explanation.

Perhaps a panting dog on a hot day can help you formulate your theory of "heat."

6.1 Thermal Energy

SECTION EXPECTATIONS

- Describe and compare temperature, thermal energy, and heat.
- Analyze situations involving the transfer of thermal energy.
- Identify the relationship between specific heat capacity and thermal energy.
- Compare observations to predictions made by the current scientific model of thermal energy.

KEY TERMS

- kinetic molecular theory
- heat
- thermal energy
- absolute zero
- thermal equilibrium
- thermosphere
- specific heat capacity
- latent heat of fusion
- latent heat of vaporization

In the development of your own theory of heat, you have asked questions similar to those asked by physicists for hundreds of years. Over the centuries, many misconceptions about the nature of heat arose. These were eventually proved incorrect by observation and experiment. How well does your concept of heat and thermal energy coincide with the current theory of heat and thermal energy?

Think It Through

- Write a criticism of each of the following statements about heat and thermal energy.
  1. "The terms 'heat,' 'temperature,' and 'thermal energy' each describes essentially the same thing."
  2. "Heat is a type of substance that resides within an object."
  3. "A piece of wood and a piece of steel, both removed from a pot of boiling water and placed in a single sealed container, will cool to different temperatures."
  4. "Increasing thermal energy will automatically increase temperature."
- As you study this chapter, revisit your criticisms and, if necessary, modify them.

Phlogiston Theory

Possibly the earliest concept of heat was proposed by the early Greek philosopher Empedocles (492–435 B.C.E.). He asserted that matter consisted of four elements: earth, air, fire, and water. According to this theory, a piece of wood contained a solid mass (earth), a great deal of moisture (water), and empty spaces filled with gas (air), and could be made to *release* its fire. It was hundreds of years before scientists began doing detailed experiments and determined that there were many types of gases, not just "air." Some gases supported burning and others did not.

Some 400 years ago, German scientist Georg Ernest Stahl (1660–1734) presented his theory that heat was a fluid that he called "phlogiston." Stahl proposed that phlogiston flowed from, into, or out of a substance during burning. For example, when wood burned, the phlogiston flowed out and the ash left behind was the pure substance. The phlogiston theory explained many observed phenomena, including the smelting of ore. However, about 100 years later, French scientist Antoine Lavoisier (1743–1794) demonstrated that combustion (burning) required oxygen. The phlogiston theory was set aside, but the concept of heat as a substance continued beyond the life of the phlogiston theory.

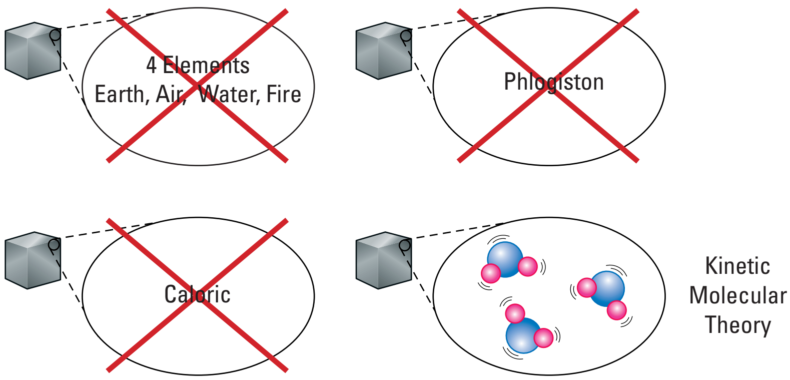


Figure 6.1 The kinetic molecular theory of heat dismisses the earlier false assumption that heat was a substance.

Caloric Theory

British chemist and physicist Joseph Black (1728–1799) performed extensive experiments in an effort to understand heat. His discoveries led to yet another theory of heat, based on a substance called "caloric." Caloric was an invisible, "massless" substance that existed in all materials. It could not be created or destroyed, and exhibited "self-repulsive" forces that made it flow from high concentrations to low concentrations (hot to cold). Everyday experience, as well as most scientific observations, seemed to support this caloric theory. However, one exception eventually brought an end to the theory. Friction, as simple as rubbing your hands together, creates heat. If caloric could not be created or destroyed, how could the act of rubbing two cool objects together — doing mechanical work — generate heat? Many scientists, such as James Joule, began to search for the "mechanical equivalent of heat."

Kinetic Molecular Theory

The current theory of heat evolved along with the discovery that all matter was made up of particles. The **kinetic molecular theory** is based on findings of scientists of the mid-nineteenth century. The findings showed that all matter is composed of particles that are always in motion. Particles in hot objects move more rapidly, thus have more kinetic energy, than particles in cooler objects. **Heat** is now defined as the *transfer* of thermal energy. Heat is not a substance. It does not "flow." **Thermal energy** is the kinetic energy of the particles of a substance due to their constant, random

History Link

Benjamin Thompson (1753–1814), who later became Count Rumford, Imperial Count of the Holy Roman Empire, used science to solve a wide variety of practical problems. When he was superintendent of an arsenal in Bavaria, he observed that, when boring cannons, the metal became extremely hot. He made measurements and showed that the amount of heat produced was proportional to the work done by the boring process. He was one of the first scientists to seriously challenge the caloric theory. It was many years after his death, however, that the scientific community finally accepted the concept that mechanical work can be transformed into thermal energy.

ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner to learn more about the theories discussed here.

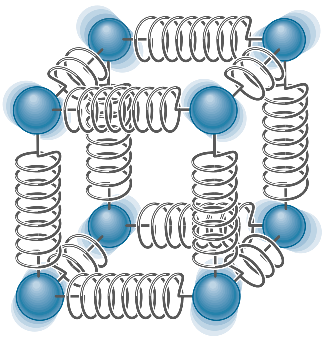


Figure 6.2 Although the molecules in a solid are held together, they can still move and vibrate, as though connected by springs.

Biology Link

When your skin's surface temperature falls too low, your nervous system activates certain muscles. The muscle fibres slide and rub against one another, generating thermal energy. As more clusters of muscles become involved, more heat is produced. Your bloodstream then carries this heat to surrounding tissues, which helps raise your temperature back to normal. Shivering is a very efficient method of generating thermal energy in your body. What are some ways that other organisms use to generate thermal energy? Consider lizards, dogs, and butterflies.

motion. The transfer of thermal energy is the result of fast-moving particles colliding with slower-moving ones, and in the process, transferring energy — thermal energy.

Work and heat are the two methods by which energy can be transferred between a system and its surroundings. These concepts make it possible to express the first law of thermodynamics in quantitative form, as shown in the box below.

FIRST LAW OF THERMODYNAMICS

The change in the energy of a system is the sum of the work and heat exchanged between a system and its surroundings.

$$\Delta E = W + Q$$

Quantity	Symbol	SI unit
change in energy of a system	ΔE	J (joule)
work	W	J (joule)
heat	Q	J (joule)

When using the quantitative form of the first law of thermodynamics, remember the following points.

- When a system does work on its surroundings, it loses energy, so W is negative.
- When the surroundings do work on the system, the energy of the system increases, so W is positive.
- When heat transfers thermal energy out of a system, the system loses energy, so Q is negative.
- When heat transfers thermal energy into a system, the system gains energy, so Q is positive.

Currently, all observed phenomena associated with the heating and cooling of objects support the kinetic molecular theory of heat and thermal energy. Like all forms of energy, thermal energy can do work or can be the result of work. So, the next time you are waiting for the bus on a cold winter day and you rub your hands together to warm them up, remember that you are doing work, transferring muscle energy of movement into thermal energy of warmth, and in the process, disproving the caloric theory of heat.

Figure 6.3 Rubbing your hands together transforms mechanical work into thermal energy.

Table 6.1 The Changing Theories of Heat

Observations	Caloric theory	Kinetic molecular theory
Objects expand when heated.	More heat means more caloric has flowed in, causing an increase in volume.	More energetic random motions cause the particles to occupy more space.
Thermal energy lost by one object will equal the heat gained by another.	The heat or "caloric" flowed from one object to the other.	Energy is transferred from one object to another by collisions.
States of matter (solid, liquid, gas)	The more caloric contained within a substance determined its state. For example, a gas occupies a lot of space; therefore, it must contain a lot of caloric.	As the kinetic energy of the molecules increases, they are able to break bonds with neighbouring molecules and change from a solid to a liquid or a liquid to a gas.
Temperature increases are caused by friction; for example, by rubbing hands together.	The act of rubbing two objects of the same temperature together and getting heat means that caloric was created — which does not fit the theory. The caloric theory *fails* here.	Mechanical work can be transformed into thermal energy. The work done on the particles increases their random motion.

Temperature

The concept of temperature is also fraught with misconceptions that stem from the original error of assuming heat was a substance. Recall that the kinetic molecular theory defines thermal energy as the random motion of the particles that make up an object. Although all particles of a substance are not moving at the same speed, the *average* speed or kinetic energy is a useful property of the substance. The temperature of a substance is a measure of the *average* kinetic energy of its atoms or molecules.

An analogy may clarify this concept. Consider the average height of a Grade 9 versus a Grade 12 class. The average height of the Grade 9 class will be much less than that of the Grade 12 class, even though there may very well be some Grade 9 students who are taller than most of those in Grade 12, or some Grade 12 students who are shorter than most of those in Grade 9. In a hot object, a greater percentage of particles will have higher kinetic energies than they will in a cool object.

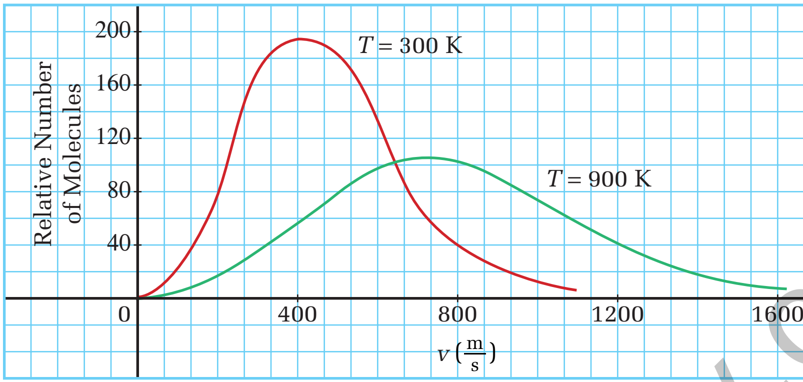


Figure 6.4 These velocity distributions for nitrogen show that a much higher percentage of molecules move at higher speeds in nitrogen gas at 900 K than at 300 K.

Figure 6.5 A full kettle of hot water has more thermal energy than a full cup of the same water.

The temperature of an object does not depend on its mass, but the total thermal energy of an object does. If a pot of boiling water and a cup of boiling water both have a temperature of 100˚C, the amount of thermal energy in the pot of water will be much greater than that in the cup. If the hot water heater was broken and you had to take a bath in cold water, you would obviously choose to pour a full pot of hot water into the tub rather than a full cup of hot water.

The Celsius Temperature Scale

Normal human body temperature is 37˚C (degrees Celsius). Comfortable room temperature is usually 20˚C. You know that your body temperature is warmer than room temperature, but do you know how these values were determined? An old thermometer may measure body temperature in ˚F (degrees Fahrenheit). Normal body temperature using the Fahrenheit scale is 98.6˚F. The fact that normal body temperature is readily represented by two different values highlights the difficulties in developing a theory of heat and defining temperature. Scientists attempted to assign numerical values to temperature before understanding the kinetic molecular theory of matter. Several temperature scales were proposed, but the most popular scale today was established by the Swedish physicist, Anders Celsius (1704–1744). Celsius chose the freezing point of water at standard atmospheric pressure (101.3 kPa) to be 0˚C and the boiling point to be 100˚C. Therefore, one degree Celsius is one one-hundredth of the temperature difference between the freezing and boiling points of water.

PHYSICS FILE

When Celsius devised his temperature scale in 1742, he assigned values in reverse to what are used today (freezing point was 100˚C and the boiling point was 0˚C).

The Kelvin Scale and Absolute Zero

What would it mean for the temperature of a substance to be absolute zero? Since temperature is directly related to the average kinetic energy of the particles in a substance, then **absolute zero** would have to be the temperature at which the substance has zero kinetic energy. There would be no movement of particles.

If particles did not move, they could not collide with each other or with the walls of a container. No collisions would mean no pressure.

In 1848, William Thomson, who became Lord Kelvin, applied concepts from the newly developing field of thermodynamics (movement of thermal energy) to theoretically devise an absolute temperature scale. At about the same time, several scientists were attempting to experimentally determine the coldest possible temperature. The agreement between the theoretical and the experimental approach was excellent. Absolute zero was determined to be –273.15˚C.

Absolute zero was experimentally determined by supercooling low-density gases, such as hydrogen or helium, at constant volume. A graph of pressure versus temperature was plotted. The resulting plot (see Figure 6.6) formed a straight line. When extrapolated to zero pressure the line crossed the temperature axis at –273.15˚C. Further cooling would result in a gas that exerted a negative pressure and that cannot and does not exist.

The size of one unit on the Kelvin scale is the same as one degree on the Celsius scale. However, the unit is not called a degree. Scientists have agreed on the convention that temperatures using the Kelvin scale will be reported without the word "degree." For example, water freezes at 273.15 kelvins, not 273.15 *degrees* kelvin. The SI unit for temperature is the kelvin (K). To convert from Celsius to kelvin, use the relationship shown in the box below.

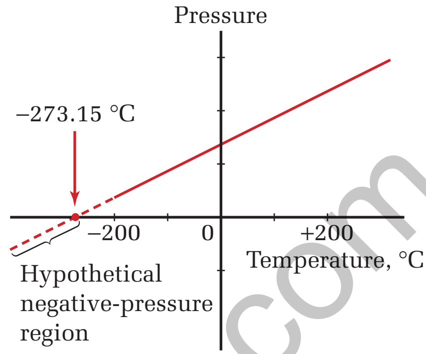


Figure 6.6 Absolute zero temperature is unattainable in the laboratory because, as quantum theory asserts, the lowest possible energy level for atoms and molecules is not zero energy. Nevertheless, temperatures very close to absolute zero can be obtained and you can extrapolate a graph to zero pressure (thus zero energy) and determine the position of absolute zero on a temperature scale.

CELSIUS TO KELVIN SCALE CONVERSION

The temperature in kelvins is the sum of the Celsius temperature and 273.15.

$$T = T_C + 273.15$$

Quantity	Symbol	SI unit
temperature on the Kelvin scale	T	K (kelvin)
temperature on the Celsius scale	T_C	none (˚C is not an SI unit)

Think It Through

- Extrapolating the line on the pressure-versus-temperature plot provided the value of absolute zero.

1. Predict what a volume-versus-temperature plot might look like when cooling a low-density gas.
2. At what point would the line cross the horizontal axis?
3. Describe the significance of this intercept.

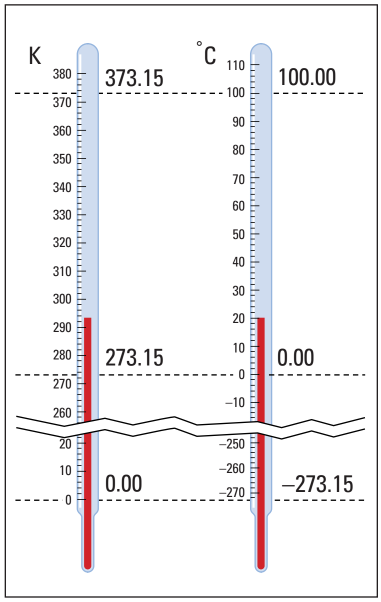


Figure 6.7 A comparison of the temperature scales shows that one Celsius degree is the same size as its kelvin counterpart.

TRY THIS...

Hot or Cold?

Human temperature receptors can readily sense temperature differences but, surprisingly, estimating the actual temperature is not always that simple. Obtain three large beakers. Place hot water (but not so hot that you cannot put your hand in it) in one beaker, room temperature water in another, and ice water in the last. Simultaneously submerge one hand in the hot water and one in the ice water for 60 s. Then remove both hands and place them in the beaker filled with water at room temperature. Describe how the room temperature water feels to each hand. In terms of the kinetic molecular theory, explain why the room temperature water feels different to each of your hands.

Thermal Equilibrium

Place an ice cube in a glass of pop. The ice cube will start to melt and the pop will start to get cooler. This is the natural result of placing two objects of different temperatures together. According to the kinetic molecular theory, energy is being transferred from the warmer pop to the cooler ice cube by millions of collisions. Eventually, the melted ice cube and the pop will reach the same temperature — or **thermal equilibrium**. Although the second law of thermodynamics can be quite complex, one way to express it in a simple form is to state that "thermal energy is always transferred from an object at a higher temperature to an object at a lower temperature" or "an isolated system will always progress toward thermal equilibrium."

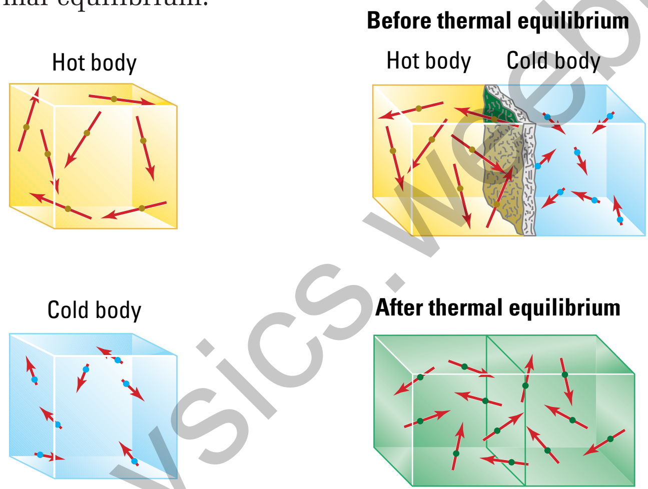


Figure 6.8 **(left)** Particles in a hot object have greater speeds and therefore, greater kinetic energy, than do particles in cold objects; **(right)** thermal energy is transferred from a hot object to a colder object until thermal equilibrium is reached.

Space Link

The top portion of our atmosphere, called the ***thermosphere***, is approximately where the space shuttle flies. There the temperature reaches extraordinarily high values, up to 1500°C during the daytime. When the astronauts leave the shuttle to repair satellites or construct portions of the International Space Station, they require a very special suit. The suit protects them from debris (moving faster than the speed of sound), from harmful ultraviolet radiation, and from freezing to death. How could they freeze to death if the temperature is 1500°C? The answer lies in the difference between thermal energy and temperature. The atmosphere at that altitude is at an extremely low pressure. When a molecule interacts with a high-energy ultraviolet ray, it gains a large amount of kinetic energy and starts moving extremely fast. Since temperature is a measure of how fast the molecules are moving, the temperature is very high. However, there is very little thermal energy at this altitude because there are so few molecules moving about. If an astronaut held out a thermometer to take the temperature, the chance that it would be struck by a fast-moving molecule is slim. Although the temperature is high, the total amount of thermal energy is exceedingly small.

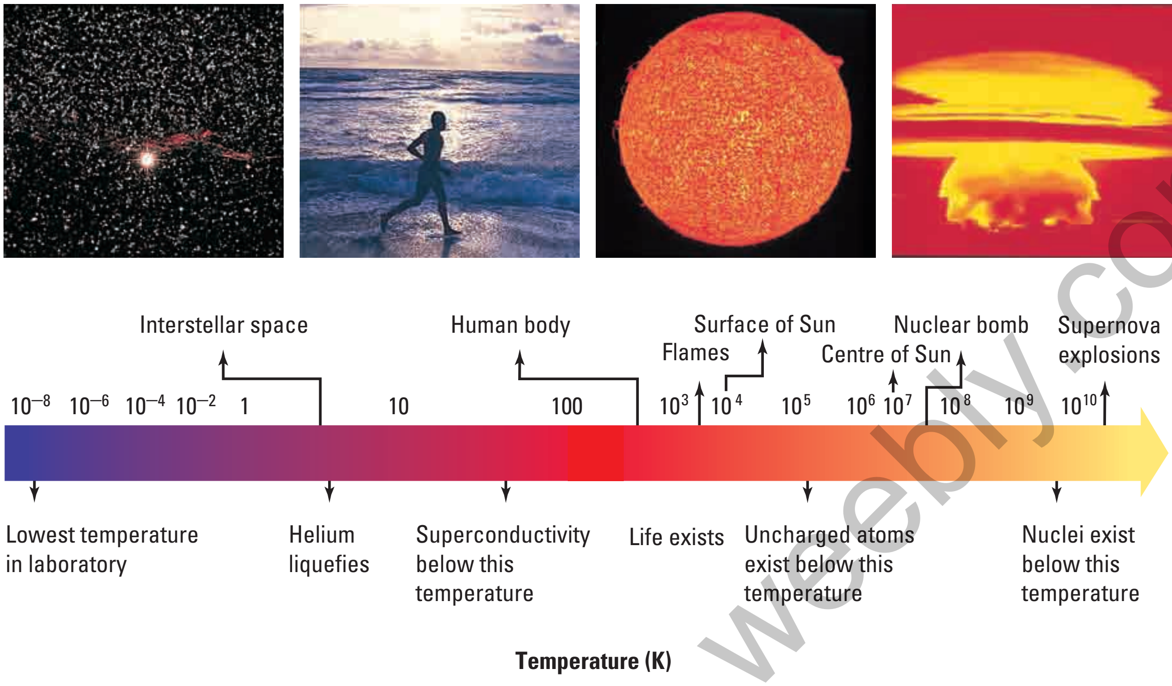


Figure 6.9 An extremely wide range of temperatures can be found throughout the universe.

Think It Through

- Will putting pop cans in a mixture of ice and water cool the pop more or less quickly than placing them in ice alone?

Specific Heat Capacity

Just knowing that thermal energy is always transferred from an object at a high temperature to an object at a lower temperature cannot tell you what the equilibrium temperature will be. The amount of mass of an object and the nature of the material determine the extent of the temperature change. Clearly, for any two objects made of the same material, the object with more mass will require more heat to achieve a specific rise in temperature. The nature of the material plays an equally important role in determining the amount of temperature increase. Different materials have varying capacities to absorb heat for a given temperature change. The specific heat capacity of a substance depends on the type of material and must be obtained experimentally. The **specific heat capacity** of a substance is the amount of energy that must be added to raise 1.0 kg of the substance by 1.0 K. Table 6.2 on the following page provides specific heat capacities for some common substances.

Web Link

www.school.mcgrawhill.ca/resources/

The Sun's surface temperature is about 6000°C, but the corona (the Sun's atmosphere) is much hotter — millions of degrees hotter. How does all of that energy get into the corona without heating up the surface? Try to answer this question, then visit the above web site to compare your answer with that of the experts. Follow the links for **Science Resources** and **Physics 11**.

PHYSICS FILE

The extraordinarily large specific heat capacity of water is one of the reasons why you can go outside in the middle of winter or on the hottest day of the summer without a significant, possibly dangerous, change in your body temperature. A large specific heat capacity means that a great deal of heat transfer must occur before the temperature of water will change significantly. Since the composition of the human body includes a very large percentage of water, a large amount of heat must be added or removed to change the body temperature. The human body also has very capable thermoregulation systems that maintain our body temperature within a couple of degrees Celsius.

Table 6.2
Specific Heat Capacities of Some Representative Solids and Liquids

Substance	Specific Heat Capacity J/kg · °C
Solids	
aluminum	900
copper	387
glass	840
human body (37°C)	3500
ice (–15° C)	2000
steel	452
lead	128
silver	235
Liquids	
ethyl alcohol	2450
glycerin	2410
mercury	139
water (15° C)	4186

HEAT REQUIRED FOR A TEMPERATURE CHANGE

The amount of heat (Q) required to raise the temperature of a quantity (m) of a substance by an amount ΔT is the product of the mass, specific heat capacity, and temperature change.

$$Q = mc\Delta T$$

Quantity	Symbol	SI unit
amount of heat transferred	Q	J (joule)
mass	m	kg (kilogram)
specific heat capacity	c	J/kg · K (joules per kilogram per kelvin)
change in temperature	ΔT	K (kelvins)

Note: The size of a K and a ˚C are the same. Therefore, when temperature *changes* are used, the two scales will give the same result. Most tables report c in J/kg · ˚C.

The specific heat capacity of a *gas* is dependent not only on the type of gas, but also on the variations in pressure and volume. Different values are obtained for specific heat capacities when the measurements are made under conditions of constant pressure compared to those obtained under constant volume. Table 6.3 lists the different values for specific heat capacity that are obtained for selected gases.

Table 6.3 Specific Heat Capacity of Gases

	Specific heat capacity J/kg · °C	
Gas	**Constant pressure, c_p**	**Constant volume, c_v**
ammonia	2190	1670
carbon dioxide	833	638
nitrogen	1040	739
oxygen	912	651
water vapour (100°C)	2020	1520

All values are for 15°C and 101.3 kPa of pressure, except for water vapour.

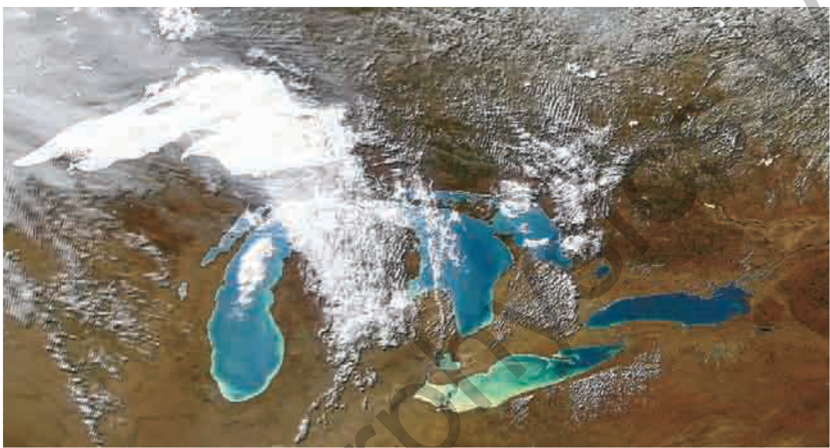


Figure 6.10 This thermograph of the Great Lakes shows dramatic temperature differences in the water. Warmer water is yellow (about 25°C), cooling through dark blue (about 5°C). Cloud cover appears white.

Earth Link

The large specific heat capacity of water plays an important role in weather and climate patterns. For example, Lake Ontario is very deep, containing much more water than Lake Erie. In the winter, Lake Ontario stays much warmer than the cold air masses that move over it. The result is that the warmer water heats the moving air masses above it and loads the air with moisture. When the air mass moves back over the much colder land, the air mass cools and the excess moisture is released as snow. This type of snowfall is termed "lake-effect snow." The city of Buffalo receives significantly more snow than Toronto because of lake-effect snow. Attemp to determine the time of year when the image in Figure 6.10 was captured. Do a web search to find a thermograph of an area of interest to you. Are you able to identify in what season the thermograph was taken?

MODEL PROBLEMS

Calculating a Temperature Change

1. A 55.0 kg person going for an hour-long, brisk walk generates approximately 6.50×10^5 J of energy. If the body's temperature-regulating systems did not remove this thermal energy, by how much would the walker's body temperature increase?

Frame the Problem

- *Thermal energy* generated by muscle action is normally removed by body thermoregulation systems.
- If the thermal energy was to remain in the body, the *body temperature would increase.*
- The thermal energy generated by the muscles, Q, is transferred to all parts of the body by the bloodstream, distributing the heat throughout the body.

continued ▶

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Identify the Goal

Change in body temperature, due to walking briskly for one hour, if no heat was released from the body

Variables and Constants

Involved in the problem		Known	Implied	Unknown
Q	c	$Q = 6.50 \times 10^5$ J	$c = 3500 \frac{\text{J}}{\text{kg} \cdot {}^\circ\text{C}}$	ΔT
m	ΔT	$m = 55.0$ kg	(Obtained from Table 6.2)	

Strategy

The equation for heat transfer causing a temperature change applies.

Calculations

$$Q = mc\Delta T$$

Substitute in given variables and solve.

Substitute first

$$6.50 \times 10^5 \text{ J} = (55.0 \cancel{\text{kg}})\left(3500 \frac{\text{J}}{\cancel{\text{kg}} \cdot {}^\circ\text{C}}\right)\Delta T$$

$$6.50 \times 10^5 \text{ J} = \left(1.925 \times 10^5 \frac{\text{J}}{{}^\circ\text{C}}\right)\Delta T$$

$$\frac{6.50 \times 10^5 \cancel{\text{J}}}{1.925 \times 10^5 \frac{\cancel{\text{J}}}{{}^\circ\text{C}}} = \frac{\cancel{\left(1.925 \times 10^5 \frac{\text{J}}{{}^\circ\text{C}}\right)}}{\cancel{1.925 \times 10^5 \frac{\text{J}}{{}^\circ\text{C}}}}\Delta T$$

$$\Delta T = 3.376^\circ\text{C}$$

Solve for ΔT first

$$\frac{Q}{mc} = \frac{\cancel{mc}\Delta T}{\cancel{mc}}$$

$$\frac{Q}{mc} = \Delta T$$

$$\Delta T = \frac{6.50 \times 10^5 \cancel{\text{J}}}{(55.0 \cancel{\text{kg}})\left(3500 \frac{\cancel{\text{J}}}{\cancel{\text{kg}} \cdot {}^\circ\text{C}}\right)}$$

$$\Delta T = 3.376^\circ\text{C}$$

The walker's body temperature would increase by 3.38˚C (resulting in a body temperature of 40.3˚C) if the heat generated by walking was not removed. A temperature increase of 3.38˚C is considered to be a serious fever, not something that an evening walk should cause.

Validate

Specific heat capacity of an average human body was taken from Table 6.2. Temperature has units of ˚C, which is correct.

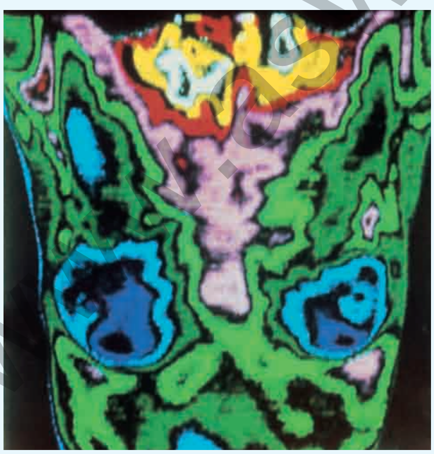

Figure 6.11 Changes in body temperature in different body organs can be detected using thermographs. Physical activity speeds up certain cellular processes, and so does cell division, as shown here. **(left)** Healthy breasts register a bluish colour in thermographs, indicating cooler temperatures. **(right)** The red to white colour shown here indicates higher temperatures, associated with accelerated cell division of malignant tissue.

2. A typical warm-water shower (without an energy-saving showerhead) consumes 130 kg (1.30×10^2 kg) of water at a temperature of 65.0°C.

(a) Calculate how much energy is required to heat the water if it begins at a temperature of 15.0°C.

(b) Calculate the electrical cost of the shower if the utility company's charge is \$0.15 per kilowatt-hour (kW · h). A kilowatt-hour is a convenient way for electrical utility companies to track the amount of energy that your home consumes in a month.

Frame the Problem

- The *temperature* of water is to be *increased*.
- An amount of heat, Q, must be added to raise the water temperature.
- *Electric energy* will be *transformed* into *thermal energy* of the water.

Identify the Goal

(a) The amount of heat, Q, required to raise the water temperature

(b) The cost of the electric energy required to heat the water

Variables and Constants

Involved in the problem	Known	Unknown
Q	$m = 1.30 \times 10^2$ kg	Q
m	$c = 4186 \dfrac{\text{J}}{\text{kg} \cdot {}^\circ\text{C}}$	ΔT
c	cost/kW · h = \$0.15 per kW · h	
ΔT	$T_{\text{initial}} = 15.0^\circ\text{C}$	
T_{initial}	$T_{\text{final}} = 65.0^\circ\text{C}$	
T_{final}		

Strategy / Calculations

Find the change in temperature.

$$\Delta T = T_{\text{final}} - T_{\text{initial}}$$
$$\Delta T = 65.0^\circ\text{C} - 15.0^\circ\text{C}$$
$$\Delta T = 50.0^\circ\text{C}$$

Find the energy required to cause the temperature change by using the formula for heat.

$$Q = mc\Delta T$$
$$Q = (1.30 \times 10^2\ \cancel{\text{kg}})\left(4186\ \frac{\text{J}}{\cancel{\text{kg} \cdot {}^\circ\text{C}}}\right)(50.0^\circ\text{C})$$
$$Q = 2.721 \times 10^7\ \text{J}$$

(a) 2.72×10^7 J of energy must be added to raise the temperature of 130 kg of water by 50.0°C.

continued ►

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Strategy	Calculations
Find the conversion factor from kilowatt hours to joules.	$(1\ \cancel{\text{kW}\cdot\text{h}})\left(\frac{1000\ \cancel{\text{W}}}{\cancel{\text{kW}}}\right)\left(\frac{1\frac{\text{J}}{\cancel{\text{s}}}}{\cancel{\text{W}}}\right)\left(\frac{3600\ \cancel{\text{s}}}{\cancel{\text{h}}}\right) = 3.6\times10^{6}\ \text{J}$
Use the conversion factor to convert energy, Q, to kW · h.	$Q = (2.72\times10^{7}\ \cancel{\text{J}})\left(\frac{1\ \text{kW}\cdot\text{h}}{3.6\times10^{6}\ \cancel{\text{J}}}\right) = 7.558\ \text{kW}\cdot\text{h}$
Determine the total cost.	$(7.558\ \cancel{\text{kW}\cdot\text{h}})\left(\frac{\$0.15}{\cancel{\text{kW}\cdot\text{h}}}\right) = \$1.134$

(b) Heating the water for an average shower costs \$1.14. (**Note:** Utility companies always round dollar figures up.)

Validate

A joule is a small amount of energy, and a large amount of thermal energy is required to change the temperature of water significantly. Thus, 2.72×10^{7} J is a reasonable amount of energy. The units cancel to give dollars in the final answer, which is the expected unit.

PRACTICE PROBLEMS

1. A community pool holds 1.10×10^{6} kg of water. First thing in the morning, the temperature of the pool was 20.0°C. When the temperature was checked later in the day, it was 27.0°C. Calculate how much energy was required to raise the temperature of the water.
2. A scientist added 1500 J of energy to each of two 1.0 kg samples of gas kept at constant volume. One gas is CO_2 and the other is O_2. Calculate the final temperature difference between the two samples if they both started at 20°C.
3. Washing the evening dishes requires 55.5 kg of water. Tap water is at a temperature of 10.0°C and the dishwasher's preferred water temperature is 45.0°C. Find the amount of energy that is required to heat the water. Calculate the electrical cost of washing the dishes if the local utility company charges \$0.120 per kilowatt-hour.
4. A covered beaker of ethanol is sitting in a window in the sun. The temperature changes from 8.00°C to 16.00°C. If this requires 2.00×10^{4} J of energy, find the amount of ethanol in the beaker in kilograms.

Phase Change

The kinetic molecular theory neatly describes how energy can be added to a system without causing an increase in the temperature of the system. Consider a glass full of ice cubes. As thermal energy is added to the ice, the average kinetic energy of the particles increases, which is then reflected in a temperature increase. When the temperature reaches 0°C and energy continues to be added, the ice will melt into liquid water that also has a temperature of 0°C.

Adding more energy will melt more ice, until all of the ice is melted. Only after all of the ice has melted will the water temperature begin to increase once more. The kinetic molecular theory explains that as energy is added, the kinetic energy of the particles increases to a point where it is able to break the bonds that keep the ice cube solid. The temperature will not increase when energy is added during a phase change (from solid to liquid or liquid to gas). The added energy is being used to do work on the bonds that keep the object in a given state.

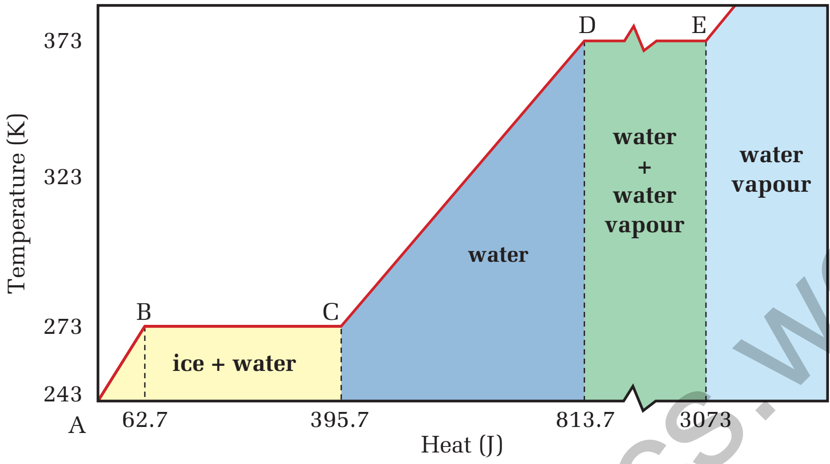


Figure 6.12 This is the heating curve of water. The plateaus on this heating curve are associated with phase changes.

Phase changes require a change in internal energy. The amount of energy required for a phase change depends on the substance and whether the change of state is from solid to liquid (melting) or from liquid to gas (vaporization). The temperature remains constant during a phase change and, therefore, the "heat" remains hidden. For this reason, it is called the "latent heat" or hidden heat of a transformation of a substance. Table 6.4 lists the **latent heat of fusion** (melting) and **latent heat of vaporization** of several substances.

Table 6.4
Latent Heats of Fusion and Vaporization for Common Substances

Substance	Latent heat of fusion L_f (J/kg)	Latent heat of vaporization L_v (J/kg)
helium	5 230	20 900
oxygen	13 800	213 000
ethyl alcohol	104 000	854 000
water	334 000	2 260 000
lead	24 500	871 000
gold	64 500	1 578 000

Biology Link

Fur seals that live in Arctic waters not only have a thick layer of fur, but they also have a layer of fat just below their skin that acts as excellent thermal insulation. When in the frigid water, they lose excess heat through their fins. However, if they move over land, the heat generated by muscle action cannot escape from their bodies and, thus, it increases their body temperatures excessively. Death due to heat prostration is common, even when air temperatures are below 10°C. Do some research on the *counter-current mechanisms* of their circulatory systems that also help keep their body temperature regulated.

Language Link

When a gas condenses, the heat per unit mass given up is called the "latent heat of condensation" and is equal to the latent heat of vaporization. Likewise, when a liquid freezes, the heat per unit mass given up is called the "latent heat of solidification" and is equal to the latent heat of fusion. What does *latent* mean?

Have you ever been outside on a calm winter's day when beautiful, large snowflakes flutter down from the sky? If you have, you may recall that the ambient temperature always seems a little warmer than it is on days without snow. There is some real physics behind that perception. When water vapour condenses into ice crystals, forming snowflakes, energy must be liberated. Looking at Table 6.4, you can see that 2.26×10^6 J of energy are released for every kilogram of snow formed. That is a lot of energy being released into the environment, which often results in a perceptible rise in air temperature.

HEAT AND CHANGES OF STATE

The heat required to change the state of an amount of mass, m, is the product of the latent heat of the transformation and the mass.

$$Q = mL_f \quad \text{or} \quad Q = mL_v$$

Quantity	Symbol	SI unit
heat required to change state	Q	J (joule)
mass	m	kg (kilogram)
latent heat of fusion	L_f	J/kg (joules per kilogram)
latent heat of vaporization	L_v	J/kg (joules per kilogram)

MODEL PROBLEM

Heat Removed by Evaporation

When the ambient temperature is higher than your body temperature, the only way your body can rid itself of excess heat is by sweating. The sweat evaporates from the surface of your skin by absorbing energy from your body, thus lowering your temperature. Calculate the amount of energy that must be absorbed to evaporate 5.0 g of water.

Frame the Problem

- *Thermal energy* in your skin is *absorbed* by the *water*.
- When the water *evaporates*, the thermal energy is *removed* from your body.
- The amount of energy required to evaporate the water is dependent on the *latent heat of vaporization* of water.

PROBLEM TIP

When using the equation containing latent heat of fusion or vaporization, always ensure that the mass and latent heat values have appropriate units. If the mass is in grams, then the latent heat must be in J/g. If the mass is in kg, then the latent heat must be in J/kg.

Identify the Goal

Amount of energy absorbed by the water to evaporate 5.0 g

Variables and Constants

Involved in the problem	Known	Implied	Unknown
Q	$m = 5.0$ g	$L_v = 2.26 \times 10^6$ J/kg	Q
m			
L_v			

Strategy / Calculations

The energy of vaporization formula applies to this situation.

$$Q = mL_v$$

Convert the mass to kilograms.

$$(5.0\ \cancel{\text{g}})\left(\frac{1\ \text{kg}}{1000\ \cancel{\text{g}}}\right) = 5.0 \times 10^{-3}\ \text{kg}$$

Substitute known values into formula and simplify.

$$Q = (5.0 \times 10^{-3}\ \cancel{\text{kg}})(2.26 \times 10^6\ \text{J}/\cancel{\text{kg}})$$
$$Q = 1.13 \times 10^4\ \text{J}$$

Round to two significant figures.

$$Q = 1.1 \times 10^4\ \text{J}$$

In order to evaporate, 5.0 g of water needs to absorb 1.1×10^4 J of energy.

Validate

Equivalent mass and latent heat values were used; therefore, the units of mass cancelled.

The water was evaporating; therefore, the latent heat of vaporization was used. Energy has units of joules, which is correct.

PRACTICE PROBLEMS

5. Calculate the quantity of heat that must be removed by an ice-maker converting 4.0 kg of water to ice at 0.0°C.
6. Repeat the above calculation substituting ethyl alcohol for the water.
7. The Canadian Mint regularly produces gold coins. Calculate the amount of pure gold that the Mint could melt in one hour with a furnace capable of generating heat at a rate of 25 kJ/min.

   (Read the Technology Link on the following page before attempting problems 8 and 9.)
8. Assuming that the snow is –4°C and that the water is dumped at +4°C, calculate the amount of heat energy required to operate a Metromelt for one hour.
9. Compare the heat energy required to operate a Metromelt for one day (eight hours) to the equivalent number of hot showers the energy could supply to the citizens of Toronto. Assume that an average morning shower uses 40 kg of water that has been heated from 15°C to 70°C.

PHYSICS FILE

Why Steam Burns

You must add 3.35×10^5 J of energy to 1.00 kg of ice to cause it to melt into liquid water. Remember, the energy being added is not causing the temperature to change, but rather causes the state to change from solid to liquid. It takes considerably more energy, 2.26×10^6 J, to turn 1.00 kg of 100°C water into 100°C steam. Likewise, to condense 100°C steam into 1.00 kg of 100°C water, 2.26×10^6 J must be removed. This is the reason that steam causes such terrible burns. Water at 100°C is not hot enough to cause very serious burns. The energy that is released from the steam condensing on the skin is what causes the injury.

Technology Link

In some large cities across Canada, snow removal after a large storm poses a difficult problem. It must be cleared from roadways and from sidewalks. In the densely packed downtown city core, there is no place to put the snow. One solution to the problem is to melt the snow, using a specially designed machine. Toronto has five such machines, called "Metromelts." Each machine is 16 m long, 3 m wide, and 3.6 m tall. This giant boiler on wheels has a mass of 60 000 kg empty and can travel up to 24 km/h when it is not melting snow. The Metromelt is capable of melting 150 000 kg of snow in one hour. What are some other alternatives to Metromelts that other cities use?

6.1 Section Review

1. MC Why do some pots have copper bottoms?
2. K/U If you were to walk outside on a cold winter evening and touch a piece of wood, a metal fence pole, and a handful of snow, which would feel coldest? Justify your answer.
3. a) K/U Why is the specific heat capacity of the human body, although quite large, less than that of water?
   b) MC How does this large value help our survival?
4. I Extremely hot water is poured into two glasses. One glass is made of pure silver, the other of pure aluminum. Which glass will be hot to the touch first, the silver or aluminum glass? Explain.
5. K/U What happens to the work done when a bottle of lemonade is shaken?
6. K/U When wax freezes, is energy absorbed or released by the wax?
7. C A typical heating curve contains two plateaus. Describe why the plateaus exist.
8. I Why does rubbing alcohol at room temperature feel cool when a drop of it is placed on your skin?

UNIT INVESTIGATION PREP

Dramatic changes in temperature can affect the performance of athletes and sporting equipment.

- Identify the role of temperature in your investigation topic.
- How do materials used in sporting equipment compensate for changes in temperature?

6.2 Power and Efficiency

A 400 t passenger jet, loaded with over 450 people and their luggage, waits at the end of a runway. In less than 60 s, the jet will speed down a 2 km long runway and lift into the air. Meanwhile, halfway around the world, in the Andes Mountains, an old converted school bus slowly bounces along a gravel road. Both the jet and the bus burn fuel to obtain energy for motion. The difference between these vehicles is, of course, the rate at which they convert the chemical energy into motion.

Figure 6.13 Jet engines do an incredible amount of work in a very short interval of time. They generate a large amount of *power*.

SECTION EXPECTATIONS

- Define and describe power and efficiency.
- Analyze the factors that determine the amount of power generated.
- Apply quantitative relationships among power, energy, and time.
- Design and conduct experiments related to the transformation of energy.
- Consider relationships between heat and the law of conservation of energy.

KEY TERMS

- power
- efficiency

Power

The engine in an old school bus could, over a long period of time, do as much work as jet engines do when a jet takes off. However, the school bus engine could not begin to do enough work fast enough to make a jet lift off. In this and many other applications, the rate at which work is done is more critical than the amount of work done. **Power** is the rate at which work is done. Since work is defined as a transfer of energy, power can also be defined as the rate at which energy is transferred.

Technology Link

The powerful machine shown here removed eighty million cubic metres of dirt from beneath the English Channel in less than six years. Two rail tunnels and a service tunnel, 52 km in length, now connect England to France. How important is the tunnel in stimulating trade between the United Kingdom and the European continent? What kinds of vehicles are allowed in the tunnel, and how are their exhaust gases controlled? You may find answers to these and other questions you would be interested in by investigating further.

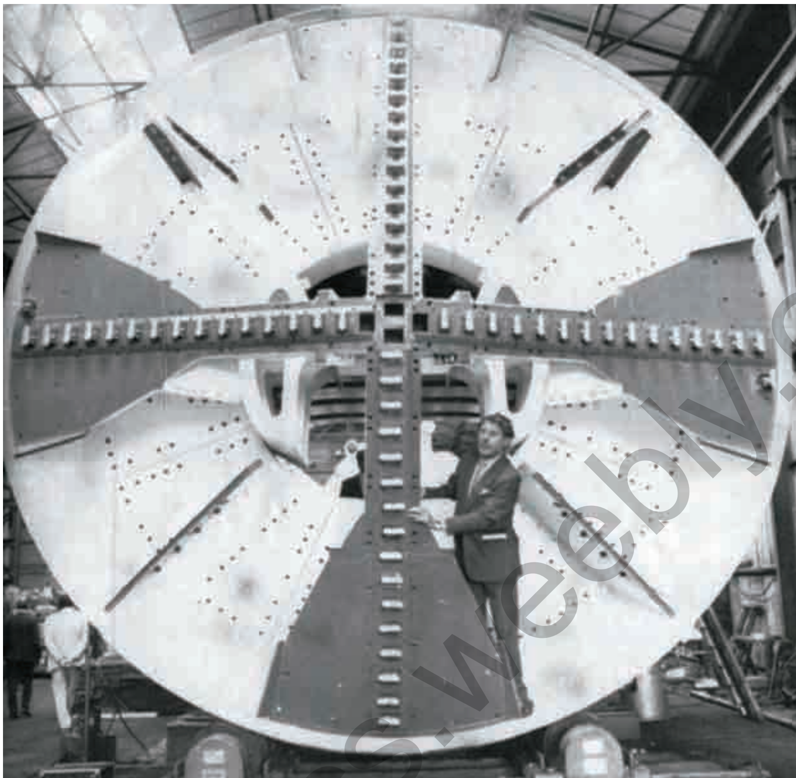


Figure 6.14 Light bulbs and electric appliances are often labelled with a power rating.

DEFINITION OF POWER

Power is the quotient of work and time interval.

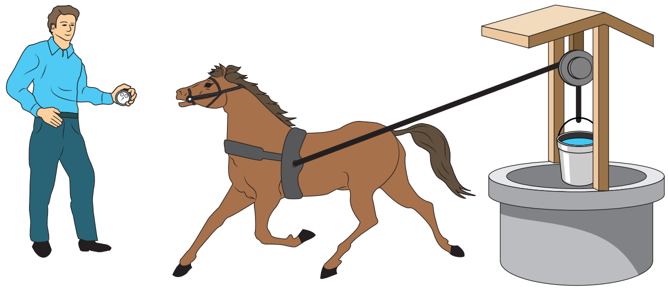
$$P = \frac{W}{\Delta t} \quad \text{or} \quad P = \frac{E}{\Delta t}$$

Quantity	Symbol	SI unit
power	P	W (watt)
energy transferred	E	J (joule)
work done	W	J (joule)
time interval	Δt	s (seconds)

Note: A watt is equivalent to a joule per second: $\mathrm{W} = \frac{\mathrm{J}}{\mathrm{s}}$

Any machine that does mechanical work or any device that transfers energy via heat can be described by its power rating; that is, the rate at which it can transfer energy. The SI unit of power, the watt, can be used to quantify the power of motors, rockets, or even dynamite, but it is most familiar as a power rating for a light bulb. A 60 W bulb transforms 60 J of electric energy into thermal energy and light in 1 s, as compared to a 100 W bulb that transforms 100 J of electric energy into light and thermal energy in 1 s.

The language of power is subtle and different from that of work. Recall that work is done *on* an object and results in a *transfer* of energy to that object. The *rate* of this energy transfer, or power, is often referred to as the power that is *generated* in doing the work. The term "power" not only applies to the rate at which energy is transferred from one object to another or transformed from one form to another, but also to the rate at which energy is transported from one location to another. For example, electric *power lines* carry electric energy across vast stretches of land.



History Link

The unit, the watt, was named in honour of the Scottish engineer, James Watt, who made such great improvements in the steam engine that it hastened the Industrial Revolution. The ability to do work did not change, but the rate at which the work could be accomplished did. Watt did experiments with strong dray horses and determined that they could lift 550 pounds a distance of one foot in 1 s. He called this amount of power one horsepower (hp). Converting to SI units, 1 hp is equivalent to 746 W. What do you think your horsepower is? Design a simple experiment that you could use to determine your horsepower, and then read ahead in the Multi Lab in this section to see another way to determine your horsepower.

MODEL PROBLEMS

Calculating Power

1. **A crane is capable of doing 1.50×10^5 J of work in 10.0 s. What is the power of the crane in watts?**

Frame the Problem

- The crane did *work* in a specified *time interval*.
- *Power* is defined as work done per unit time.
- Simply apply the power definition.

PROBLEM TIP

Remember that a capital "*W*" is the variable that represents work done and "W" also represents the unit of power, the watt. Be careful not to confuse the two, as they are very different. To help distinguish the difference, in this text, symbols for quantities are in italics while units are in roman print.

continued

continued from page 23

Identify the Goal

Power generated by the crane

Variables and Constants

Involved in the problem	Known	Unknown
W	$W = 1.50 \times 10^5$ J	P
Δt	$\Delta t = 10.0$ s	
P		

Strategy

Use the formula for power.

Calculations

$$P = \frac{W}{\Delta t}$$

All needed variables are given, so substitute the variables into the formula.

$$P = \frac{1.50 \times 10^5 \text{ J}}{10.0 \text{ s}}$$

Divide.

$$P = 1.50 \times 10^4 \text{ J/s}$$
$$P = 1.50 \times 10^4 \text{ W}$$

The crane is able to generate 1.50×10^4 W of power.

Validate

Work was given in joules and time in seconds.
Power is in J/s or W, which is correct.

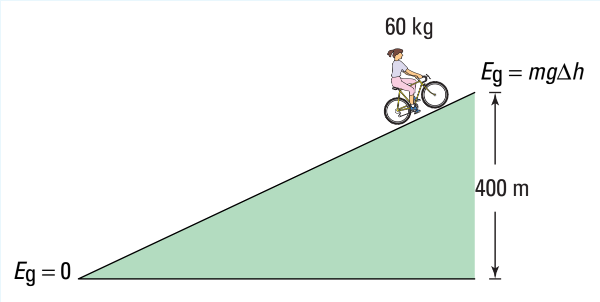
2. A cyclist and her mountain bike have a combined mass of 60.0 kg. She is able to cycle up a hill that changes her altitude by 4.00×10^2 m in 1.00 min.

(a) How much work does she do against gravity in climbing the hill?

(b) How much power is she able to generate?

Frame the Problem

- The cyclist is *doing work* against gravity by cycling uphill, thus *changing her altitude*.
- She is therefore *changing* her *gravitational potential energy*.
- Her *work done* will be equal to her change in *gravitational potential energy*.
- The *time interval* is given, and you can calculate the work done. Therefore, you can use the formula for *power*.



Identify the Goal

(a) Her work done, W, in climbing the hill

(b) The power, P, that she generated

Variables and Constants

Involved in the problem		Known	Implied	Unknown
m	g	$m = 60.0$ kg	$g = 9.81\ \frac{\text{m}}{\text{s}^2}$	W
Δd	P	$d = 4.00 \times 10^2$ m [up]		E_g
Δt	E_g	$\Delta t = 1.00$ min		P
W				

Strategy / Calculations

Work done is equal to change in gravitational potential energy.

$$W = E_g$$
$$E_g = mg\Delta h$$

Substitute known values.

$$E_g = (60.0\ \text{kg})\left(9.81\frac{\text{m}}{\text{s}^2}\right)(4.00 \times 10^2\ \text{m})$$

Multiply.

$$E_g = 2.3544 \times 10^5 \frac{\text{kg} \cdot \text{m}}{\text{s}^2} \cdot \text{m}$$
$$E_g = 2.3544 \times 10^5\ \text{N} \cdot \text{m}$$
$$E_g = 2.3544 \times 10^5\ \text{J}$$
$$W = 2.3544 \times 10^5\ \text{J}$$

(a) Therefore, the work done by the girl to cycle to the top of the 400 m hill is 2.35×10^5 J.

Use the formula for power.

$$P = \frac{W}{\Delta t}$$

Convert time to SI units.

$$t = (1.00\ \cancel{\text{min}})\left(\frac{60\ \text{s}}{\cancel{\text{min}}}\right)$$
$$t = 60.0\ \text{s}$$

The values are known, so substitute. Divide.

$$P = \frac{2.3544 \times 10^5\ \text{J}}{60.0\ \text{s}}$$
$$P = 3.924 \times 10^3\ \frac{\text{J}}{\text{s}}$$
$$P = 3.924 \times 10^3\ \text{W}$$

(b) The cyclist generated 3.92×10^3 W of power. That amount of power is equivalent to 5.25 hp or sixty-five 60 W light bulbs.

Validate

The power is in watts, which is correct.

continued ►

continued from previous page

PRACTICE PROBLEMS

10. A mover pushes a 25.5 kg box with a force of 85 N down a 15 m corridor. If it takes him 8.30 s to reach the other end of the hallway, find the power generated by the mover, in watts.

11. A chair lift carries skiers uphill to the top of the ski run. If the lift is able to do 1.85×10^5 J of work in 12.0 s, what is the power of the chair lift in both watts and horsepower?

12. A 75.0 kg student runs up two flights of stairs in order to reach her next class. The total height of the stairs is 5.75 m from the ground level. If the student can generate 200 W of power and has 20.0 s to reach her classroom at the top of the stairs, will the student be on time for class?

13. A small car travelling at 100 km/h has approximately 3.6×10^5 J of kinetic energy.

(a) How much water in kg could that much energy warm from room temperature (20°C) to boiling (100°C)?

(b) What amount of power would be generated if the total mass of water was warmed in 11 min?

14. A well-insulated shed, built to house a water pump, is heated by a single 100 W light bulb.

(a) If the shed has 10.4 kg of air (assumed to be mostly nitrogen), how long, in minutes, would it take the light bulb to raise the air temperature from –8°C to +2°C? Assume that all of the bulb's energy is thermal energy.

(b) Is your answer to part (a) reasonable? What assumptions could you improve?

15. A 2.0 kg bag of ice is used to keep a cooler of pop cold for 5.5 h. If the ice had an initial temperature of –4°C and, after 5 h, was liquid water with a temperature of 3°C, find the power of energy absorption.

MULTI LAB Investigating Power

Work, Power, and Gravity

You will need two marbles of different sizes, a golf ball, a stopwatch, and a board to act as a ramp. Set up the board so that it forms a ramp approximately 45° to the horizontal. Time the marbles and golf ball as they race to the bottom of the ramp. Verify that the race is fair by controlling necessary variables.

Analyze and Conclude

1. What did you notice about the time required for the different-sized balls to reach the bottom of the ramp?
2. What did you notice about the relative speed of each ball when it reached the bottom of the ramp?
3. What effect did mass have on the time or speed?
4. What ball required the most power to be generated?
5. If gravity is generating the power, what limits exist on the amount of power that could be generated?
6. How does society make use of the power generation of gravity?

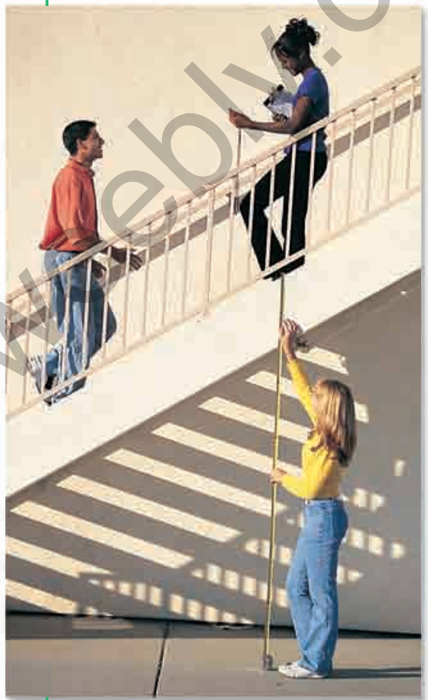
TARGET SKILLS

- Predicting
- Performing and recording
- Analyzing and interpreting
- Identifying variables
- Communicating results

What Is Your Horsepower?

How much horsepower can you develop? How important is speed? How important is mass? To determine your horsepower, all you need is your mass, a stopwatch, and a staircase of known height. Have a classmate record the time it takes you to climb a flight of stairs. Choose a relatively high flight of stairs and run more than one trial.

CAUTION If you have any respiratory or heart problems or any physical condition that could be compromised by running up stairs, do not actively participate in this investigation. Do the theory and calculations only.

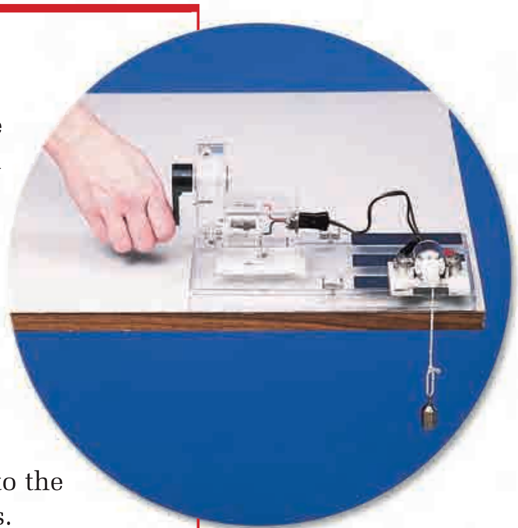


Analyze and Conclude

1. Make an educated guess as to what your horsepower will be. Refer to the History Link on page 277 to help you with your guess.
2. Calculate the work you did against gravity.
3. Use the amount of work you did to calculate the power you generated.
4. Report your answer in watts (W) and in horsepower (hp). **Note:** 746 W = 1 hp.

Generating Power, Transforming Energy

Using a hand-held electric generator and electric winch assembly as shown, investigate what variables determine the amount of power generated. Try different masses and be very careful to observe the relative difficulty you experience when turning the hand crank.



Analyze and Conclude

1. What was generating the electric power?
2. What was generating the mechanical power?
3. What variables affect the amount of power generated?
4. Trace the energy path from your muscles all the way to the gravitational potential energy stored in the lifted mass.

Efficiency

A light bulb is designed to convert electric energy into light energy. A car engine is designed to convert chemical potential energy stored in the fuel into kinetic energy for the car. However, both the light bulb and the car engine become extremely hot while they perform their designed function. Obviously, they have transformed much of the energy into thermal energy. While the light bulb and the car engine are transforming some of the potential energy into the desired form of energy, much energy is "lost."

As you well know, energy cannot be destroyed. However, it can be, and is, converted into forms that do no work or do not serve the intended purpose. Transforming energy from one form to another always involves some "loss" of useful energy. Often the lost energy is transformed into heat. The **efficiency** of a machine or device describes the extent to which it converts input energy or work into the intended type of output energy or work.

Web Link

www.school.mcgrawhill.ca/resources/

Gravity is the force behind the generation of power in many examples in nature. Learn more about power generation in nature by searching the Internet. Follow the links for **Science Resources** and **Physics 11**.

DEFINITION OF EFFICIENCY

Efficiency is the ratio of useful energy or work output to the total energy or work input.

$$\text{Efficiency} = \frac{E_o}{E_i} \times 100\% \quad \text{or} \quad \text{Efficiency} = \frac{W_o}{W_i} \times 100\%$$

Quantity	Symbol	SI unit
useful output energy	E_o	J (joule)
input energy	E_i	J (joule)
useful output work	W_o	J (joule)
input work	W_i	J (joule)
efficiency	(none)	none; efficiency is a ratio; units cancel in ratios

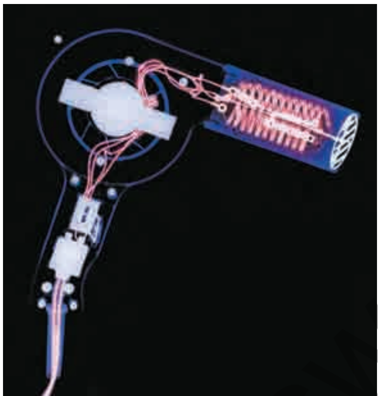
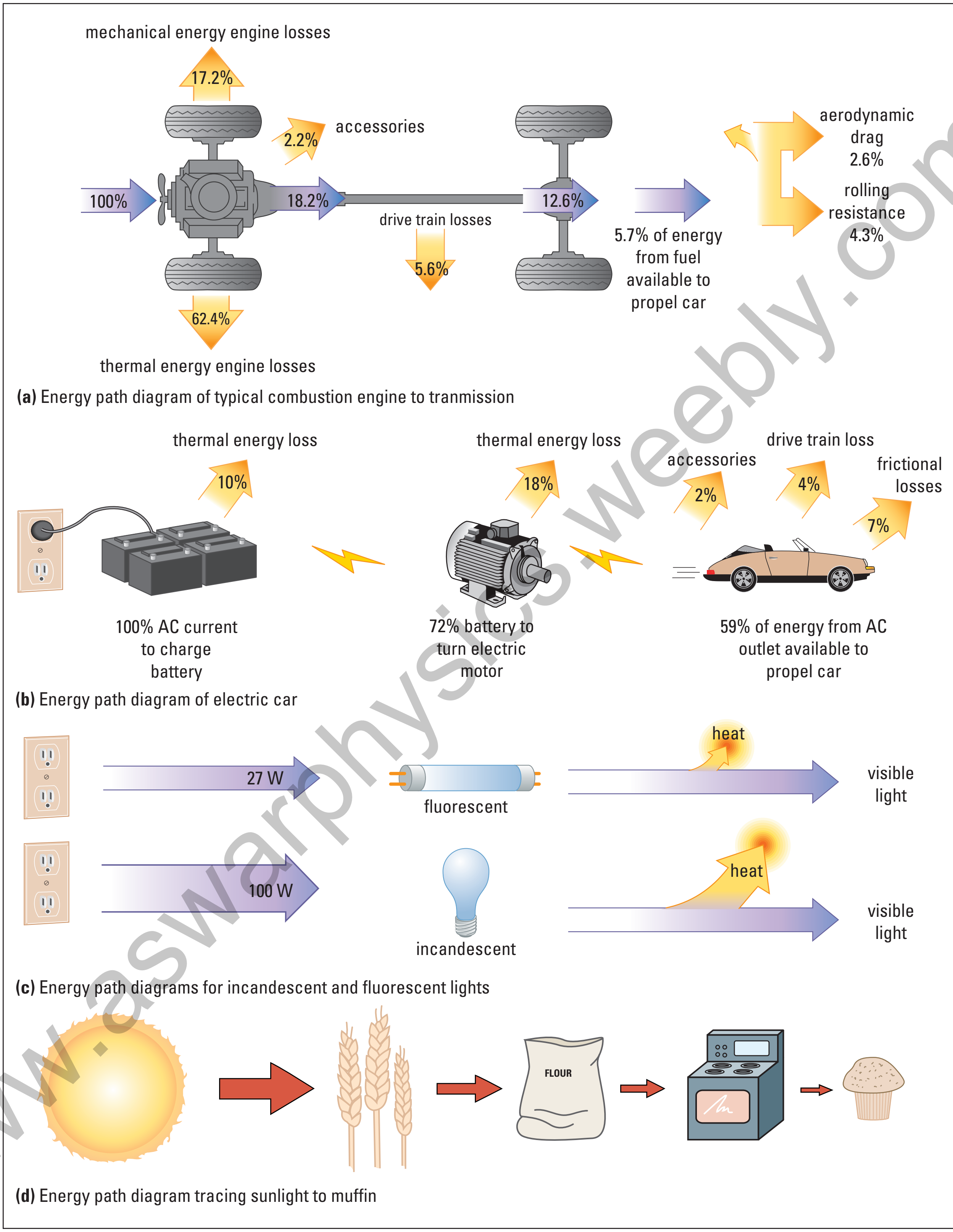


Figure 6.15A Even a hair dryer that is designed to produce thermal energy is not 100% efficient. What other "wasted" forms of energy does it produce?

In most machines and devices, as well as in natural systems, there is more than one energy transformation process. Energy path diagrams provide a visual way to represent how well the energy being put into a system is being transferred into useful work. They also show how and where the input energy is being lost — that is, being transformed into unwanted forms of energy. A few examples are shown in Figure 6.15B.



(a) Energy path diagram of typical combustion engine to tranmission

(b) Energy path diagram of electric car

(c) Energy path diagrams for incandescent and fluorescent lights

(d) Energy path diagram tracing sunlight to muffin

Figure 6.15B Energy path diagrams illustrate energy transformations into both useful and wasted forms.

PHYSICS FILE

French scientist Sadi Carnot (1796–1832) developed a theoretical approach to determine the maximum possible efficiencies that a heat engine could obtain. His work has become fundamental to the field of thermodynamics. He showed that a typical combustion engine, similar to any car engine, could reach a maximum of only 30% efficiency. In fact, combustion engines are only 15 to 20% efficient — much less than the theoretical maximum. The engines lose heat through the friction of their moving parts, through the engine block itself, and by losing a large amount of heat through the exhaust.

Second Law of Thermodynamics

The three processes pictured in Figure 6.16 represent ones that do not violate the first law of thermodynamics, and yet they never occur spontaneously. The reason lies in the second law of thermodynamics, which (recall from Section 6.1) requires that thermal energy is always transferred from an object at a higher temperature to an object at a lower temperature. Part A of the figure can be compared to putting an ice cube in a drink to cool it, only to discover that the ice cube got colder and the drink got hotter. You would be shocked if this happened.

This concept can be applied to machines such as steam engines. While thermal energy is going from high- to low-temperature objects, some of the heat can do mechanical work. The second law of thermodynamics goes one step further by asserting that during the process of heat transfer and doing mechanical work, some thermal energy will leave the system without doing work. As illustrated in part B of the figure, it is not possible to use 100% of the thermal energy of a system to do work. No machine is 100% efficient.

Finally, part C of Figure 6.16 indicates that a random system will not spontaneously become ordered. Try to imagine that you are holding a glass of water and it suddenly feels warm, because all of the energetic molecules (hot) migrated to the walls of the glass, while the less energetic molecules (cool) moved to the centre.

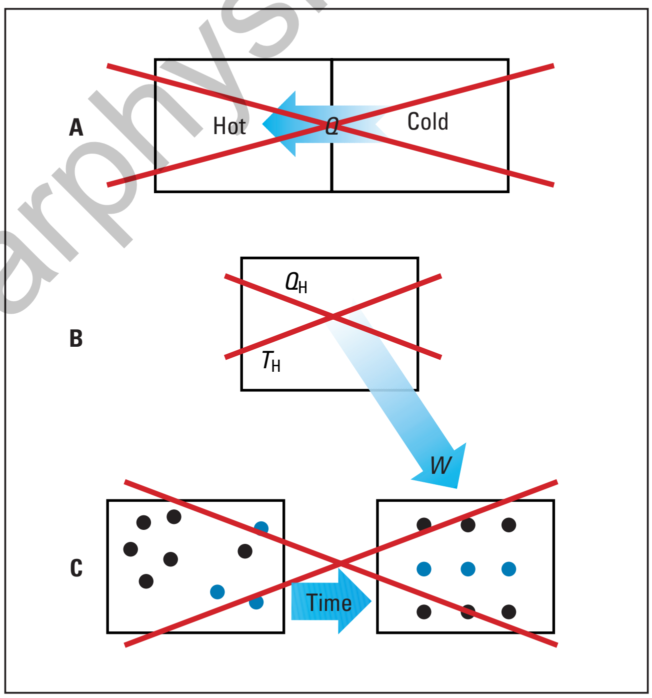


Figure 6.16 The three processes shown here are allowed by the first law of thermodynamics but are forbidden by the second law.

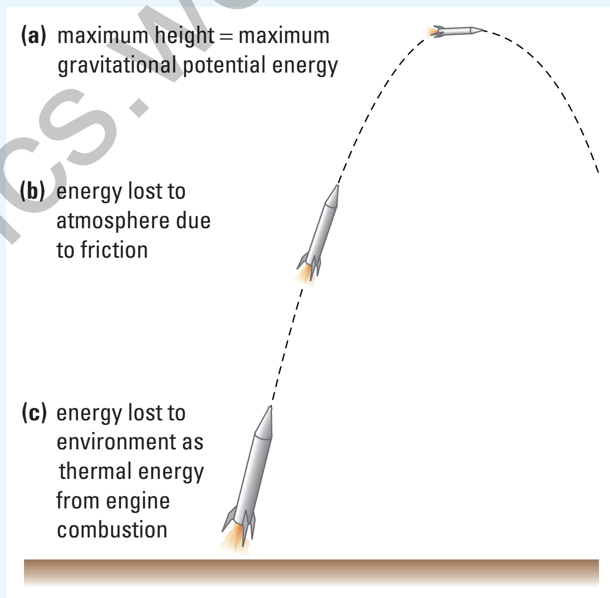
MODEL PROBLEM

Calculating Efficiency

A model rocket engine contains explosives storing 3.50×10^3 J of chemical potential energy. The stored chemical energy is transformed into gravitational potential energy at the top of the rocket's flight path. Calculate how efficiently the rocket transforms stored chemical energy into gravitational potential energy if the 0.500 kg rocket is propelled to a height of 1.00×10^2 m.

Frame the Problem

- The rocket engine transforms *chemical potential energy* first into kinetic energy that will propel the rocket *upward* against gravity.
- The kinetic energy is transformed into *gravitational potential energy*.
- If the energy transformation was 100% *efficient*, then the rocket would reach a height such that its *gravitational potential energy* would be equal to the chemical energy stored in the explosives.
- That will not happen, because a great deal of *energy is lost* as *thermal energy* created both by the combustion of the fuel and by friction with the rocket and the atmosphere.



Identify the Goal

Efficiency of the rocket and engine system in transforming chemical potential energy into gravitational potential energy

Variables and Constants

Involved in the problem		**Known**	**Implied**	**Unknown**
m	W_i	$m = 0.500$ kg	$g = 9.81 \frac{m}{s^2}$	W_o
Δh	W_o	$\Delta h = 1.00 \times 10^2$ m		efficiency
g	efficiency	$W_i = 3.50 \times 10^3$ J		

continued ►

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Strategy / Calculations

The useful work output is the gravitational potential energy.

$W_o = E_g$

Calculate the gravitational potential energy that the rocket has at the top of its flight.

$E_g = mg\Delta h$

Substitute in the variables and multiply.

$W_o = E_g = (0.500\ \text{kg})\ (9.81\ \frac{\text{m}}{\text{s}^2})(100\ \text{m})$

$W_o = 490.5 \frac{\text{kg m m}}{\text{s}^2}$

$W_o = 490.5\ \text{N} \cdot \text{m}$

$W_o = 490.5\ \text{J}$

All the variables needed to calculate the efficiency have been determined.

$\text{Efficiency} = \frac{W_o}{W_i} \times 100\%$

Calculate the efficiency.

$\text{Efficiency} = \frac{490.5\ \cancel{\text{J}}}{3500\ \cancel{\text{J}}} \times 100\% = 14\%$

The energy stored in the rocket engine is transformed into gravitational potential energy (height) of the rocket with an efficiency of 14%. Most of the "lost" energy is transferred to the surroundings as thermal energy.

Validate

The gravitational energy at the rocket's maximum height is correctly assumed to be the W_o.

Efficiency is given as a percentage, which is correct.

PRACTICE PROBLEMS

16. A portable stereo requires 265 J of energy to operate the CD player, yielding 200 J of sound energy.

(a) How efficiently does the stereo generate sound energy?

(b) Where does the "lost" energy go?

17. A 49.0 kg child sits on the top of a slide that is located 1.80 m above the ground. After her descent, the child reaches a velocity of 3.00 m/s at the bottom of the slide. Calculate how efficiently the potential energy is converted to kinetic energy.

18. A machine requires 580 J of energy to do 110 J of useful work. How efficient is the machine?

19. An incandescent light bulb transforms 120 J of electric energy to produce 5 J of light energy. A florescent bulb requires 60 J of electrical energy to produce the same amount of light.

(a) Calculate the efficiency of each type of bulb.

(b) Why is the fluorescent bulb more efficient than the incandescent bulb?

20. A microwave oven transforms 345 J of radiant energy into 301 J of thermal energy in some food. Calculate the efficiency of this energy transformation.

21. A 125 g ball is thrown with a force of 85.0 N that acts through a distance of 78.0 cm. The ball's velocity just before it is caught is 9.84 m/s.

(a) Calculate the work done on the ball.

(b) Calculate the kinetic energy of the ball just before it is caught.

(c) What fraction of the energy transferred to the ball was lost to the atmosphere during flight?

22. Rubbing your hands together requires 450 J of energy and results in a thermal energy increase in your palms of 153 J. Calculate how efficiently the kinetic energy is converted to thermal energy.

23. A 1500 W hair dryer increases the thermal energy of 0.125 kg of carbon dioxide gas at constant pressure by 2.0×10^3 J in 2.0 s. Find the temperature rise of the carbon dioxide gas and the dryer's efficiency.

CANADIANS IN PHYSICS

Shifting Energy Sources: Piotr Drozdz and Azure Dynamics Inc.

For 100 years, combustion engines have supplied our cars with energy. This old-fashioned technology, however, is not efficient. Car and truck exhaust emissions are a major environmental problem, and owning a car is becoming more difficult with the rising cost of gasoline.

Electric cars have received a lot of attention as a possible alternative to combustion engines. They do not produce harmful emissions and they are more efficient, but the batteries that supply the electric energy need to be recharged frequently. Currently, there is little or no infrastructure to allow drivers to recharge their car batteries each day.

Piotr Drozdz, vice-president of technology at Azure Dynamics Inc. in Vancouver, is a pioneer in the field of hybrid electric vehicles (HEVs). HEVs combine the best of two worlds. They have combustion engines to provide the power needed when a car is travelling at high speeds, and electric motors for more efficient energy use at lower speeds. HEVs also do not have to be recharged. They generate their own energy through "regenerative braking." In HEVs, the brakes are coupled to the electrical system so that the kinetic energy of motion is converted to electrical energy.

Drozdz is the primary inventor of a system that acts as the "brains" and decides whether a hybrid electric vehicle uses its combustion engine or its more environmentally friendly electrical motor. The system uses sensors that ensure that energy use is as efficient as possible.

Vehicles powered by electricity is not a new idea. Electric cars like the one above were produced early in the last century. The electric motor was patented in 1821.

Web Link

www.school.mcgrawhill.ca/resources/

For more information about hybrid electric vehicles and other types of alternatively powered cars, buses, and trucks, go to the above web site. Follow the links for **Science Resources** and **Physics 11**.

INVESTIGATION 6-B

Muscle Efficiency and Energy Consumption

TARGET SKILLS

- Hypothesizing
- Performing and recording
- Analyzing and interpreting
- Communicating results

No real process is 100% efficient at transforming stored energy into either mechanical work or heat. Just as it is possible to calculate the efficiency of a light bulb or an automobile motor, with some basic assumptions, it is also possible to determine the approximate efficiency of your muscles.

Problem

You can demonstrate quantitatively that your muscles lose energy when they work. How can the results be put in terms of work done, muscle efficiency, and food energy equivalence?

Hypothesis

Form a hypothesis about the form the lost energy of the muscle will take. Predict the efficiency of your biceps muscle.

Equipment

computer
data collection interface
temperature probe
dumbbell

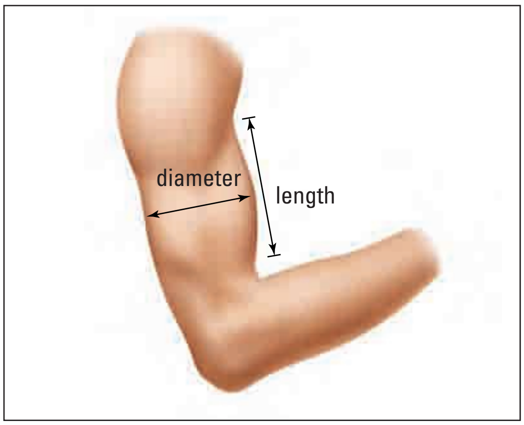
Procedure

The Workout

1. Select a dumbbell with which you will just be able to do 10 biceps curls with one arm.
2. Connect and activate the computer interface and temperature probe.
3. Obtain a base temperature reading for your muscle by holding the probe firmly against your rested biceps for 60 s.
4. With the probe still firmly pressed against your biceps, perform 10 biceps curls with the dumbbell, using only one arm.

Calculating Efficiency

5. Calculate the approximate volume of your biceps muscle. Assume that your arm is essentially a cylinder. Biceps curling involves the muscles on the front half of this cylinder. Therefore, you are able to approximate the volume of your biceps by measuring the length and circumference of your upper arm. Then, calculate the approximate volume of your biceps, using the method shown in the chart on the facing page.



Volume of a cylinder	$V_{cylinder} = \pi r^2 h$
Circumference of a circle	$C = 2\pi r$
Solve for *r*.	$r = \frac{C}{2\pi}$
Substitute into the volume formula.	$V_{cylinder} = \pi\left(\frac{C}{2\pi}\right)^2 h$
Expand.	$V_{cylinder} = \frac{\pi h C^2}{4\pi^2}$
Simplify.	$V_{cylinder} = \frac{hC^2}{4\pi}$
Divide by two for half of a cylinder.	$V_{half\ cylinder} = \frac{hC^2}{8\pi}$

6. Measure C and h. If you take measurements in centimetres, your volume will be in cubic centimetres.

7. To approximate the mass of your biceps muscle, recall that a large percentage of your muscle fibres are water. Convert your biceps volume to the equivalent mass of water that it could contain by using the following relationship: 1 mL of water = 1 cm^3 = 1 g.

8. Calculate the quantity of heat generated. Recall:

   $Q = mc\Delta T$, where m = mass of biceps converted to kg

   c = 3500 J/°K kg (specific heat capacity for the human body)

   ΔT = change in temperature during workout

9. Determine the work done during the 10-repetition workout.

   Recall that $W = F_{\parallel}\Delta d$.

   In this case, the force is equal in magnitude but opposite in direction to the force of gravity acting on the mass: $F = mg$.

   The distance the mass is moved is equal to the length of the arm.

10. Calculate your biceps muscle's approximate efficiency.

    Recall: Efficiency $= \frac{W_o}{W_i} \times 100\%$,

    where W_o = useful work output
    W_i = total work output

    In the case of curling a mass, the total work input is the sum of both the work done on the mass and the heat generated in the biceps. The useful work output is only the work done on the mass.

Analyze and Conclude

1. How did the biceps curls affect the temperature of your working arm?

2. What caused the observed changes?

3. What is the approximate efficiency of your biceps muscle?

4. List all of the assumptions that you made in determining efficiency. How could your estimate be improved?

5. What biological function(s) generated the heat?

6. A single chocolate chip cookie contains 1.34×10^6 J of energy. Calculate how many times you would have to curl the mass you used in the experiment to consume all of the energy supplied by the cookie.

QUICK LAB

Keeping Warm

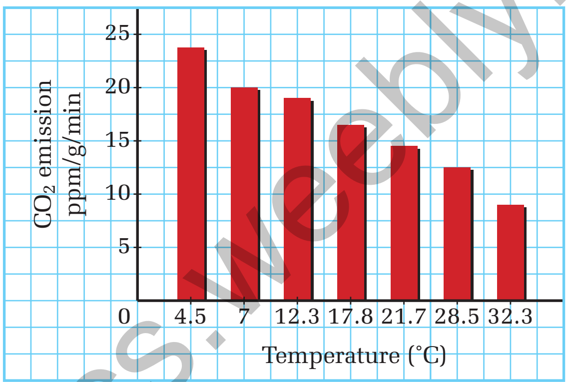
TARGET SKILLS
- Analyzing and interpreting
- Communicating results

Birds and mammals need to maintain a nearly constant body temperature. Even with insulation such as fur or feathers, they still lose heat by radiation and conduction. Two Ontario high school students, Sandra Amicone and Laura Anderson, conducted an experiment to determine how an animal might maintain its body temperature as the ambient temperature (temperature of the surrounding air) dropped. The students placed a hamster in an environmental cage. They controlled the ambient air temperature surrounding the hamster and measured the amount of CO_2 that the animal exhaled. Their graph of CO_2 emission versus air temperature is shown here.

Analyze and Conclude

1. Analyze the students' graph to determine how the hamster maintained a constant body temperature as the ambient temperature dropped.
2. Write a paragraph explaining the conclusion you drew from the data.

Hamster CO_2 Emission versus Temperature



6.2 Section Review

1. K/U Describe the difference between work and power.
2. C Generate an energy-path diagram to show the electric energy consumed in your home.
3. I Develop an algebraic relationship for power in terms of force, F, and constant velocity, v. (Hint: Begin with the power formula and make substitutions for work, W.)
4. MC Based on the second law of thermodynamics, does an air conditioner pump "cold" in or "heat" out of a house?
5. I Consider Table 6.5. Draw an energy path diagram to suggest where energy is being consumed when travelling by (a) city bus and (b) ocean liner.
6. MC Using Table 6.5, compare cycling efficiency to driving, flying, and using a snowmobile.

Table 6.5
Transportation Energy Requirements

Mode of transportation	Energy consumption (kJ/km)
bicycle	52
walking	170
city bus	360
car	674
jumbo jet	2252
snowmobile	6743
ocean liner	8117

6.3 Energy Alternatives

Near the beginning of this unit, you read a description of a typical Canadian's morning routine. The routine required the use of several different forms of energy, such as electricity to run the refrigerator and the microwave, gasoline to power the car, and even light for a solar calculator. Scientific and technological advances have led society from a world that required only food energy to be transformed into muscle power, to one that makes use of every imaginable form of energy. As well, you learned in the last section that, in every energy-transformation process, some useful energy is lost. Clearly, society cannot continue to demand more and more energy without consideration for the future generations.

The next challenge is to develop energy sources and processes that are sustainable. A sustainable resource is one that will not deplete over time and will not damage Earth's sensitive biosphere, while still being able to provide for the energy demands of society. To that end, the use of fossil fuels, which have significant detrimental effects on our biosphere, needs to be and is being replaced with the use of alternative fuel sources.

SECTION EXPECTATIONS

- Analyze the economic, social, and environmental impacts of various energy sources.
- Analyze various energy-transformation technologies from social, economic, and environmental perspectives.
- Synthesize, organize, and communicate energy transformation concepts using diagrams.

KEY TERMS

- fission
- fusion
- biogas
- wind power
- wave power
- tidal power
- geothermal energy
- photovoltaic cell
- fuel cell
- space-based power

Survey of Forms of Energy

A fundamental understanding of the physics of energy forms and transformations will help you to better evaluate the potential sources of energy for society. As you have learned, all forms of energy can be classified as one of two *types*, either as stored or potential energy or as moving or kinetic energy. Figure 6.17 on page 292 provides a survey of common forms of both potential and kinetic energies.

Energy Sources for Today and Tomorrow

Following the review of scientific principles of energy, you will find a survey of technologies related to our energy sources. The short topics highlight current and alternative energy sources, their benefits, and their inadequacies. The dynamic nature of science guarantees that new discoveries will take future research into yet unimagined directions. The following descriptions provide background information and vocabulary to provide a starting point for meaningful discussion and research.

Technology Link

Dutch researchers have developed carbon dioxide-trapping technologies, using both the ocean and underground rock deposits. These technologies may help to reduce the ever-increasing amount of greenhouse gas in the atmosphere. What are some technologies that are helping to reduce carbon dioxide emissions? Keep abreast of technological developments in this area as you progress through the course.

Figure 6.17 Common forms of potential and kinetic energies

POTENTIAL ENERGIES

Energy Form	Explanation
Chemical Potential 	Chemical potential energy is the energy contained within the bonds between atoms. These bonds can take many different forms, including energy derived from carbohydrates in food to energy stored in gasoline. Food energy allows us to do work and gasoline allows our vehicles to do work.
Elastic Potential 	Elastic potential energy is the energy stored within a stretched or compressed object, such as an elastic band or a car bumper. Pole-vaulters store elastic energy in the pole and then use it to glide over the bar.
Electric Potential 	Since opposite charges attract, electric potential energy can be stored by a separation of positive and negative charges. Electric potential energy does work as the electrons move from negatively to positively charged objects.
Gravitational Potential 	Gravitational potential energy is the energy of position. A roller-coaster cart poised at the top of a large hill contains gravitational energy that will result in the cart's passengers' enjoyment of the ride.
Nuclear 	Nuclear energy consists of the energy stored within the nucleus of an atom. When extremely large atoms, such as uranium or plutonium, undergo **fission**, or split in two, tremendous amounts of energy are released. Nuclear power stations use this energy to generate electric energy. Research continues in an attempt to harness energy released when two extremely small atoms undergo **fusion**, or join together.

Kinetic Energies

Energy Form	Explanation
Mechanical Kinetic 	Kinetic energy is the energy of motion. Any object that is moving has kinetic energy, from atoms and molecules to cars, to planets.
Sound 	Sound energy travels through a substance as a wave. (You will study sound waves in Unit 3.) As a sound wave passes through, the atoms or molecules of the substance vibrate back and forth, colliding with the adjacent atoms or molecules. Sound vibrations cause a person's eardrums to vibrate.
Thermal 	Thermal energy is the energy of random motion of the particles that make up an object or system. A bathtub filled with 65°C water has much more thermal energy than a teacup of water at the same temperature.
Radiant 	Radiant energy travels as an electromagnetic wave. Although electromagnetic waves do not involve a moving mass, they do carry energy through space. In fact, in some applications, radiant energy is treated as massless particles or packets of energy called "photons." Radiant energy from the Sun supplies Earth with all of the energy required to sustain life. It also drives all weather systems.

Think It Through

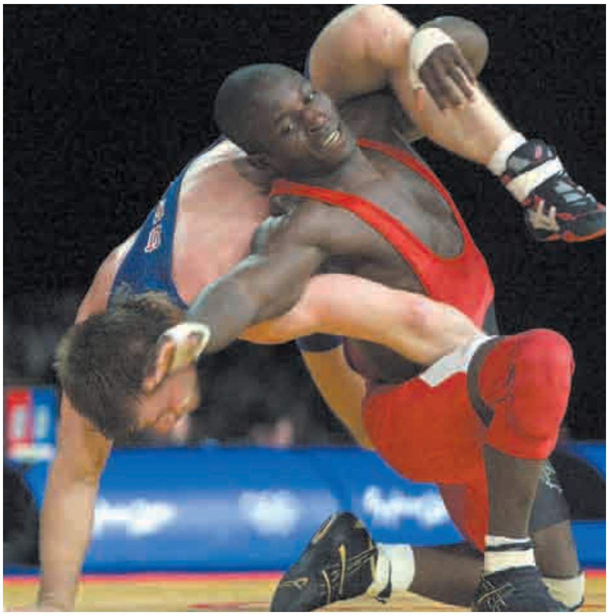
- List the nine forms of energy identified in Figure 6.17 and provide two examples of each that are different from those given there.
- A fraction of energy is always "lost" as energy is transferred from one form of energy to another. What form of energy does this "lost" quantity usually take?

Web Link

www.school.mcgrawhill.ca/resources/

Check out the above web site to learn more about the latest in energy research and technology. Follow the links for **Science Resources** and **Physics 11**.

Muscle Power



Canadian wrestler Daniel Igali, Sydney Olympics gold medal winner

Hunting and gathering were a way of life for people of the Stone Age. With the beginning of agriculture, societies began to herd animals, as well as using animal muscle power to plow their fields. As human settlements increased in size, the energy needs required to circulate goods led to the domestication of animals not only for food but also for transport. Once the muscle power of animals was in use, the opportunity to build and pull heavy carts became evident. With the advent of the wheel, roads were required to travel on, and the construction of roadways demanded more human and animal muscle power than ever before.

Developing countries still depend on muscle power for the majority of their daily tasks, such as getting water from a distant well. First World countries still employ the use of muscle power, but often more for leisure than for sustaining life.

Advantages

- Muscle power is 100% environmentally sustainable, there are no toxic by-products, and when the equipment (human or animal) expires, the remains fold neatly back into Earth's nutrient cycle.

Disadvantages

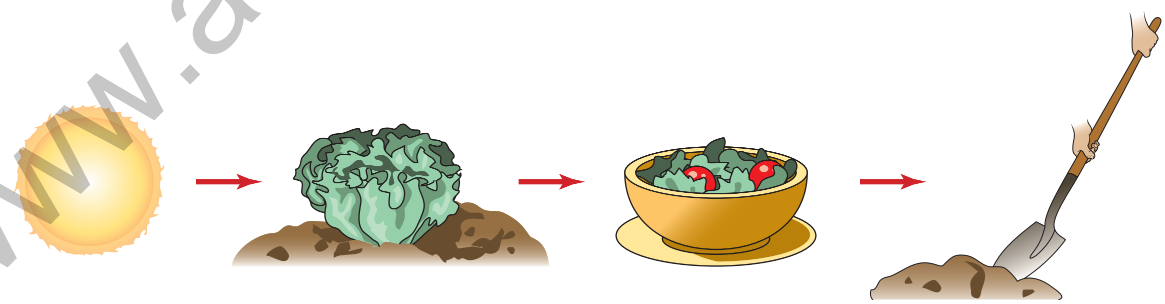
- The amount of work that can be accomplished is limited to the physical strength and power of the work force.
- Human rights violations, such as child labour, occur, as well as unsafe working conditions.

IN CANADA

Energy Consumption
(kJ/passenger-kilometre)

bicycle	52.7 kJ
walking	170 kJ
small car	674 kJ

Muscle Power Energy Path



Fossil Fuels

Steam-driven devices had been in existence for centuries before colonial times. However, they were inefficient and impractical. Then, James Watt made modifications that made steam engines so efficient that they sparked the Industrial Revolution. Soon, steam engines were being employed in every conceivable area of manufacturing and transport. The steam engine required energy — first wood, then coal was used to fuel society's appetite for production.

Fossil fuels are the remains of million-year-old plant life — now coal — or aquatic animal life — now gasoline and natural gas. Fossil fuels were first put to use by the Chinese and then the Romans, but it is the much more recent industrialization of so many societies that has made fossil fuels the primary fuel source of our planet. Approximately 1.4 trillion tonnes of coal are recovered annually.

Coal remained the primary fuel source until the mid-1950s, when oil-fired electricity generation and combustion engines became more economical. The consumption of oil increased rapidly, doubling every 15 years.

Today, 80% of available oil is consumed in North America, Western Europe, the former Soviet Union, and Japan. Two-thirds of the world's oil production comes from five Middle Eastern countries — Iran, Iraq, Kuwait, Saudi Arabia, and the United Arab Emirates.

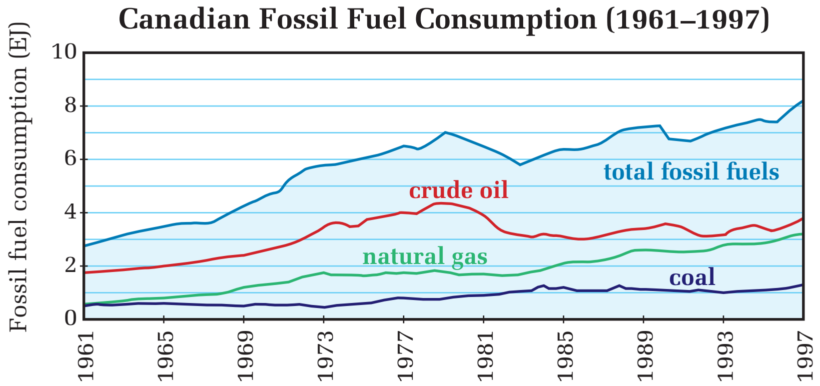
Advantages

- Fossil fuels are relatively inexpensive to process because the infrastructure to do so already exists.

Disadvantages

- Combustion of coal and oil products releases harmful by-products into the air, reportedly contributing to 1000 deaths per year in Toronto alone.
- Combustion products are a source of greenhouse gases and contribute to global warming.
- The production of all types of plastics requires oil by-products, including materials required to create solar panels and other alternative energy transformation equipment.
- Supplies of fossil fuels are limited.

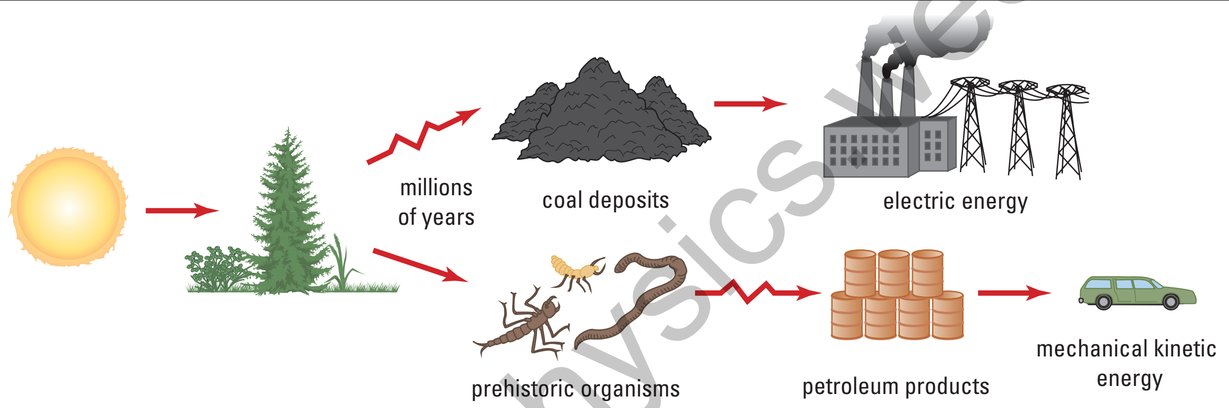
IN CANADA



Math Link

Statistics Canada and the United Nations archives keep detailed records over a wide range of social, economic, and scientific data. Do research to obtain up-to-date data. Have the types of fuels Canadians use changed since the last data on this graph?

Fossil Fuel Power Energy Path



Biomass

"Bio" means life, so bioenergy is energy from living things. The term "biomass" refers to the material from which we get bioenergy. Biomass is produced when the Sun's solar energy is converted into plant matter (carbohydrates) by the process of photosynthesis. Only green plants and photosynthetic algae, containing chlorophyll, are able to use solar energy that originated 150 million kilometres from Earth to synthesize biomass from which we get bioenergy. The simplest process employed to make use of this energy is eating. Every time you eat a fruit, a vegetable, or a processed version of either, you are taking advantage of the energy stored as biomass.

There are many methods currently used around the world to make the best possible use of biomass energy. Burning wood is becoming increasingly popular as a method of electricity generation. Combustion fuels that burn more cleanly are being developed. They use alcohol derived from corn as an additive. This fuel, while marginally more expensive, is available in Canada at agricultural co-operatives. This is an attempt to promote the environmental benefits as well as to provide another use for agricultural products.

Rotting plant matter breaks down under the action of bacteria in the same way that food energy is extracted in the human digestive tract. One tonne of food waste can produce 85 m^3 of **biogas**, which is composed of methane, carbon dioxide, and hydrogen sulfide gas. The biogas is 60% methane and the rest is primarily carbon dioxide. It is an excellent source of fuel for heat- and power-generating plants. It is considered to be a CO_2 neutral fuel because the carbon dioxide that is released was only very recently removed from the atmosphere. Burning wood is also considered to be CO_2 neutral, unlike burning fossil fuel, which releases carbon dioxide that has not been in the atmosphere for millions of years. These types of systems are increasing dramatically in popularity in Scandinavian and European countries.

Advantages

- Biogas systems are highly suitable for processing liquid manure and industrial wastes. The residues can be used as nutrient-rich fertilizers.
- Utilization of biogas systems for farm manure reduces nitrate pollution and the chance of water contamination from E-coli bacteria.

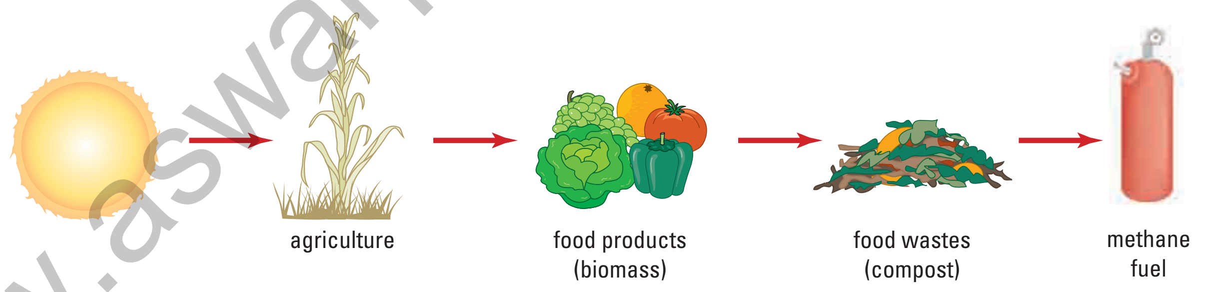
Disadvantages

- Successful biogas systems currently rely on the co-operation of regional farmers and industrial sites to supply a centralized plant. This co-operation can be difficult to achieve.

IN CANADA

- There is limited use of biomass energy generation.
- Most common use is combustion of wood for home heating.

Biomass Power Energy Path



PHYSICS & TECHNOLOGY

TARGET SKILLS

- Select information from sources
- Analyze and solve problems

How should Toronto keep its cool?

Lake Ontario: Toronto's New Air Conditioner

Summertime in Toronto can be sweltering. Despite the summer heat, thousands of Torontonians go to work in downtown office buildings every day. Air-conditioning systems are used to keep the buildings cool, and the people inside them comfortable. These systems require massive amounts of energy, however, and they contribute to pollution and greenhouse gas production.

As a result, Enwave District Energy Ltd., a utility company, and the city of Toronto have decided to experiment with a more environmentally friendly air-conditioning system. The system makes use of the frigid temperature of the deepest water of Lake Ontario, and is called "deep-water cooling."

Office buildings are kept cool by circulating chilled water through air-conditioning systems. In traditional systems, the cooling of the water is electricity-driven and may require the burning of fuel, resulting in the emission of carbon dioxide. Older systems also use refrigerants, such as chlorofluorocarbons and hydrochlorofluorocarbons (CFCs and HCFCs), which damage the ozone layer.

The deep-lake cooling system in Toronto will use cold water from the depths of Lake Ontario near the Toronto Islands to cool the interiors of the city's buildings. Water will be drawn from about 70 m below the surface, where the temperature usually remains at 4°C. Onshore pumps will then suck the water from the lake and draw it into a heat exchanger through already existing pipes.

The heat exchanger transfers heat energy from the existing warm water to the cold lake water. As heat is transferred, the existing water becomes cooler. Finally, water distribution pipes circulate the new, chilled water throughout the building's air-conditioning system, cooling the office air.

Juri Pill, president of Enwave, says the deep-lake cooling project is in its final stages of design. In a few years, he claims, water from the depths of Lake Ontario will be cooling 46% of office buildings in the downtown Toronto core.

Going further

1. Find out more about the construction costs of the project. How soon would the savings in electricity bills cover these costs?
2. The Deep-Lake Cooling Project uses 90 percent less electricity than regular air-conditioning systems, and will reduce carbon dioxide and refrigerant emissions. However, no new system is ever perfect, environmentally or otherwise. Consider the negative impacts or challenges of the project. Conduct a town hall meeting and address the concerns of possible opponents of the project.

Wind Power

Tiverton, Ontario, wind generation station

The kinetic energy of the wind is thought to have carried Australian Aborigines from the mainland of southeast Asia to Australia 40 000 years ago. Travel by boat, using both muscle power and **wind power**, brought about the first contacts between distant people and created trade routes for merchandise and knowledge. Early civilizations harnessed wind power for sailing, but it was not until about 2000 years ago that the first windmills were constructed in China, Afghanistan, and Persia. The windmills were used mainly to pump water for irrigation of farmland. Over 1000 years ago, people of the country we now know as Holland used windmills to pump out large inland lakes that were prone to flooding. The land left behind became fertile farmland.

Wind power is currently used in many parts of the world to generate electricity. By 1996, the wind-turbine installation at California's windy Altamont Pass had a total generating capacity of 3000 MW. This generating capacity is the same as the capacity of one of the Bruce nuclear plants in Ontario. A wind-farm test site, capable of generating 6 MW, has also been installed in Tarifa in southern Spain, a location known as a popular windsurfing destination. The purpose of the test site was not only to determine the suitability of the site, but also to develop locally the required infrastructure of technologies, financing, and materials. Should the tests be successful, the site will provide the community of Tarifa with the ability to implement an 8000 MW facility by 2005. The 6 MW site has already contributed power to the local electrical grid and reduced the use of local oil-fired plants. During the first year of operation, the emissions of CO_2 were reduced by about 12 000 t, SO_2 by 5 t, and NO_x gases by 4 t. Currently, Ontario operates a 0.6 MW facility in Tiverton.

Advantages

- Electricity generation is possible with zero emissions of greenhouse gases.
- There is very limited potential for accidents that could cause widespread ecological damage.

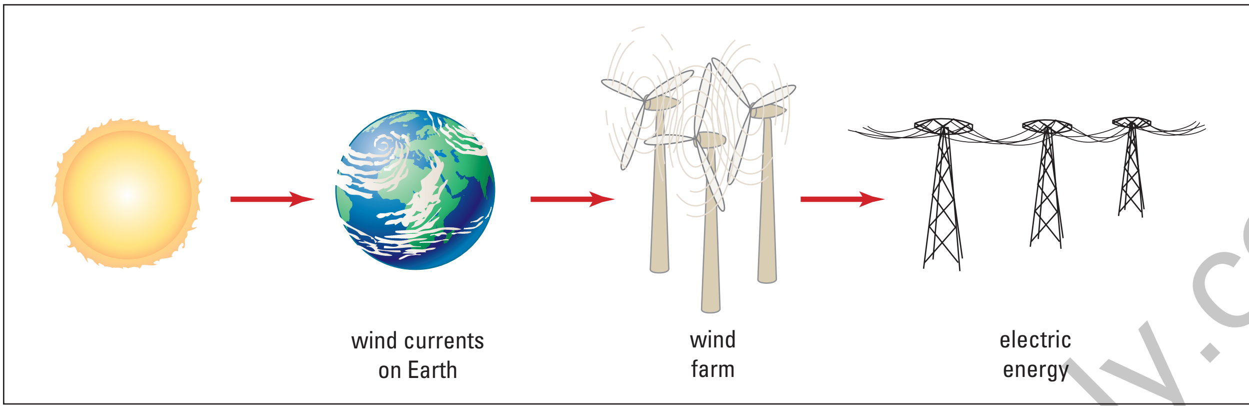
Disadvantages

- It is expensive to develop the needed infrastructure.
- Wind power use is viable only where there is a relatively constant wind of sufficient strength.
- Wind farms require a great deal of open space.
- Suitable sites are often migratory paths for birds. This can cause injury or death to some of the birds.

IN CANADA

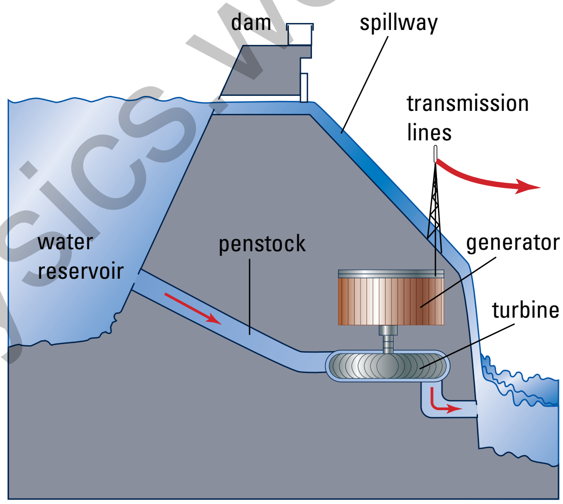
- Canada's landscape and climate have the potential to provide 485 GW.
- Currently, 124 MW are produced — enough to power 34 000 homes.

Wind Power Energy Path



Water Power

Canadian La Grande Complex in northern Québec



Energy is stored in the reservoir due to the tremendous mass of water and its height above the base of the dam. The turbine and generator convert this stored energy — gravitational potential energy — into electric energy.

Electric energy generation using the gravitational potential energy of water is known as hydroelectric generation. In Ontario, seven separate facilities generate up to 2278 MW of power from the fast-moving waters approaching Niagara Falls. Ontarians are so familiar with the concept of generating power using water power that the term “hydro” is often used in place of electricity. The force of gravity does work on the water, pulling it down and providing it with a tremendous amount of kinetic energy. This kinetic energy is transformed into electric energy by very large turbines.

The production of electric energy in this way appears to be a perfect solution, with minimal cost to the environment. This perception is false. In northern Québec, a massive hydro-electric generating dam project called the Canadian La Grande Complex was started in 1973. When completed, it will be the largest dam project in the world. The plan calls for the diversion of three rivers, reversing the flow of a fourth, and then channelling the water from all of those rivers into the La Grand-Rivière, which flows into James Bay. The Chinese government is currently constructing the Three Gorges Dam, which will be the largest single dam in the world when completed. For more details, read "Physics in the News" on page xxx.

Such large reservoirs sometimes flood thousands of hectares of farmland. In other cases, they drastically alter the ecosystem with unknown consequences. For many years, engineers did not have the technology to economically use smaller reservoirs for generating electricity. With improvements in technology, smaller generation facilities are becoming much more popular. Table 6.6 lists the number and capacity of small hydro-electric facilities in selected countries throughout the world.

Table 6.6
Number and Capacity of Small Hydro-Electric Facilities Worldwide

Country	Number of small hydro plants	Power generation capacity (MW)
Canada	500	58 000
China	60 000	13 250
France	1 500	1 646
Italy	1 400	1 969
Sweden	1 350	8 400
United States	1 700	3 420

Advantages

- Power generation is efficient.
- Once the facilities are operational, there is usually limited environmental impact.
- There are well-developed technologies and infrastructure.

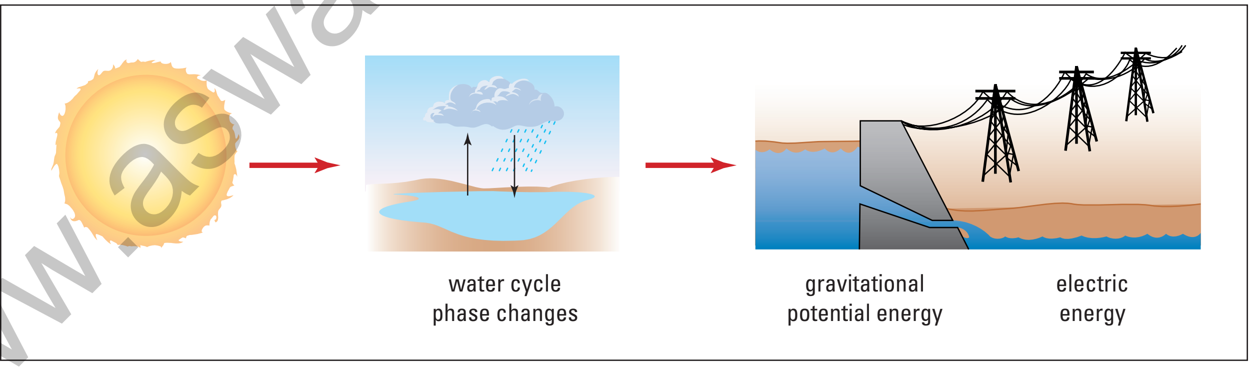
Disadvantages

- Water power requires fast-flowing water.
- Tremendous ecological damage often results from large generating facilities.

IN CANADA

- 58 000 MW total hydro-electric generating capacity in Canada, including
  - 34 632 MW Québec
  - 8072 MW British Columbia
  - 7309 MW Ontario
- Canada exports power to the United States.

Water Power Energy Path



PHYSICS IN THE NEWS

TARGET SKILLS

- Conducting research
- Analyzing and interpreting

China's Controversial Three Gorges Dam

The Three Gorges Dam on China's Yangtze River will be the largest dam ever built if it is completed as planned in 2008, but it may also be the most controversial construction project ever undertaken.

China's Three Gorges Dam

Almost 2 million Chinese citizens are being forced to leave their homes because a massive reservoir will be created upstream from the dam. About $120\ \mathrm{km}^2$ of land will be flooded, including farms and significant archeological sites. Many people believe the dam will cause irreparable environmental damage and species extinction. Since the Chinese government began the project in 1994, environmentalists and other groups have tried to put an end to it.

Many people believe, however, that the future dam will benefit China and the environment. It will supply the country with needed energy in clean hydro-electric form. When water from the Yangtze River falls from the 185 m high dam, it will generate 16 750 MW of electrical power from 26 turbines — roughly the power output of 18 nuclear power plants. The dam will also cut back on the burning of fossil fuels, and thus reduce carbon dioxide emissions. Proponents also hope the dam and the newly available electrical energy will help boost China's economy. In addition to supplying energy, the dam will help control flooding of the Yangtze River, the third-largest river in the world. Hundreds of thousands of people have died in Yangtze River floods over the past 100 years.

In Canada, the dam has received mixed reviews. Canada's Export Development Corporation (EDC) has provided funds for the dam. The EDC reviewed the environmental and social impacts of the project and decided it met the requirements for financial support, says Rod Giles, EDC spokesperson.

Other Canadians remain steadfastly opposed to the dam and believe it comes at too high a price. "The Three Gorges Dam is unnecessary and costly," says Patricia Adams, executive director of Probe International, a Toronto-based watchdog group. Probe International has been trying to convince Chinese citizens and government officials in China and the Western world that the dam should not be supported.

Going Further

1. Controversy has surrounded other dam projects. A Canadian example is the James Bay Project. Find out what made this dam controversial and compare the issues surrounding it with the issues surrounding the Three Gorges Dam.
2. Suggest key steps in the planning and approval of a project such as the Three Gorges Dam that would help resolve controversial issues more effectively.

Ocean-Based Energy

Two thirds of Earth is covered by water, undoubtedly the largest solar collector available. The waves that ripple the ocean's surface only hint at the amount of energy collected and stored by the water. A better window for glimpsing the power that is stored as thermal energy in the oceans is to study the seasonal weather systems that form out in the middle of the Atlantic and Pacific Oceans — hurricanes and cyclones. The destructive power of hurricanes is demonstrated every year, as coastal communities are besieged by storms with winds of over 180 km/h. The ultimate source of the energy for these giant storms is the thermal energy of the ocean waters.

Tapping into the energy of the ocean in a reliable and predictable way has been approached in three basic ways — wave power, tidal power, and ocean thermal power. Tides were used as early as the eleventh century along the coast of present-day England to operate flour-grinding mills. Japan started researching the extraction of power from the ocean as a means to generate electricity as far back as 1945. Since then, engineers in several countries have studied numerous techniques for taking advantage of the power of the oceans. The invention of special turbines and hydraulic machines are opening the way toward practical uses of energy stored in the oceans.

IN CANADA

Wave Power
Canada has open-water ocean coastlines capable of generating 70 MW/km of power on both the east and west coasts.

Tidal Power
The Bay of Fundy has more potential than anywhere else in the world.

Ocean Thermal Power
No development

Wave Power

Wave power devices serve coastal communities in two important ways. One type of device, created in Japan and called "The Mighty Whale," is capable of extracting 60% of the waves' energy and, in doing so, reducing the waves' height by 80%. This provides both electric energy generation and shoreline protection. The sheltered region of shoreline may be suitable for aquaculture — farming of specific fish species. A Norwegian plant was successfully generating 0.5 MW of power until 1988 when 10 m high storm swells destroyed the facility.

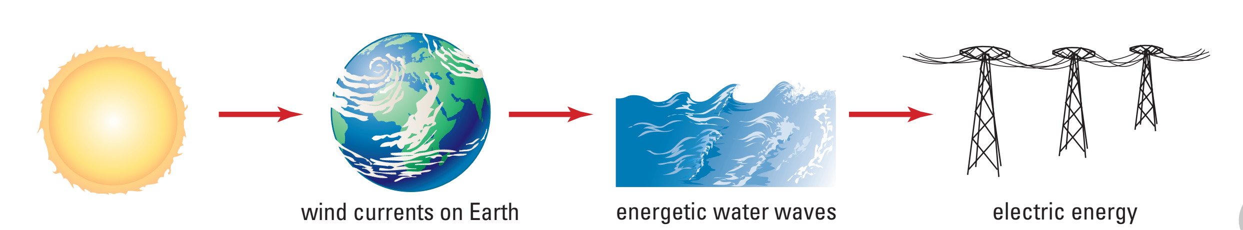
Advantages

- Countries that have access to an ocean have the potential to take advantage of wave power.
- There is a minimal threat to the environment.

Disadvantages

- Currently few countries have invested in wave power research.
- Technology is expensive.

Wave Power Energy Path



Tidal Power

The gravitational attraction of the moon as it orbits Earth causes bulges in the oceans nearest and farthest from the Moon. As our world rotates completely around on its axis once every 24 h, these two bulges become tides twice a day. Capturing high-tide waters, only to release them through turbines during low tide, is another method for generating electrical power from the ocean.

The first modern **tidal power** generation plant, with a capacity of 0.04 MW, was constructed in China in 1956. Since then, eight more tidal power stations have been built in China, with a total generating capacity of 6.2 MW. Canada built North America's first tidal power facility in 1994. The 17.8 MW plant was built on the Annapolis River west of Halifax in Nova Scotia. The Bay of Fundy Tidal Power Review studied several potential sites throughout Nova Scotia and New Brunswick. One of the most promising sites could generate an estimated 3800 MW of power. However, there are no current plans to construct tidal facilities because of the high production costs and the availability of several untapped sites that are suitable for hydro-electricity generation.

Physicists have calculated that rising and falling tides dissipate energy at a rate of two to three million megawatts. Unfortunately, only a small fraction of that energy is recoverable, approximately 23 000 MW worldwide, or about 1% of the available power from hydro generation. This, and the fact that tidal facilities are viable in only a few locations around the world, means that tidal power will not become a global energy resource anytime soon.

Tidal Power

Generation facility location	Power generation capacity (MW)
France	240.0
Canada	17.8
China	6.2

Bay of Fundy tidal power facility

Advantages

- Zero greenhouse gas emissions are produced during the operation of the facility.
- There is a limited environmental impact at the power plant site.

Disadvantages

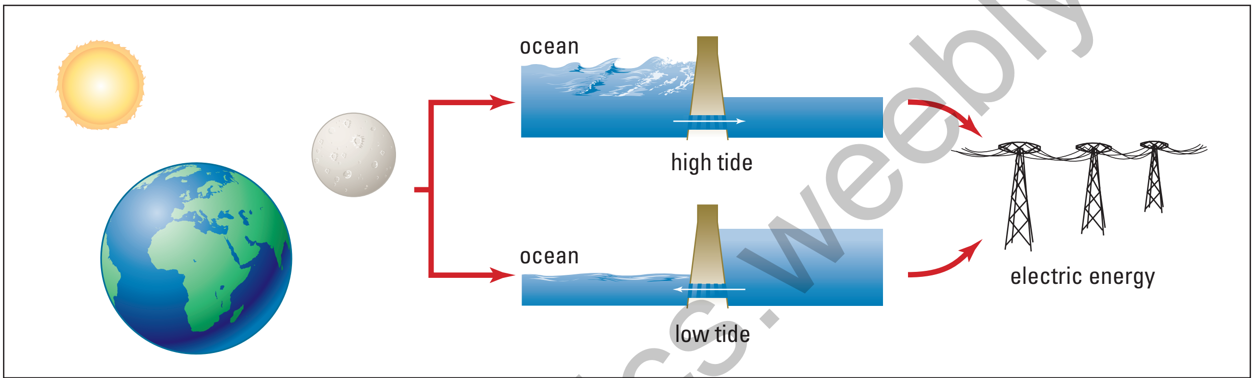
- Few regions on Earth can take advantage of tidal power.
- Theoretical maximum power output per tidal cycle is only three times the power of one wind turbine.

Web Link

www.school.mcgrawhill.ca/resources/

To learn more about tides and the potential of tidal power, go to the above web site. Follow the links for **Science Resources** and **Physics 11**.

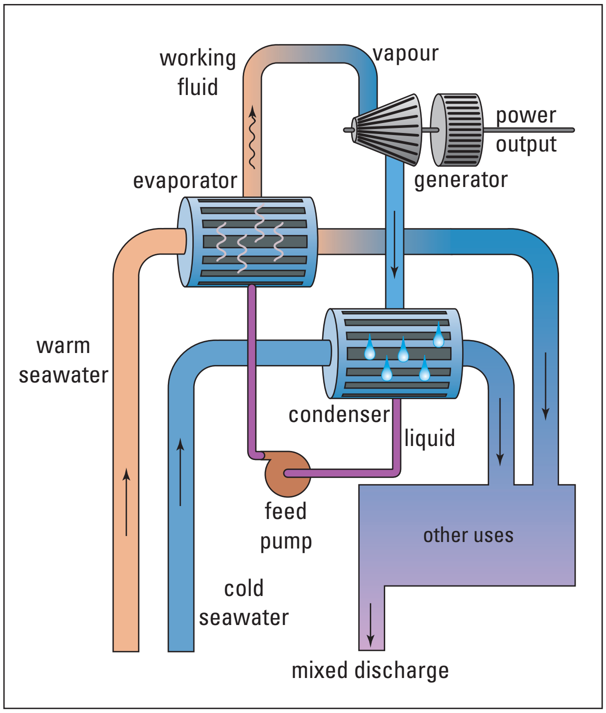
Tidal Power Energy Path



Ocean Thermal Power

In 1881, a French physicist, Jacques d'Arsonval, proposed that the temperature differences between the surface and deep water of the oceans could be used to generate power. His system consisted of a large closed loop that would carry ammonia from the surface to the depths of the ocean and then back again. The ammonia would vaporize as it rose, surrounded by warm water, and drive electrical turbines. Then, it would condense again in the cold section of the loop at the bottom of the sea. In 1930, Georges Claude, a student of d'Arsonval and inventor of the neon light, built and tested an "open cycle" system in the waters off Cuba. The latest adaptation of both the open and closed systems uses temperature differences of at least 20°C between surface and deep waters to generate both electricity and fresh water. The system is known as the ocean thermal energy conversion (OTEC) system.

The Sun's energy warms the tropical ocean water to temperatures close to 30°C. The water,



Closed-cycle OTEC system

due to its high specific heat capacity, maintains this temperature night and day, all year long. The water 1 km below the surface is significantly cooler, often around 4°C (water is most dense at 4°C). The electrical power generated by the OTEC system could be transmitted to a local power grid or used on site to produce hydrogen gas through the electrolysis of water. The electrical energy could also be used to make other valuable substances such as ammonia or methanol, which could be piped to other locations.

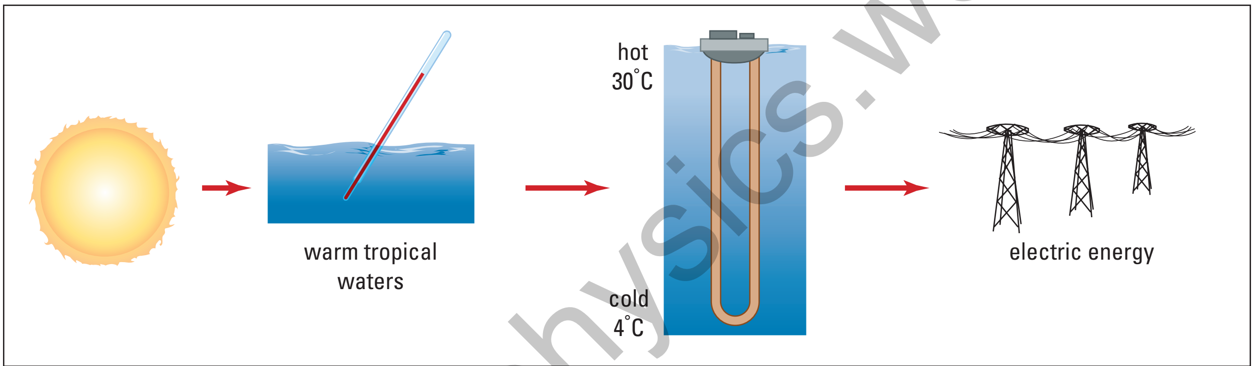
Advantages

- OTEC operational systems would not contribute to greenhouse gas emissions.
- It is environmentally non-destructive at the site of the operation.

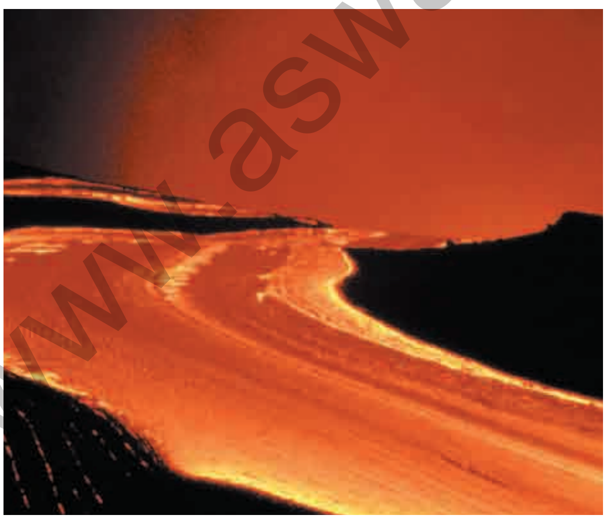
Disadvantages

- It is suitable only in tropical ocean waters near the equator.
- Floating platform construction is expensive.

Ocean Thermal Power Energy Path



Geothermal Power



Geothermal energy is the energy recovered from Earth's core. The thermal energy contained within Earth's core results from energy trapped almost 5 billion years ago during the formation of the planet, and from the heating effects of naturally decaying radioactive elements. The rate of heat flow through Earth's crust is 5000 times slower than the rate of energy arriving from the Sun. Therefore, Earth's surface temperature is the result of energy from the Sun, and not the heat flowing from its core.

Geothermal energy is not, in fact, a renewable energy source, because heat is extracted much more quickly than it is replaced. Although the total thermal energy is finite, the time it would take to deplete this resource would be measured in millennia because of the enormous size of Earth. For this reason, geothermal energy is considered to be renewable.

The four basic geologic formations that allow for the extraction of geothermal energy are hydrothermal; geopressurized; hot, dry rock; and magma. The distribution of favourable sites around the globe tends to be localized near regions of geologic instability that often experience active volcanoes or tectonic movement. These regions are areas where Earth's crust is relatively thin, allowing economical access to the thermal energy beneath it. In Canada, British Columbia is the only area where it is currently feasible to use geothermal energy. California, Iceland, Italy, New Zealand, and Japan all have areas where geothermal energy is used on a significant scale. Geothermal energy is used to heat buildings, including homes, or to create steam that turns electrical generators.

Advantages

- There are no greenhouse gas emissions.
- Geothermal energy is almost unlimited.
- It is a continuous power source that is not affected by weather or other factors.

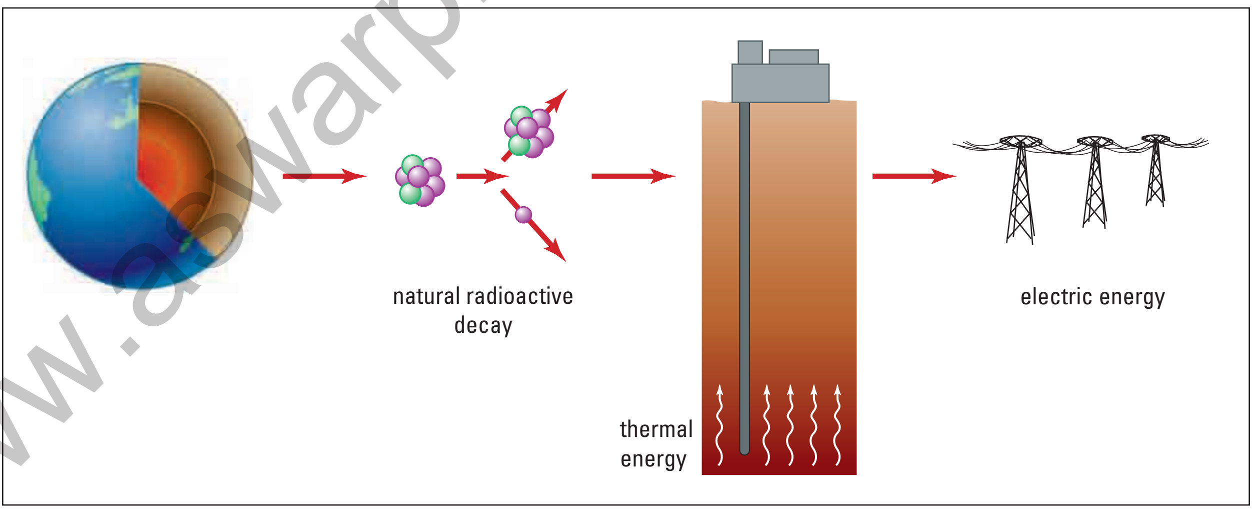
Disadvantages

- There are limited locations on Earth where it is economically viable.
- Naturally occurring, dissolved corrosive salts from the brine that is circulated cause problems for equipment and the environment.
- Hydrogen sulfide (H_2S) gas discharge does occur. It is toxic and even fatal in high concentrations.

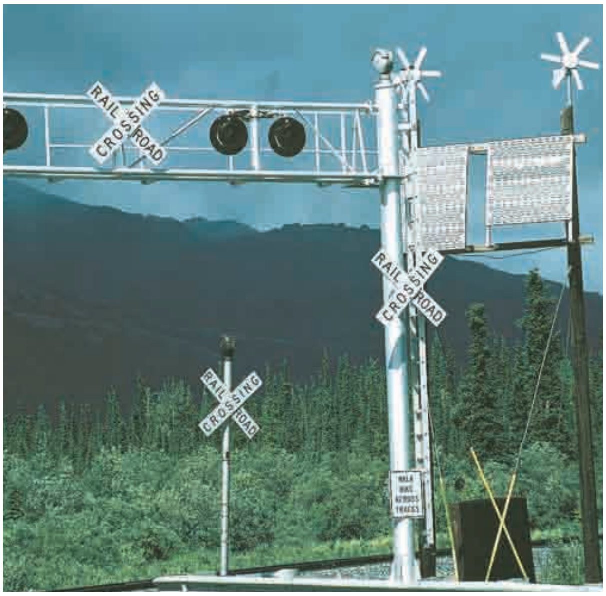
IN CANADA

- Only the west coast of Canada offers geothermal potential.
- Currently, a 60 MW test facility operates on British Columbia's Mount Meager.
- Mount Meager's wells turn water into 270°C steam.

Geothermal Power Energy Path



Photovoltaic Cells



A solar-powered railroad crossing sign

In 1839, French physicist Edmund Becquerel (1820–1891) first discovered that generating electric current directly from sunlight was possible. Another 100 years would pass before commercial applications of the technology would appear. Today, solar cells are used to power everything from calculators and watches to small cities. Sunlight, the fuel required by solar cells, is 100% free and allows for electric energy generation that is completely free of greenhouse gas emissions.

Photovoltaic cells are composed of semiconductors, such as silicon. The sunlight knocks an electron from the crystal structure. Impurities added to the semiconductor do not allow the electron to fall directly back into place. The liberated electron will therefore follow the path of least resistance, which in the case of semiconductors is an external circuit. The flow of electrons in the external circuit can be used directly or stored in batteries for later use.

Several different materials and techniques are used to create photovoltaic cells. Very expensive cells are able to convert sunlight into electrical energy with efficiencies approaching 50 percent. Other procedures use thin films of amorphous silicon deposited on a variety of bases. These cells are much more economical to produce and have the advantage of being flexible and more durable. The weakness of amorphous silicon cells is that they degrade with exposure to sunlight, losing up to 50 percent of their efficiency over time.

Photovoltaic cells have been used very successfully in space, to provide power for satellites and space stations. The variety of different types of solar collectors has also allowed successful implementations throughout the world, from pole to pole. Small-scale power generation, for road signs or individual homes, is gaining popularity as storage battery systems improve. Large-scale solar power generation has been slower off the mark. This slow progress is due to the variability of sunlight. In addition, weather has a dramatic effect on a photovoltaic cell's ability to generate electric current. During nighttime hours, energy must be supplied by solar energy stored during the day. This type of intermittent power supply is a drawback of most renewable sources.

Solar cells are widely used in developing countries, where systematic power-delivery infrastructure does not exist. Individual homes consume the power to cook and cool their food and heat their homes. Industrialized countries demand significantly more power during the workday, when the sun is shining, than at night, so perhaps solar power generation will offer a supplement to help reduce the use of fossil fuels.

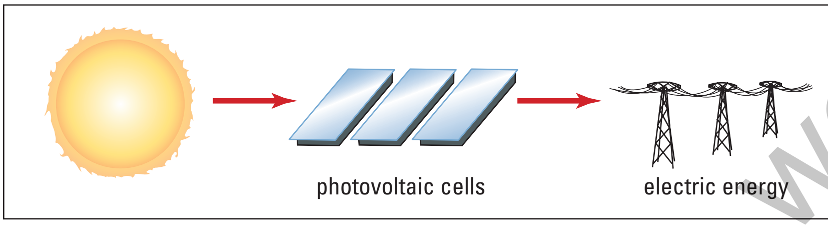
Advantages

- Solar cells are 100% free of greenhouse gas emissions during operation.
- Silicon is the second most abundant element in Earth's crust.
- Reliable technology has already been successfully tested in various locations.

Disadvantages

- Potentially toxic chemicals are released during manufacturing.
- Significant land area is required to produce significant amounts of electricity.

Solar Power Energy Path

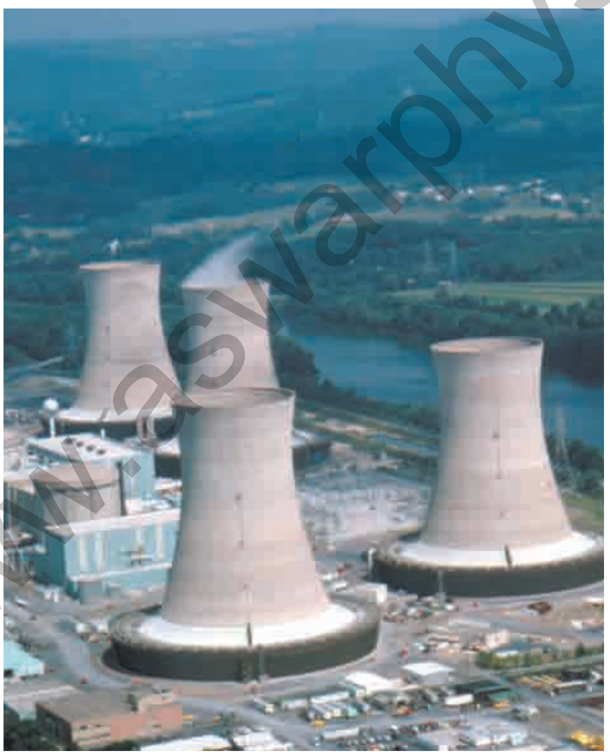


IN CANADA

3375 kW	Off-grid* generation for industrial purposes
2157 kW	Off-grid generation for cottage and recreational purposes
297 kW	On-grid generation
5829 kW	Total generation (1999)

*"Off-grid" refers to electric power generation that does not contribute to the electrical grid infrastructure that powers our country.

Nuclear Power



After World War II, nuclear power was retooled for "peaceful" uses. In 1955, a U.S. Navy submarine, *Nautilus*, travelled almost 100 000 km powered by the controlled nuclear fission of a lump of uranium the size of a golf ball. Nuclear energy promised to be a clean, efficient energy source to meet rising global energy demands. Compared to coal, the amount of uranium that would need to be extracted from the ground was almost negligible. Further, electricity produced by nuclear fission did not involve the release of greenhouse gases into the environment.

Nuclear fission is the process of splitting extremely large atoms into two or more pieces, which releases an enormous amount of energy in the form of radiation or heat. The heat is used to boil water that eventually turns an electrical generator. Canada's CANDU reactor is a very popular choice worldwide because it has the capability of using unenriched uranium as fuel and has the fortunate record of never having had a catastrophic accident.

Nuclear power is currently used to generate approximately 16% of the global energy demand, which falls far short of the early visions of what nuclear power was to be. Nuclear power production faces two major problems: waste and safety. Some waste products of nuclear fission are extremely radioactive and will remain that way for thousands of years. Proponents of nuclear power note that the most radioactive by-products disintegrate within 100 years, leaving the remaining waste products much less hazardous to living creatures. They also point out that all of the nuclear waste ever stockpiled in Canada would barely fill two ice hockey rinks to the height of the boards. The safety issue is not as easily dismissed. Memories of the 1979 Three Mile Island accident in Pennsylvania and the 1986 disaster at Chernobyl in the former U.S.S.R. do not soon fade. The catastrophic consequences of a full-blown core meltdown similar to Chernobyl have led Sweden and Germany to legislate the reduction of nuclear generating facilities in their countries. Canada, although never having experienced a serious nuclear accident, has also scaled back reactor use because of both financial and safety reasons. Unfortunately, greenhouse-gas-belching plants fired by coal are now generating the electrical power that would have been generated by the nuclear plants.

Nuclear fusion could produce almost endless amounts of energy without greenhouse gas emissions or long-lived dangerous radioactive waste products. A 1000 MW fusion generator would have a yearly fuel consumption of only 150 kg of deuterium and 400 kg of lithium. However, scientists and engineers have yet to develop a method to sustain and control nuclear fusion reactions. Some researchers predict that within 40 to 50 years, fusion power will be available. Unfortunately, to date the only application of fusion is the hydrogen thermonuclear bomb. Will nuclear fusion, the energy that powers our Sun, become a mainstream power source?

Web Link

www.school.mcgrawhill.ca/resources/

Current nuclear research is directed toward finding ways of using the spent fuel to generate more power and reduce nuclear waste. Learn more about the potential and problems associated with nuclear power by going to the above web site. Follow the links for **Science Resources** and **Physics 11**.

Advantages

- There are no greenhouse gas emissions during electric energy generation.
- Small quantities of fuel generate enormous amounts of energy.

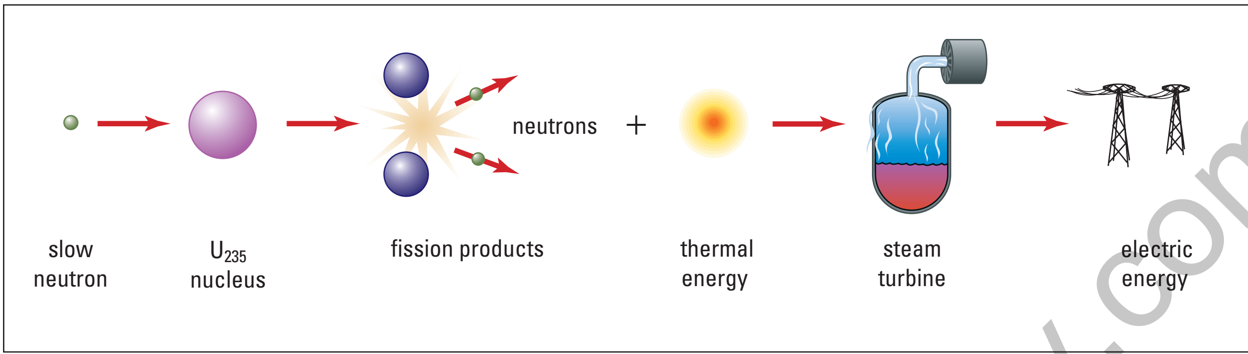
Disadvantages

- There is the potential for catastrophic damage to human life and the environment that an accident — however unlikely — could cause.
- Operation requires continual monitoring by specially skilled individuals.
- Nuclear generating facilities are expensive to build and maintain.

IN CANADA

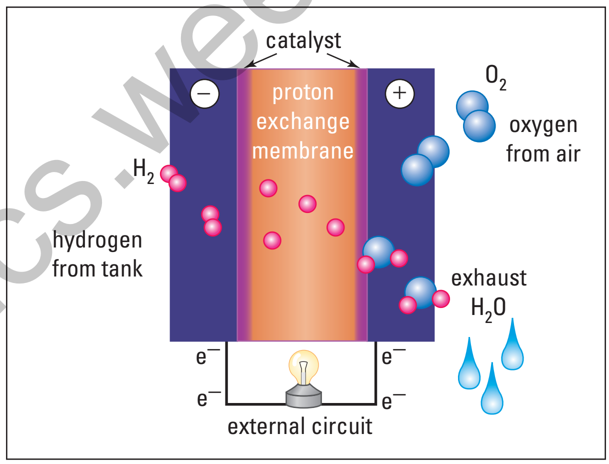
- The CANDU reactor is the world's safest reactor.
- Canada is the world leader in uranium exports, holding 40% of the market share, totalling $1 billion per year.

Nuclear Power Energy Path



Hydrogen Fuel Cells

One of Vancouver's fuel cell-powered buses



Fuel cell schematic

The most promising, and currently the most actively researched, method of non-fossil fuel power generation is the **fuel cell**. A fuel cell requires hydrogen as fuel at the anode and oxygen, or air, at the cathode. A reaction splits the hydrogen atom into an electron and a proton in the presence of platinum, which acts as a catalyst. The electrons take a different path from the anode to the cathode than do the protons. The electrons may therefore be used as electric current. The only waste product from the reaction is water vapour.

The technology to create fuel cells was first demonstrated at the University of Cambridge in 1839. It was not until the U.S. drive to put someone on the Moon that the technology was developed to a point of usefulness beyond a university laboratory. NASA first considered fuel-cell technology simply to produce potable water for the astronauts during the long trip to the Moon. The finished fuel cell versions that flew into space were used to produce both water and electric power on board the space capsule.

Fuel cell research and large-scale production have been limited due to the need for large amounts of very expensive platinum. In the past, platinum sheets were required, but new technology allows engineers to coat cheaper materials with a very thin layer of platinum. This method produces a large surface area of platinum, required for sustained reactions, at significantly reduced cost.

Applications of fuel cell technology have subsequently exploded in research popularity. Fuel cells are used to power automobiles, individual homes, and even remote villages. Vancouver has fuel cell-powered city buses operating on its downtown streets.

The real advantage of fuel cell technology is its ability to use common combustion fuels, such as methanol or even gasoline, as a source of hydrogen. Using gasoline in a fuel cell is more than twice as efficient as burning it in a combustion engine. Any technology that significantly reduces greenhouse gas emissions, while at the same time making use of existing infrastructure, such as the oil-refining systems, will be more readily adopted.

Advantages

- The only emission is water vapour.
- Reformers allow current fuels to be utilized without combustion.
- There is scalable power generation. The cell produces only the required amount of electric current to power everything from laptops to whole towns.

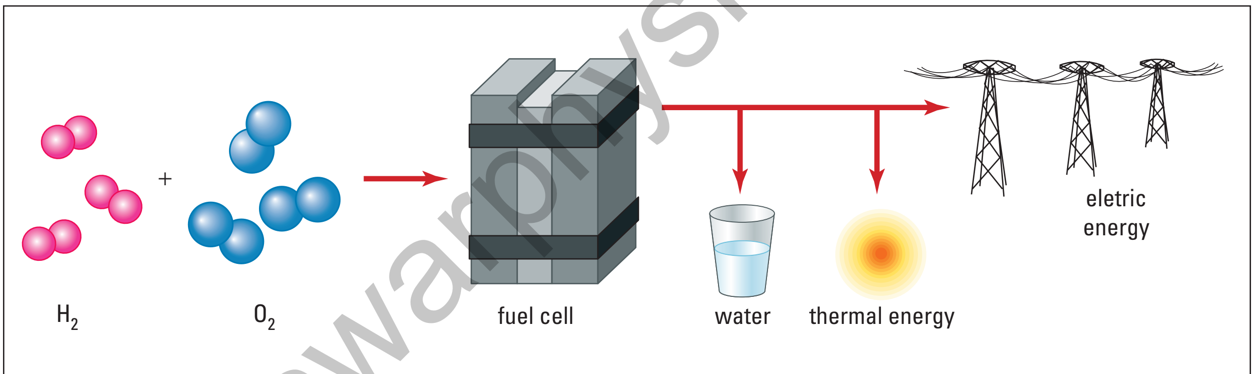
Disadvantages

- Hydrogen storage technology is new.
- Size and weight problems must be dealt with in smaller vehicles.

IN CANADA

- Vancouver operates some city buses powered by fuel cells.
- Vancouver trials have lead to a new generation of fuel cell bus that is 2000 kg lighter, capable of 205 kW or 275 hp.

Hydrogen Power Energy Path



Web Link

www.school.mcgrawhill.ca/resources/

Fuel cells may have the brightest future of any non-fossil fuel energy source. Billions of dollars are invested in research worldwide every year, resulting in exciting advances and innovative applications. Check out the above web site for more information about the latest in fuel-cell research and technology. Follow the links for **Science Resources** and **Physics 11**.

Solar Energy Transmission from Space

A microwave-receiving antenna needs to be very large, but because it allows up to 70% of visible light through, the land underneath can still be utilized.

Capturing solar energy on Earth is limited by weather conditions during the day and darkness at night. One solution to this inconsistency is to capture the solar energy in outer space and beam it to Earth.

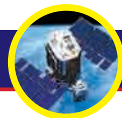
The concept of transmitting power without the use of wires is not new. It was first tried in 1888. In 1908, U.S. engineer Nikola Tesla (1856–1943) attempted to transmit power around the globe by using a very tall tower in New York. His attempt failed, but the idea of transmitting power without wires did not die.

A Canadian experiment in 1987 demonstrated that a small aircraft could be kept flying indefinitely by using ground-based power that was beamed to the plane using microwaves. NASA demonstrated the ability to transmit 30 kW of power over 1.5 km with 82% efficiency. Efficiency is lost in large part because Earth's atmosphere attenuates, or weakens, energy beams by absorbing energy. Energy beams are radiant energy called "electromagnetic waves."

Electromagnetic waves include everything from very long TV and radio waves through microwaves, visible light, X rays, and very short gamma rays. Experiments show that microwaves with a frequency of 2.45 GHz pass through the atmosphere with little loss of energy — 2% during good weather conditions and up to 13% during storm conditions. The second advantage to using 2.45 GHz microwaves is that the magnetron tubes capable of producing them are already mass-produced for the more than 150 million microwave ovens now in operation.

The amount of solar radiation reaching the surface of Earth is about half of the power density, 1360 W/m^2, present in outer space. By placing satellites in geosynchronous orbit with very large solar collectors, approximately 50 km^2, we could take advantage of the increased intensity. The satellites would convert the solar power into microwaves and send it back to Earth in the same way communication satellites transmit data. A large rectifying antenna or rectenna, possibly 130 km^2, would capture the microwave energy and convert it into electrical power for distribution. The large rectennas could be placed on land or at sea, wherever power is required. The rectennas have the advantage of being largely transparent to visible light, and therefore the land beneath them could still be used for farming.

COURSE CHALLENGE



Does it Really Work?

Investigate the concept of space-based power from an environmental assessment perspective. Attempt to identify direct (e.g. launching the satellite) and indirect (e.g. mining the silicon for PV cells) impacts that implementing a space-based power system would have on our global environment. Present the information in an energy path diagram.

Learn more from the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** to find *Physics 11 Course Challenge*.

Advantages

- Solar energy is virtually 100% renewable without any CO_2 emissions.
- Power is readily deliverable to remote or developing areas.
- Solar energy is more sparing of land resources than other renewable sources of energy.

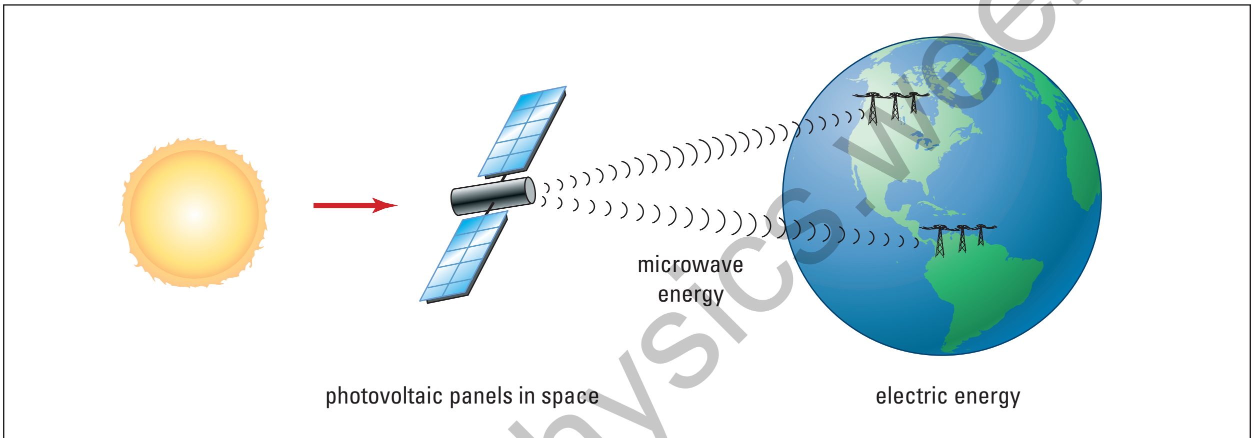
Disadvantages

- The initial expense is large.
- Launching spacecraft releases CO_2 into the atmosphere.
- Communication bandwidth interference problems need more research.

IN CANADA

- Canada is a leader in space technology.
- Canada successfully demonstrated wireless power transmission in 1987.

Solar Energy Path in Space



6.3 Section Review

1. **C** Most sources of energy are used to generate electric energy. Describe why the relative efficiency with which the energy is transformed is so important.
2. **K/U** Using microwaves to beam power to Earth will provide almost continuous power, although some of the beam power will be lost when transmitted through storm conditions on Earth. Why will stormy days cause the atmosphere to absorb more of the beam's power than days with clear skies will?
3. **MC** Hundreds of companies are investing millions of dollars into various ways of producing electric energy. Put yourself in the role of the president of one of those companies and research a source of energy that could provide sustainable power in Canada. Put together a presentation designed to convince the Canadian federal government to accept your plan for providing Canadians with electrical power.

CHAPTER 6 Review

REFLECTING ON CHAPTER 6

- Thermal energy is a measure of the overall energy of an object, based on the random motions of the object's atoms and molecules.
- Temperature is a measure of the average kinetic energy of the atoms and molecules of a substance.
- Specific heat capacity of a substance is the amount of energy that must be added to raise 1.0 kg of material by 1.0 K. Specific heat capacity is used when calculating quantity of heat in joules.
$$Q = mc\Delta T$$
- Latent heat of a substance is the amount of energy required to cause the material to change state. Latent heat of fusion (melting or freezing) and latent heat of vaporization (vaporizing or condensing) are different for any one material. Latent heat capacity is used when calculating quantity of heat, in joules, required for a phase change.
$$Q = \mathrm{mL}$$
- The first law of thermodynamics restates, and completes, the law of conservation of energy. Chapter 5 detailed how energy can be transferred from one system to another by doing work. This chapter details a second method of transferring energy, by heat.
- The second law of thermodynamics states that thermal energy moves from a system at a higher temperature to a system at a lower temperature. It includes the concept that no process is 100% efficient.
- Power, measured in watts, is defined as the amount of work done or energy transferred in a specific amount of time.
$$P = W/\Delta t$$
- Efficiency, provided as a percentage, is a comparison ratio between the useful work output of a system compared to the total work input.
$$\text{Efficiency} = \frac{W_o}{W_i} \times 100\%$$
- There are two types of energy — kinetic and potential. There are several forms of energy. Energy transformations change energy from one form to another. The transformation of energy from one form to another is never 100% efficient.
- Society requires energy to function, from simple methods of cooking our food to complex electrical grids that power our cities. Continued research and technological advancement will help meet our global energy demands in a sustainable way.

Knowledge/Understanding

1. Describe the difference between thermal energy and temperature.
2. Differentiate between heat and thermal energy.
3. Describe the caloric theory of heat and its major flaw.
4. How does the kinetic molecular theory of heat explain the fact that rubbing your hands together generates thermal energy?
5. How is power different from work?
6. Define the two *types* of energy and provide four *forms* of energy for each type.
7. Define thermal equilibrium.
8. Describe the first law of thermodynamics and provide an example of the law in action.
9. Describe three processes that are allowed by the first law, but forbidden by the second law of thermodynamics.
10. Define specific heat capacity of a substance.
11. A news anchor reports that new batteries recently developed are able to generate twice the power of standard batteries for four times as long. How much more work can these new batteries do compare to their standard counterparts?

12. Does it take the addition of more energy to melt 1.0 kg of 0˚C ice or boiling 1.0 kg of 100˚C water? Explain.
13. Farmers often spray plants growing in their fields with water when unseasonably cold temperatures threaten to drop slightly below zero. How does this practice help keep the plants from freezing?
14. On a hot summer day, would a metal lawn chair have a higher temperature than a wooden lawn chair if they were both in the shade?
15. **(a)** Sketch and energy path diagram detailing a perfectly efficient bicycle-rider combination.
    (b) List several reasons why a bicycle-rider combination cannot be perfectly efficient.
16. Describe the fundamental limitation of muscle power.
17. Is the use of biomass through biogas generation considered to be $C0_2$ neutral? Explain.
18. How does a large body of water moderate the temperature (cooler summers, warmer winters) of a nearby area?
19. What provides the energy extracted in a tidal power electrical generating station? (Hint: What actually causes the tide?)

Inquiry

20. Wind generation of electric power relies on almost continuously suitable wind conditions. These conditions are often present in areas that also serve a migration routes for birds. Devise a system that would allow the generation stations to co-exist with the birds.
21. Two friends are roasting marshmallows on an open fire. One friend uses a stick made from wet, green wood and the other uses a metal coat hanger. Which friend could hold their skewer nearer to the tip to remove the marshmallow after holding it in the fire?
22. Two young children are racing up a hill. Matt decides to run directly up the hill while Jen decides to zigzag to the top, exactly tripling her total distance as compared to Matt. They both reach the top of the hill at the same time.
    (a) Who did the most work?
    (b) Who was required to exert the most force?
    (c) Who developed the most power?

Communication

23. Beginning with the Phlogiston theory, describe the historical misconception about heat. Explain what experimental evidence eventually demonstrated the historical error.
24. A burn from boiling water is often much less serious than a burn caused by steam. Explain why steam causes so much more serious injury.
25. Describe the basic physical concepts behind the operation of a fuel cell. What advantages does fuel cell derived energy have over more historical energy sources?
26. Hydrogen fuel cell technology supplied energy and fresh water to astronauts in the 1960’s. What factors, scientific, political and otherwise kept this technology from gaining widespread use in industrialized economies?

Making Connections

27. The human body, composed largely of water, has a specific heat capacity of approximately 3500 J/kg · ˚C. How does this value help aid in human survival?
28. Discuss the process of societal evolution that caused humans to move from a society primarily based on muscle power to one that requires energy transformation technologies.
29. **(a)** Canadian demand for electric power was projected to be several times the current value in the early eighties. Why do you think that the projections overestimated the actual need for electric energy?
    (b) Suggest innovations or societal changes that you believe will help reduce electric energy demand in Canada over the next decade.
30. How has transportation energy transformation technologies impacted industrialized societies?
31. What advantages help make photovoltaic cell, electric systems popular in developing countries?

Problems for Understanding

32. Calculate the amount of heat required to change the temperature of 2.0 kg of liquid water by 15˚C.

33. A 21 kg aluminum block absorbs 1.5×10^5 J of energy. Calculate the change in temperature.

34. A perfectly insulating pail contains water that is heated, adding 4.5×10^3 J of energy while simultaneously being stirred which adds an additional 6.0×10^2 J of energy. According to the first law of thermodynamics, what is the total change in energy of the water?

35. Complete the table of temperature values.

Degrees Celsius	Kelvin
0˚C	
	373.15 K
20	

36. Heating a home is substantially more costly if the air is humid (contains excess water vapour). Calculate the amount of energy required to raise the temperature of 5 kg of nitrogen gas and 5 kg of water vapour (100˚C) by 15˚C at constant volume.

37. During construction of the trans-Canada railway, each length of iron track needed to be welded to the next piece. This welding process was accomplished using a special chemical reaction, called the thermite reaction that generated incredibly hot temperatures and liquid iron. Calculate the amount of heat required to melt 5.0 kg of iron (L_f = 289000 J/kg for iron).

38. Calculate the power developed by a runner able to do 7.0×10^2 J of work in 2.0 s.

39. Calculate the amount of energy required to operate each of the following devices for 30 min.
(a) 150 W light bulb
(b) 900 W hair dryer
(c) 2000 W portable heater
(d) 2.5×10^6 W electric motor

40. A 12 kg sled is pulled by a 15 N force at an angle of 35˚ to the horizontal along a frictionless surface.
(a) Sketch the situation.
(b) Calculate the acceleration of the sled.
(c) Calculate the distance traveled by the sled in 3.0 s if it started from rest.
(d) Calculate the work done on the sled in 3.0 s.
(e) Calculate the power generated in pulling the sled.

41. A homemade go-cart has the following efficiencies:
- Transformation of fuel energy to rotational energy of the axle – 15%
- Transformation of the axle rotation to forward motion – 60%
- Loss of forward motion due to air resistance – 16%

Draw an energy path diagram detailing the efficiency of the go-cart.

42. A farmer is contemplating using a small water fall on his property for hydroelectric power generation. He collects data, and finds that 3000 kg of water fall 15.0 m every minute. Assuming the highest possible efficiency that he is able to achieve in transforming the water's gravitational potential energy to electric energy is 74%, what continuous power in Watts could he generate?

43. A wave power electric generating facility protects a shoreline from damage caused by large waves. During a storm 11.0 m swells bombard the facility and lose 80% of their height. Calculate the height of the waves reaching the shoreline.

Numerical Answers to Practice Problems

1. 3.22×10^{10} J **2.** 0.05˚C **3.** 8×10^6 J; 27 cents **4.** 1.02 kg **5.** 1.3×10^6 J **6.** 4.2×10^5 J **7.** 23 kg **8.** 5×10^{10} J **9.** 47 000 **10.** 1.5×10^2 W **11.** 15.4 kW; 20.7 hp **12.** No, the student will be 1 second late **13.** **(a)** 1.1 kg **(b)** 540 W **14.** 12.8 min **15.** 39 W **16.** **(a)** 75% **(b)** into friction of moving parts **17.** 26 % **18.** 19% **19.** **(a)** $Eff_{incand} = 4.2\%$, $Eff_{fl} = 8.4\%$ **(b)** the fluorescent bulb heats up less than the incandescent bulb **20.** 87.2% **21.** **(a)** 6.24 J **(b)** 6.05 J **(c)** 3% **22.** 34 % **23.** 19˚C

The Physics of Sport

Background

A 2 inch × 4 inch board (5 cm × 10 cm) and some roller-skate wheels started a phenomenon that is now a bona fide sport, the extreme sport of skateboarding. There is a lot of good physics behind both a good board and a good boarder. The move pictured, called an "ollie" after Alan "Ollie" Gelfand, was invented in the late 1970s. The board seems to stick to the rider's feet, but, in actuality, the rider and the board jump up by pressing down and then controlling specific rotational characteristics of the board.

Remarkable physics lies behind both the equipment and the tricks involved in skateboarding. The "ollie" pictured is a basic boarding manoeuver.

Boarding popularity slumped in the early 1970s, but with the advent of urethane wheels, boarders gained control, coupled with speed, and they have never looked back. Wheels need to cushion the ride, stick to the pavement enough to steer (but not so much as to stop a forced slide), and also allow the rider to move quickly without losing energy. Most wheels deform, or flatten, where they come into contact with the ground. The wheel must push back against the ground quickly, removing the flat spot before losing contact with the ground. If not, the energy that went into deforming the wheel will be "lost" and speed is compromised. A logical question then comes to mind. Why not make the wheel rigid, so it does not flatten? In this case, the pavement would be forced to flatten and then even more energy would be lost — as elastic potential energy transferred to the pavement. Manufacturers are often faced with these questions in designing new equipment.

Pre-lab Focus

In this project, you will systematically analyze sporting equipment of your choice (for example, a hockey helmet, roller blades, a snowboard, etc.) by using the physics knowledge that you have just learned. In Chapter 5, you learned that work is the transfer of energy from one system to another, or from one form to another. You also noted that energy is *always* conserved: it may transfer from one object to another, or from one form to another, but the total energy in the universe remains constant. In Chapter 6, the principle of conservation of energy was extended to include thermal energy and the first law of thermodynamics. Power was defined as the rate at which work is done. Understanding these and other concepts will allow you to examine the physics of sports and sports equipment.

Materials

- Collect newspaper, magazine, and Internet articles on sports and sports equipment that are of interest to you. Attempt to gather information that will assist you in analyzing the physics concepts that make the sport possible.
- Review the materials as you collect them. You will need to decide on a theme, such as Safety, Durability, Sport-Specific "How'd They Do That," etc. Begin to focus your search for materials based on the theme you choose. Availability of resources may restrict your final choice, so be sure to collect enough materials to ensure success before locking yourself into any one specific theme.

ASSESSMENT

After you complete this investigation

- **assess your procedure by having a classmate try to duplicate your results**
- **assess your presentation based on the clarity of the physical concepts conveyed**

Initiate a Plan

A. Working with a partner, develop an investigation plan that will allow you to study, through research and experimentation, your selected sport or sporting equipment based on the energy, work, and power concepts that you have studied. Limit the equipment to be studied. Attempt to take one piece of sporting equipment through several rigorous tests, covering as much energy, work, and power content as possible, rather than testing several items in different areas.

B. Design a flowchart depicting the components of your plan (research, laboratory, presentation) and include tentative completion dates. Attempt to predict special needs (equipment, time, supervision) so that once the project is underway, you will not be sidetracked with unforeseen issues. Check with your teacher to ensure that your plan is appropriate for the allotted time.

C. Decide how the final information will be presented. You may work as a class, making decisions about how the final information needs to be presented and what the evaluation scheme will look like. For instance, you may decide as a class that you are each going to promote your selected sports equipment in a pamphlet or on an Internet site. Each promotion may be required to highlight the physics involved, the specific characteristics (safety, elasticity, durability), and the specific selling features. You may work as a class to build the assessment rubric together, ensuring that the criteria for the finished product are explicit and clear. Information presentation possibilities include a technical report; poster presentation; pamphlet or newsletter; multimedia presentation; and web site.

Laboratory Testing

1. Use your plan to develop a suitable laboratory procedure, with equipment that is available to you, to systematically investigate specific characteristics of your selected sport or equipment.
2. Work with your teacher during this phase to ensure safety issues are not overlooked.

Investigation Checklist

As your investigation proceeds, pay attention to the following checklist.

(a) Have you stated the purpose of the experiment (the question you want answered)?

(b) Have you written your hypothesis about what you expect the answer to be?

(c) Have you collected enough information from a variety of sources to design the experiment?

(d) Have you made a complete list of all the materials you will need?

(e) Have you identified the manipulated and controlled variables?

(f) Have you written a step-by–step procedure?

(g) Have you critically analyzed your procedure for possible errors or improvements?

(h) Have you repeated your experiment several times? Were the results similar each time?

Analysis

Discuss your experimental results. Was your hypothesis shown to be correct? Have you evaluated the experimental errors?

Assessing Your Experimental Design

List the successes and difficulties of your investigation. If you were to do it again, what changes would you make?

UNIT 2 Review

Knowledge and Understanding

True/False

In your notebook, indicate whether each statement is true or false. Correct each false statement.

1. Doing work on an object does not change the object's energy.
2. Mechanical kinetic energy is stored energy due to gravity.
3. Work done is proportional to the applied force and the square of the displacement in the same direction.
4. Work is done on an object by a force acting perpendicularly to the displacement.
5. It is possible to do negative work.
6. Gravitational energy is always measured from the same reference point.
7. Conservation of mechanical energy requires that a non-conservative force does the work.
8. The force of friction is a non-conservative force.
9. The first law of thermodynamics states that a change in the energy of a system is the sum of the work done and the heat exchanged between the system and its surroundings.
10. The caloric theory of heat is currently accepted as correct.
11. Temperature is a measure of the total thermal energy of a system.
12. During melting, an object releases energy.
13. Efficiency is a ratio of useful work input compared to the amount of work output.

Multiple Choice

In your notebook, write the letter of the best answer for each of the following questions.

14. Work is not energy itself, but rather
    - **(a)** it is a form of kinetic energy.
    - **(b)** it is a form of gravitational potential energy.
    - **(c)** it is a force.
    - **(d)** it is a transfer of mechanical energy.
    - **(e)** it is a result of parallel forces.
15. Which of the following are equivalent to a joule (J)?
    - **(a)** $N \cdot m^2$
    - **(b)** $kg\frac{m^2}{s^2}$
    - **(c)** $N \cdot m$
    - **(d)** $N\frac{m}{s}$
    - **(e)** both (b) and (c)
16. Work done is zero when
    - **(a)** an applied force does not result in any motion.
    - **(b)** uniform motion exists in the absence of a force.
    - **(c)** the applied force is perpendicular to the displacement.
    - **(d)** both (a) and (c).
    - **(e)** all of the above.
17. A weight lifter lowers a barbell at constant speed. Down is assigned as positive. In doing so, the weight lifter
    - **(a)** does positive work on the barbell.
    - **(b)** allows gravity to do negative work on the barbell.
    - **(c)** does not do any work on the barbell.
    - **(d)** does negative work on the barbell.
    - **(e)** allows the kinetic energy of the barbell to increase.
18. At midnight, you walk outside. The temperature of the air has been exactly –12°C for several hours. You touch a metal fence post, a block of wood, and some snow. Apply the concept of thermal equilibrium to identify the correct statement.
    - **(a)** The fence post has the lowest temperature.
    - **(b)** The brick will have the highest temperature.
    - **(c)** The fence post, the block of wood, and the snow will all be at a temperature of –12°C.
    - **(d)** The process of thermal equilibrium causes cold to flow from objects with low specific heat capacities.
    - **(e)** Determining which object will have the lowest temperature is impossible without knowing the specific heat capacities.
19. Determine the only example of potential energy from the following forms of energy.
    - **(a)** sound
    - **(b)** thermal
    - **(c)** radiant
    - **(d)** nuclear
    - **(e)** mechanical kinetic

20. A sustainable energy source derived from biological waste products is
    (a) solar power.
    (b) ocean thermal power.
    (c) biomass.
    (d) not feasible in any setting.
    (e) not considered to be CO_2 neutral.
21. Wind-based power provides some Canadians with reliable, cost-effective energy. Historians believe that wind energy was first utilized
    (a) by the Dutch to pump out inland lakes about 1000 years ago.
    (b) in regions of China 30 000 years ago.
    (c) about 2000 years ago by Persian sailors.
    (d) over 40 000 years ago to carry Australian Aborigines from mainland Asia to the island continent.
    (e) to generate electricity approximately 2000 years ago.
22. Humans have used solar energy, streaming from the Sun, for thousands of years. Which of the following energy sources do not ultimately trace back to the Sun?
    (a) fossil fuels
    (b) photovoltaic cells
    (c) ocean thermal
    (d) nuclear
    (e) biomass
23. Hydrogen fuel cells may be the single most effective sustainable power source alternative in the next 50 years. Which of the following statements concerning fuel cell technology is false?
    (a) The only waste product is water vapour.
    (b) Fuel cells are used to power automobiles, homes, and even small villages.
    (c) Hydrogen fuel cell technology was used to provide Apollo astronauts with fresh water and electric power.
    (d) Fuel cells require temperatures near $-72^{\circ}C$ to operate efficiently.
    (e) Fuel cells can utilize energy stored in gasoline through the use of reformers.

Short Answer

24. Explain how work and a transformation of energy are related.
25. What type of energy does a wind-up toy contain after being wound just before release?
26. Does your arm, lifting completely vertically, do any work on your textbook as you carry it down the hall if the book's vertical position does not change?
27. Describe the work done by a nail on a hammer as the nail is driven into a wall. What evidence is there that the work done is negative?
28. What is the factor by which a javelin's kinetic energy is changed, if its velocity is increased to five times its initial velocity?
29. Draw a graphical representation showing total mechanical energy, gravitational energy, and mechanical kinetic energy versus time for the following processes.
    (a) A block of ice, initially at rest, slides down a frictionless slope.
    (b) A moving block of ice slides up a frictionless slope and instantaneously comes to rest.
30. What common misconception about heat may be the result of the phlogiston and caloric theories?
31. What aspects of the kinetic molecular theory are supported by observations that the caloric theory cannot explain?
32. How is temperature different from thermal energy?
33. Is it possible to cool an object to 0 K or absolute zero? Explain.
34. Describe how the specific heat capacity of a substance affects its ability to change temperature.
35. Thermal energy is being added to a substance, and yet the temperature is not increasing. Explain how this is possible.
36. What sustainable energy source opportunities exist in Canada?
37. (a) Wave power utilization provides a visual example of how energy is transformed from one form to another. Explain how this can be seen in the case of wave power.
    (b) Describe the process involved in extracting energy from the thermal energy of tropical oceans.

Inquiry

38. Investigate the energy transformations that take place when an athlete is pole-vaulting.

39. Design a simple test that would allow you to differentiate between a substance with a very low specific heat capacity and one with a very high specific heat capacity.

40. How much energy do you use during the course of one week to heat water? Design a simple method of recording both the approximate quantities and the temperature changes of the hot water you use. Include everything from showers to hot coffee. Convert the energy required into a dollar value by using the price of electricity per kW · h in your area.

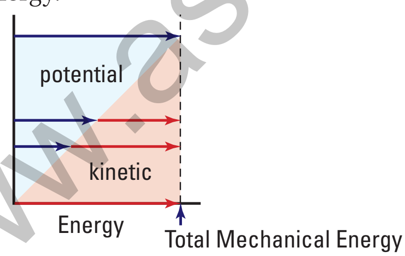
Communication

41. Can the gravitational potential energy of a golf ball ever be negative? Explain without using a formula.

42. Design a tree diagram to illustrate the relationship between work, kinetic and potential energy, and related variables for each of the following cases.

- **(a)** A high jumper converts kinetic energy and work into height (or potential energy).
- **(b)** A curler causes a curling stone that starts at rest to slide down the rink, eventually stopping.
- **(c)** A grocery store employee restocks canned goods onto a top shelf.

43. Describe how the graph represents conservation of energy.



Making Connections

44. Research an alternative source of energy that has not been discussed in the text. Determine the energy transformation efficiency and environmental impact.

45. A newspaper advertisement selling a digital daytimer claims it is 100% efficient. Is it possible that this advertisement is telling the truth? Explain your reasoning.

46. Describe which sustainable energy source you believe would be most effective, and the least environmentally harmful, in the tropics. Defend your choices with clear examples.

47. Is the temperature during a still winter day likely to increase or decrease slightly when large snowflakes begin to fall? Explain your reasoning.

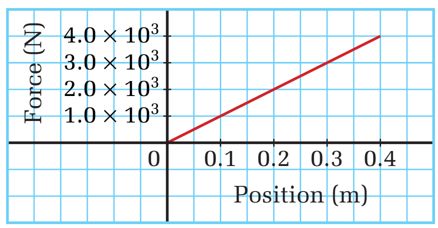
48. How has the specific heat capacity of water helped to shape life on Earth?

49. A fuel cell-powered vehicle does not produce any emissions other than water vapour during its operation. Would you be willing to spend more to purchase a fuel cell vehicle rather than one with a combustion engine? Provide both a scientific and societal rationale for your answer.

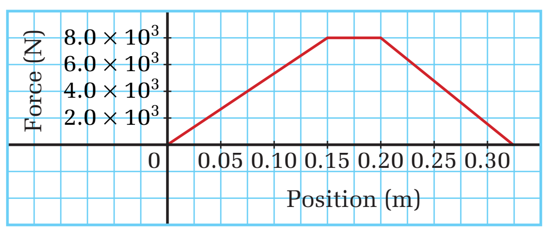
Problems for Understanding

50. The force-versus-position plots were created from data collected during low-speed automobile collisions with cars with different-style bumpers. Calculate the work done on the bumper in each case.

(a)



(b)

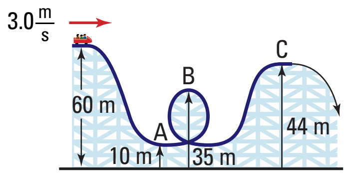


51. How fast will a 2.55 kg bowling ball be travelling if the 358 J of work done to the ball are transformed into kinetic energy?

52. Find the mass of an object if 250 J of work cause it to gain 3.2 m/s of velocity.

53. Calculate the gravitational potential energy of a 75 kg bag of salt that is 2.5 m above the ground.

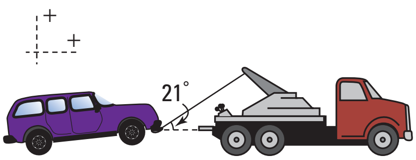
54. A 250 kg roller coaster cart loaded with people has an initial velocity of 3.0 m/s. Find the velocity of the cart at A, B, and C.



55. A raindrop reaches terminal velocity very quickly as it falls to Earth due to the work friction does during the descent.
   (a) If a 0.500 g raindrop formed 1.50 km above Earth, calculate its speed as it struck the ground if air resistance is ignored. Answer in km/h.
   (b) Determine the percentage of energy that is lost due to work done by friction if the 0.500 g raindrop reaches Earth travelling at 5.20 m/s.

56. A 45 kg cyclist travelling 15 m/s on a 7.0 kg bike brakes suddenly and slides to a stop in 3.2 m.
   (a) Calculate the work done by friction to stop the cyclist.
   (b) Calculate the coefficient of friction between the skidding tires and the ground.
   (c) Are you able to determine if the tires were digging into the ground from your answer in part (b)? Explain.

57. A tow truck pulls a car by a cable that makes an angle of 21° to the horizontal. The tension in the cable is 6.5×10^3 N.



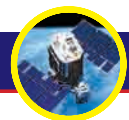
   (a) How large is the force that causes the car to move horizontally?
   (b) How much work has the tow truck done on the car after pulling it 3.0 km?

58. Glycerin, a major component of soap, is heated before being poured into moulds. Calculate the mass of glycerin if 5.50×10^3 J of energy causes a 4.20°C temperature increase.

59. The Sun heats 2.00×10^2 kg of ammonia gas that are kept at constant volume in a large tank. Assuming that solar radiation of 6.00×10^2 W caused the heating, determine the length of time it took to raise the ammonia's temperature by 12°C.

60. A garage-door opener uses 1200 W when operating. When the electric energy is transformed to kinetic energy, 20 percent of the power is lost. Friction between the chain and the support causes a loss of five percent. Friction between the rollers on the door and the track can range from 10 percent to 60 percent. The remaining power is used to actually move the door. Draw an energy path diagram to represent the power loss of the door opener.

COURSE CHALLENGE



Space-Based Power

Consider the following as you continue to build your physics research portfolio.

- Add important concepts, formulas, interesting and disputed facts, and diagrams from this unit.
- Review the information you have gathered in preparation for the end of course challenge. Consider any new findings to see if you want to change the focus of your project.
- Scan magazines, newspapers, and the Internet to find interesting information to enhance your project.

UNIT 3

Waves and Sound

OVERALL EXPECTATIONS

DEMONSTRATE an understanding of the properties of mechanical waves and sound.

INVESTIGATE the properties of mechanical waves and compare predicted results with experimental data.

EVALUATE the contributions to entertainment, health, and safety of technologies that make use of mechanical waves.

UNIT CONTENTS

On May 22, 1960, in the early afternoon, an earthquake rocked the floor of the Pacific Ocean off the coast of south-central Chile. In fishing villages on the coast, many inhabitants took to their boats to escape the shaking. This was a mistake. About fifteen minutes later, the level of the ocean water dropped. Shallow harbours emptied of water, and boats thudded down onto the seabed. Then, the sea returned in a thunderous breaker, picking up the boats and pitching them onto the land.

The giant wave, a tsunami, was generated when a huge area of the ocean floor suddenly sank several metres during the earthquake. The westbound portion of the wave raced across the Pacific at speeds of up to 700 km/h, as fast as a small passenger jet. About fourteen hours later, a wave, three storeys high, swept to the shores of the Hawaiian Islands, 10 000 km from its starting point. The force of the debris-filled waters uprooted trees, bent parking meters, and pushed houses off their foundations.

Almost a day after the quake, the wave reached Japan, half a world away from its source. It was reported that 119 people were killed.

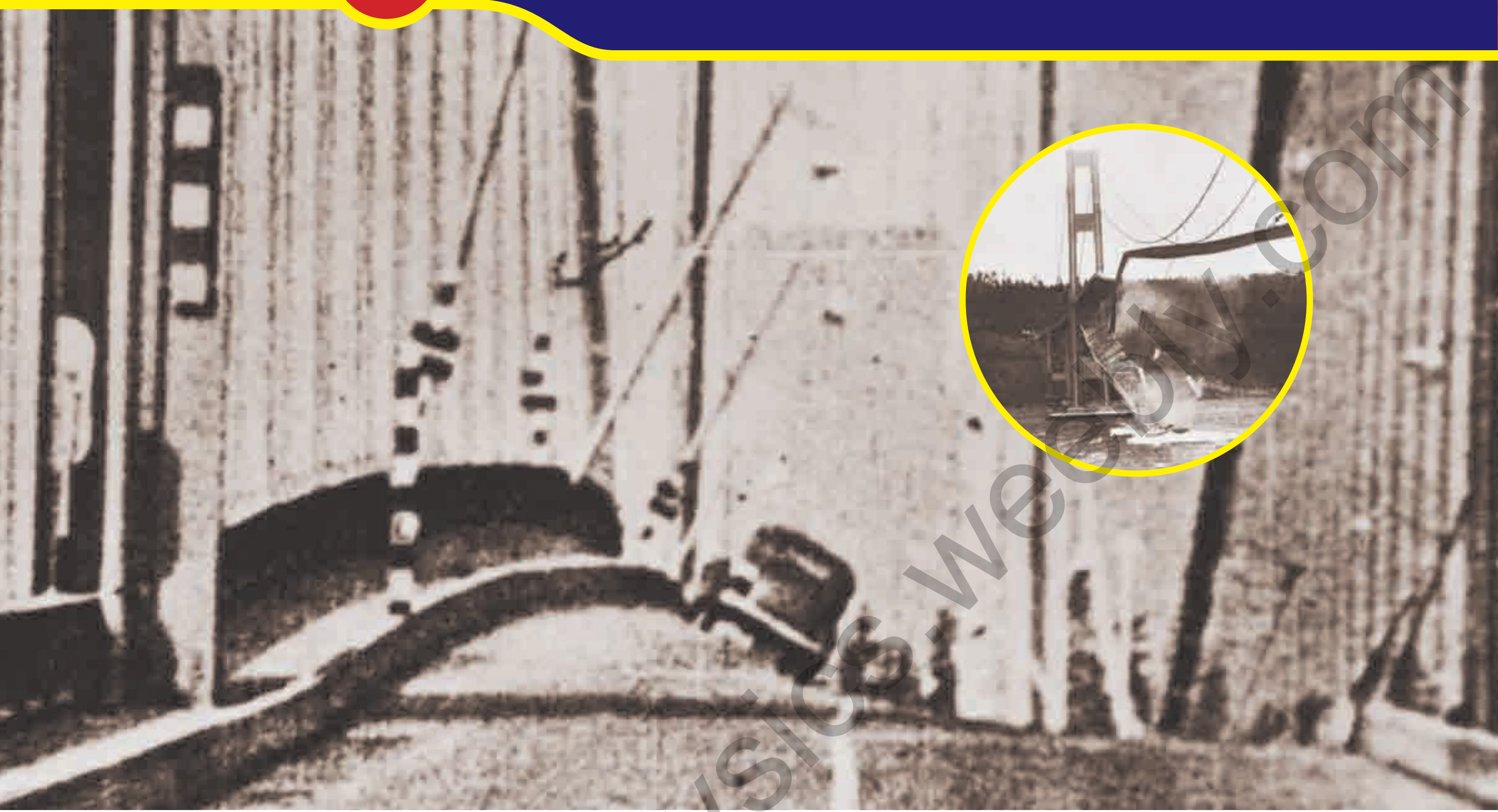
How do waves, like this tsunami, transfer their energy over such great distances? What keeps them going? What determines their speed and height? These, and other questions about wave action, can be answered through a study of waves, energy, and interestingly, the nature of sound.

UNIT ISSUE PREP

Read ahead to pages 452–453. At the end of this unit, you will develop a noise policy document.

- How does the nature of sound waves affect how you address the issue of noise in your community?

CHAPTER 7 Waves Transferring Energy



CHAPTER CONTENTS

People living in coastal areas are very aware of the energy carried by tsunamis (large ocean waves) and the destruction that they can bring. The effects of small waves combining together can also lead to destruction. On November 5, 1940, many relatively small waves combined to produce such huge vibrations in the Tacoma Narrows Bridge (as shown in the large photograph) that the bridge was torn apart. The engineers who designed the suspension bridge, located near Tacoma, Washington, had no idea that the relatively moderate winds that blew through the Narrows could produce such destructive vibrations. Today, models of bridges such as this one are routinely tested in specially designed wind tunnels to ensure that small waves cannot combine to produce disasters like the Tacoma Narrows Bridge collapse.

The transfer of energy by waves can also be beneficial. Physiotherapists commonly use high frequency sound waves to reduce the pain and swelling of athletic injuries. High frequency sound waves (ultrasound) are also used for routine monitoring of the developing fetus in expectant mothers. Ultrasound does not present the dangers associated with X-ray imaging.

INVESTIGATION 7-A

Waves in a Spring

TARGET SKILLS
- Predicting
- Identifying variables
- Analyzing and interpreting

You have probably been observing waves of some sort all of your life. As a child, you might have dropped a pebble in water and watched the waves spread over the surface. Children often develop ideas about the nature of what they observe. These ideas can be helpful but, if they are incorrect, they can stand in the way of new learning. To see if your ideas about waves are correct, test them in this investigation.

Problem

What affects the nature of a wave as it travels along a spring? What influences the speed of the wave?

Prediction

Make predictions about the factors affecting the nature of a wave pulse as it travels down a spring. For example, predict whether such factors as the tension in the spring, the height of the pulse, and the distance travelled affect the speed of a wave pulse. How might these factors do so? In each case, explain your reasoning.

Equipment

- large-diameter spring (such as a Slinky™)
- small-diameter spring
- stopwatch
- metre stick

Procedure

1. Stretch the large spring out on the floor until you and your lab partner are about 8 m apart.
2. Move your hand rapidly to one side and back in order to send a single pulse down the spring.
3. Observe its speed, size, and anything else that you find significant.
4. Find a second way to produce a wave pulse. Experiment with different motions of the end of the spring.
5. Establish a method for measuring the speed of the wave pulse. Test the effect, if any, of the following on the speed of the wave pulse.
   (a) pulse size
   (b) distance travelled
   (c) tension in the spring
   (d) use of the small spring

(Hint: Be careful when you are testing one factor to control all of the other factors. When stretching the springs, be sure to use the same distance for timing the pulse.)

CAUTION Releasing one end of a stretched spring usually results in a tangled mess! When you are finished experimenting, do not *release either end*. Instead, walk toward your partner with your end of the spring.

Analyze and Conclude

1. Compare your results with the predictions you made earlier about the factors that affect the speed of a wave pulse in a spring.
2. In each case, try to explain any discrepancies between your results and your predictions.
3. Describe any misconceptions you might have had about waves and how they travel.

7.1 Vibrations

SECTION EXPECTATIONS

- Describe and explain amplitude, frequency, and phase of vibration.
- Analyze and experiment with the components of, and conditions required for, resonance to occur in a vibrating object.

KEY TERMS

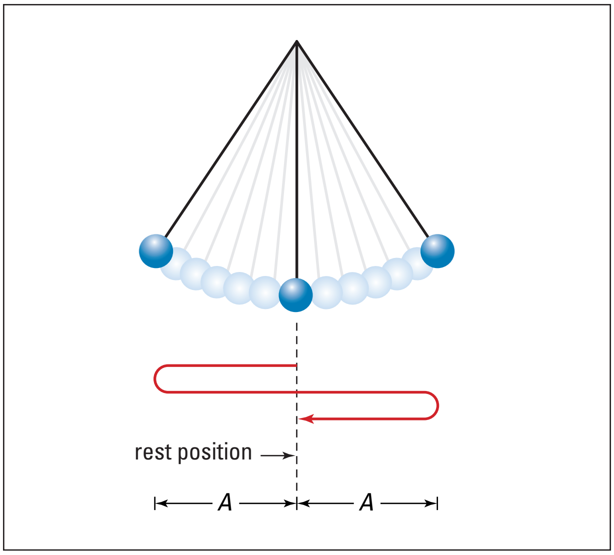
- periodic motion
- cycle
- period
- rest position
- amplitude
- frequency
- hertz
- phase difference
- in phase
- out of phase
- natural frequency
- resonance

The motion of particles in a mechanical wave and the energy transmitted by a wave are quite different from the motion and energy that you studied in Units 1 and 2. After you sent a wave pulse down the spring in the investigation, all parts of the spring returned to their original positions. As the wave pulse passed through each section of the spring, that section moved from side to side or back and forth, but then returned to its initial position. Only the *energy* travelled down the spring. To initiate the wave, you had to move your hand back and forth. Similarly, most waves are started by vibrating objects such as the student's hand in Figure 7.1. Learning how to describe vibrations is an important first step in understanding and describing waves and their motion.

Figure 7.1 You can transmit energy to the duck, making it bounce up and down, by creating water waves. Your hand, the water, and the duck vibrate only up and down, but the wave has transmitted energy from your hand to the duck.

Amplitude, Period, Frequency, and Phase of Vibrations

When an object moves in a repeated pattern over regular time intervals, it is undergoing **periodic motion**. One complete repeat of the pattern is called a **cycle** or vibration. The time required to complete one cycle is the **period** (T). Figure 7.2 shows two types of periodic motion. A simple pendulum moves from side to side, perpendicular to its length, while a mass on a spring oscillates up and down, parallel to its length. When a pendulum or a mass on a spring is not in motion but is allowed to hang freely, the position it assumes is called its **rest position**. When in motion, the distance from the rest position to the maximum displacement is the **amplitude** (A) of the vibration.



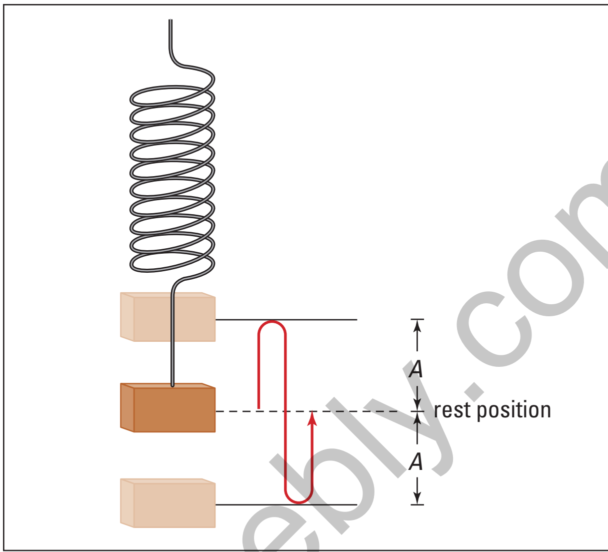


Figure 7.2 **(A)** When a simple pendulum completes one full cycle of its motion, it is in its original position. **(B)** One full cycle of the motion of the mass on a spring brings the mass back to the rest position.

One of the most common terms used to describe periodic motion is **frequency** (f), which is the number of cycles completed in a specific time interval. The frequency is the reciprocal, or inverse, of the period. The SI unit of frequency is s^{-1} or $\frac{1}{s}$ (reciprocal seconds). This unit has been named the **hertz** (Hz) in honour of German scientist Heinrich Hertz (1857–1894), who discovered radio waves.

PERIOD AND FREQUENCY

The period is the quotient of the time interval and the number of cycles. $$T = \frac{\Delta t}{N}$$

The frequency is the quotient of the number of cycles and the time interval. $$f = \frac{N}{\Delta t}$$

The frequency is the reciprocal, or inverse, of the period. $$f = \frac{1}{T}$$

Quantity	Symbol	SI unit
period	T	s (seconds)
frequency	f	Hz (hertz)
time interval	Δt	s (seconds)
number of cycles	N	none (pure number)

Note: $1 \text{ Hz} = \frac{1}{\text{s}} = 1 \text{ s}^{-1}$

PHYSICS FILE

The pendulum in the photograph is called a Foucault pendulum. It is named after French scientist Jean-Bernard-Leon Foucault (1819–1868), who built the first one in Paris. A Foucault pendulum has a very large mass suspended by a very long wire that does not constrain the pendulum to swing in a specific plane. Earth's rotation causes the plane of the swing of a Foucault pendulum to rotate very gradually. For example, the plane of Foucault's first pendulum in Paris made one complete rotation in about 32 h. This rotation was the first "laboratory" evidence that Earth rotates on its axis.

Even when vibrating objects have the same amplitude and frequency, they may not be at the same point in their cycles at the same time. When this occurs, we say that there is a **phase difference** between them. Two vibrating objects are **in phase** when they are always moving in the same direction at the same time. If, during any part of their cycles, the two objects are moving in opposite directions, they are vibrating **out of phase**. Figure 7.3 illustrates this.

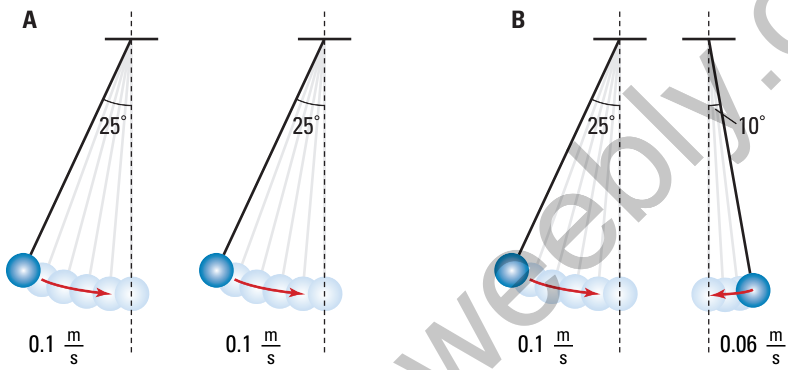


Figure 7.3 **(A)** When two pendulums are moving in unison, they are said to be "in phase." **(B)** Since these two pendulums are moving in opposite directions, they are moving "out of phase."

MODEL PROBLEM

Period and Frequency

A mass suspended from the end of a spring vibrates up and down 24 times in 36 s. What are the frequency and period of the vibration?

Frame the Problem

- The *mass* is undergoing *periodic motion*.
- The *period* is the time for one complete cycle.
- The *frequency* is the reciprocal of the *period*.

Identify the Goal

(a) The period, T, of the motion

(b) The frequency, f, of the motion

Variables and Constants

Involved in the problem		Known	Unknown
T	Δt	$N = 24$	T
f	N	$\Delta t = 36$ s	f

Strategy	Calculations
You can find the period because you know the total time interval and the number of cycles. Substitute these values into the equation.	$T = \frac{\Delta t}{N}$
Divide.	$T = \frac{36\text{ s}}{24}$
(a) The period of the vibrating mass is 1.5 s.	$T = 1.5$ s
You can also find the frequency from the number of cycles and the total time interval.	$f = \frac{N}{\Delta t}$
Substitute.	$f = \frac{24}{36\text{ s}}$
Divide.	$f = 0.67\text{ s}^{-1}$ $f = 0.67$ Hz
(b) The frequency of the vibrating mass is 0.67 Hz.	

Validate

The unit of the period was seconds, which is correct.

The unit for the frequency was seconds to the negative one, or reciprocal seconds, which is equivalent to hertz. That is the correct unit of frequency.

The period and frequency were calculated individually, but they should be the reciprocal of each other. Check to see if they are.

$$f = \frac{1}{T}$$

$$f = \frac{1}{1.5\text{ s}}$$

$$f = 0.67\text{ s}^{-1}$$

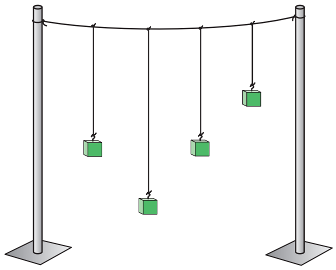
$$f = 0.67\text{ Hz}$$

The frequency is the reciprocal of the period.

PRACTICE PROBLEMS

1. A metronome beats 54 times over a 55 s time interval. Determine the frequency and period of its motion.
2. Most butterflies beat their wings between 450 and 650 times per minute. Calculate in hertz the range of typical wing-beating frequencies for butterflies.
3. A watch spring oscillates with a frequency of 3.58 Hz. How long does it take to make 100 vibrations?
4. A child swings back and forth on a swing 12 times in 30.0 s. Determine the frequency and period of the swinging.

TRY THIS...



Assemble the apparatus shown here, using strings and masses tied to retort stands or other solid supports. Make two pendulums the same length, one longer than the pair, and one shorter. One at a time, pull each pendulum to the side and let it swing. Observe any response of the other pendulums.

ELECTRONIC LEARNING PARTNER

View an excellent clip showing mechanical resonance.

Natural Frequencies and Resonance

When an object, like a simple pendulum or a mass on a spring, is allowed to vibrate freely, it vibrates at a specific frequency called its **natural frequency**. The natural frequency of a simple pendulum depends on its length — shorter pendulums have higher natural frequencies than longer ones. What determines the frequency with which a mass vibrates on the end of a spring?

When you push a child on a swing, you need not push very hard to make the child swing higher and higher. What you do have to do is to push at the right times, that is, with a frequency equal to the natural frequency of the swing and the child. As well, the cycle of pushing must be *in phase* with the motion of the child and the swing. This condition is true for all vibrating objects. If energy, no matter how small the amount, is added to a system during each cycle and none is removed, the amplitudes of the vibration will become very large. This phenomenon is called **resonance**.

QUICK LAB

Natural Frequency of a Mass on a Spring

TARGET SKILLS

- Identifying variables
- Performing and recording

What factors affect the frequency of vibration of a mass on a spring? Does the frequency change with time? Does the amplitude affect the frequency? Does the amount of mass influence the frequency? Answer these questions by carrying out the following experiment. You will need two different-sized springs, three different masses, a stopwatch, a metre stick, a retort stand, and a clamp.

Securely attach a spring to a clamp on a retort stand. Hang a mass on the end of the spring. Stretch the spring a measured distance by pulling on the mass. Release the mass and determine the length of time it takes for the mass to complete five full cycles. Calculate the frequency. Carry out the procedure for three different amplitudes.

Repeat the experiment using a different mass. To determine if the frequency changes with time, after taking one measurement, allow the mass to continue vibrating on the spring and measure the time it takes for five more cycles.

Repeat the entire procedure for a different spring.

Analyze and Conclude

1. Which factors affected the frequency of the mass on a spring?
2. Explain how you could determine that some factors did not affect the frequency.
3. What was the natural frequency of each of your combinations of spring, mass, and stretch distance?

You may have experienced another example of resonance when driving or riding in a car. If the wheels were not properly aligned and balanced, the entire car would start to vibrate severely at a certain speed. These vibrations can occur only when the vibrations produced by the spinning of the automobile's wheels are equal to a natural frequency of vibration of the automobile itself.

Mechanical resonance can cause serious problems for engineers constructing buildings, bridges, and aircraft. The Tacoma Narrows Bridge collapsed on November 7, 1940, because resonance was created in its centre span by relatively moderate winds of 60 to 70 km/h. Over a period of two hours, the vibrations of the centre span increased steadily, until they became so violent that the bridge collapsed into the river below (see Figure 7.4).

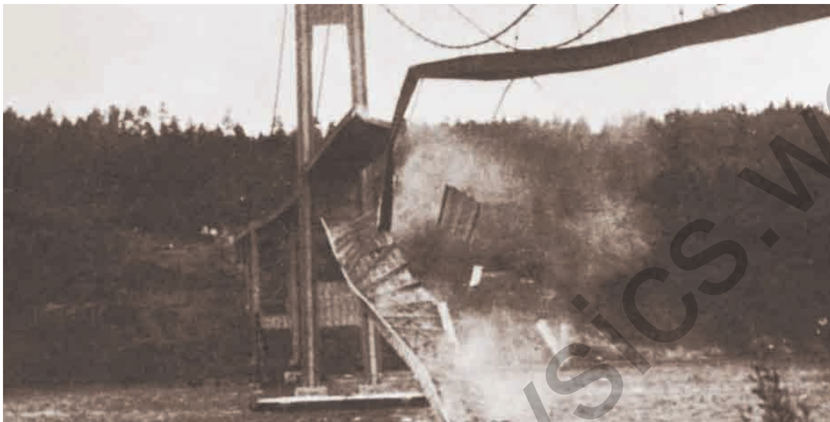


Figure 7.4 Resonance produced such violent vibrations in the original Tacoma Narrows Bridge that it collapsed.

History Link

Galileo Galilei first investigated the constant frequency of a simple pendulum around 1600. Although he never constructed it, Galileo also proposed a design for a mechanical clock regulated by such a pendulum. It was not until around 1759 that John Harrison constructed an extremely accurate clock or chronometer. Finally, seafarers could determine their longitude on long ocean voyages with the aid of this accurate chronometer. This helped the Royal Navy to control the seas and Britain to dominate world trade during the nineteenth century.

Web Link

www.school.mcgrawhill.ca/resources/

For more pictures and information about the Tacoma Narrows Bridge collapse, go to the above web site. Follow the links for **Science Resources** and **Physics 11** to find out where to go next.

7.1 Section Review

1. K/U Give three examples of periodic motion. What makes them periodic?
2. C Explain in your own words the meaning of the terms "cycle," "period," and "frequency."
3. K/U If a simple pendulum is lengthened, what happens to its frequency? To its period?
4. K/U Sketch diagrams illustrating
   (a) two masses on springs vibrating in phase
   (b) two pendulums vibrating out of phase
5. K/U Period is typically measured in units of seconds and frequency in units of hertz. How are these two units related to each other? Why are they related in this manner?
6. C Describe what happens when resonance occurs in an object. Explain how this is produced.
7. MC Provide two examples of resonance in everyday life.

7.2 Wave Behaviour

SECTION EXPECTATIONS

- Describe and define the concepts of mechanical waves including medium and wavelength.
- Compare the relationships between frequency and wavelength to the speed of a wave in various media.
- Use scientific models to explain the behaviour of waves at barriers and interfaces between media.

KEY TERMS

- wave
- medium
- mechanical wave
- crests
- troughs
- wavelength
- frequency of a wave
- transverse wave
- longitudinal wave
- wave equation

What is a wave? When you first read the word, you probably imagine an ocean wave or a crowd in the stands at an athletic event doing “the wave.” Soon you will know why the first image is a true wave in the scientific sense and the second image is not.

Figure 7.5 **(A)** The water ski does work on the water, giving it energy. The wave transmits the energy across the surface of the water. **(B)** “The wave”, in which sports fans wave their arms in unison, is not a wave at all. No energy is transmitted from one person to another. Each person is using his or her own energy to make “the wave.”

A **wave** is a disturbance that transfers energy through a **medium**. While the disturbance, and the energy that it carries, moves through the medium, the matter does not experience net movement. Instead, each particle in the medium vibrates about some mean (or rest) position as the wave passes. The behaviour of many physical phenomena can be described as waves. Disturbances in ropes, springs, and water are easily recognized as waves in which energy moves through the medium. Although you cannot see sound waves, they also are true waves. You usually think of sound waves travelling through air. However, they can also travel through water, steel, or a variety of other materials.

All of these waves travel through matter and are known as **mechanical waves**. Their speed does not depend on their size or the amount of energy they carry. Neither does it decrease as they move through a medium. Rather, the speed of any wave in a particular medium is the same as the speed of any other wave in that same medium. The speed of a wave in a medium is a characteristic property of that medium, in much the same way that its density or boiling point is a property of the medium.

The forces between the particles of the medium and the mass of those particles determine the speed of a mechanical wave. The greater the force between those particles, the more rapidly each particle will return to its rest position; hence, the faster the wave will move along. However, the greater the mass (inertia) of a particle in the medium, the slower it will return to its rest position and the slower the wave will move along. Generally, there is friction in the medium. This friction acts to dampen or reduce the size or height of the wave. Unlike the friction acting on a material object that is moving, the friction does not affect the speed of the wave. Similarly, when a wave is given more energy, the shape of the wave is affected, but the speed with which it moves through the medium is unaffected.

Describing Waves

All waves have several common characteristics that you can use to describe them. Figure 7.6 shows a periodic wave that looks as though it is frozen in time. The horizontal line through the centre is the rest or equilibrium position. The highest points on the wave are the **crests** and the lowest points are the **troughs**. The amplitude (A) is the distance between the rest position and a crest or trough. The **wavelength** (λ, the Greek letter lambda) is the shortest distance between two points in the medium that are in phase. Therefore, two adjacent crests are one wavelength apart. Similarly, two adjacent troughs are one wavelength apart.

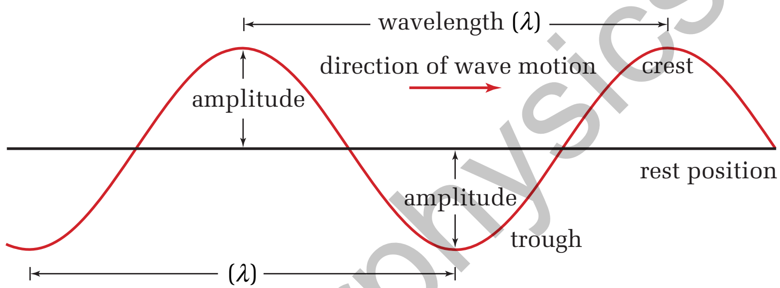


Figure 7.6 This idealized wave illustrates the features that are common to all waves.

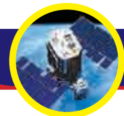
Now imagine that the wave is no longer frozen in time but is moving. The **frequency of a wave** (f) is the number of complete wavelengths that pass a point in a given amount of time. Similar to vibrating objects, the frequency of a wave is usually described in units of hertz. The frequency of a wave is the same as the frequency of the source producing it, so it does not depend on the medium. Also, similar to vibrating objects, the period of a wave is the time it takes for one full wavelength to pass a given point.

While a wave travels through a medium such as a spring, the particles do not need to vibrate in the same direction in which the wave is moving (see Figure 7.7). When the particles of a medium vibrate at right angles to the direction of the motion, the wave is called a **transverse wave**. Water waves and waves on a rope are examples of transverse waves.

PHYSICS FILE

Electromagnetic waves transmit energy just as mechanical waves do. However, electromagnetic waves do not require a medium but can travel through a vacuum. All forms of electromagnetic waves, from long radio waves, through visible light, up to gamma rays with very short wavelengths, travel at the same speed through a vacuum, 3×10^8 m/s. You could say that the speed of any electromagnetic wave is the same in the absence of a medium. However, when travelling through a medium, different wavelengths do, in fact, travel at different speeds. How fast is 3×10^8 m/s? Light can travel around the world 7.5 times in 1 s!

COURSE CHALLENGE



Interference: Communication versus Energy Transmission

Research current allocations of microwave bandwidths. How closely are these bandwidth slices packed? What kind of current research dealing with microwave interference is being done? Learn more from the **Science Resources** section of the following web site: **www.school.mcgrawhill.ca/resources/** and go to the *Physics 11 Course Challenge.*

ELECTRONIC LEARNING PARTNER

Learn more about wave terminology in your Electronic Learning Partner.

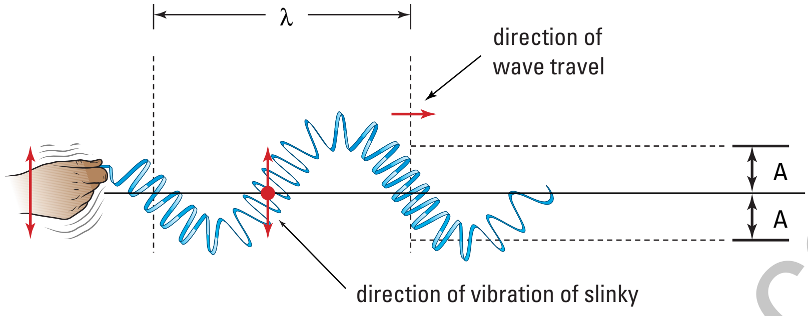


Figure 7.7 When a transverse wave travels along a spring, the segments of the spring vibrate from side to side, perpendicular to the direction of the wave motion.

ELECTRONIC LEARNING PARTNER

Visual examples of transverse and longitudinal waves are available on your Electronic Learning Partner.

When the particles of a medium vibrate parallel to the direction of the motion of the wave, it is called a **longitudinal wave** (see Figure 7.8). Once again, the speed of the wave is determined only by the medium. Sound waves, which you will study in more detail in Chapter 8, are examples of longitudinal waves.

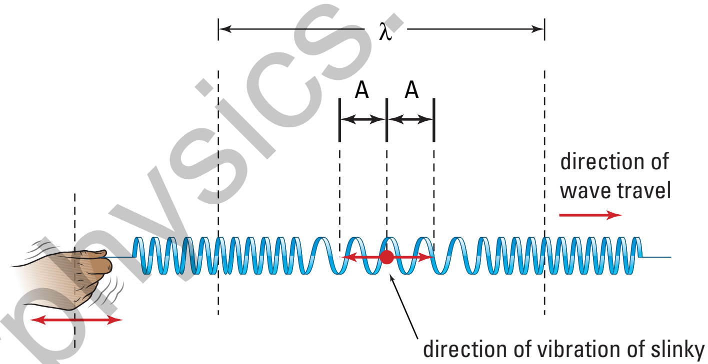


Figure 7.8 When a longitudinal wave travels along a spring, the segments of the spring vibrate parallel to the direction of the wave motion.

Earth Link

Earthquakes generate both transverse and longitudinal waves. Since the longitudinal waves travel faster through Earth and reach seismographs (earthquake detectors) first, they are called primary or P-waves. Transverse waves travel much slower and are called secondary or S-waves. From the difference in the time of arrival of the two waves, seismologists can estimate the distance from the detector to the quake. Do research for recent earthquake information. Especially focus on the recorded waves and time intervals. Attempt your own mathematical calculations for the distance between detectors and the earthquake's epicentre.

Speed, Wavelength, and Frequency: A Universal Wave Equation

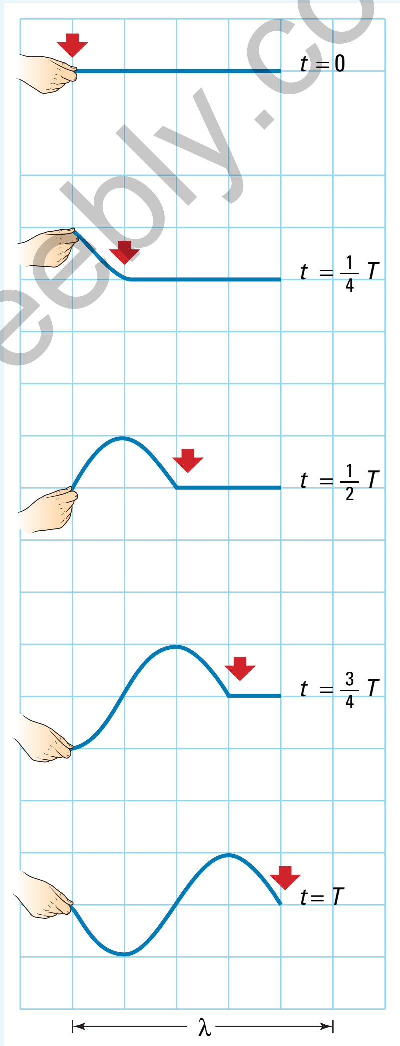
Knowing the speed of a wave provides critical information in many situations. For example, knowing the speed of waves in the deep ocean makes it possible to predict when a tsunami will hit a particular shore. Knowing the speeds of the different types of seismic waves from earthquakes enables geologists to locate the epicentre of an earthquake. As you have probably discovered, it is not easy to determine the speed of a wave pulse accurately. Fortunately, it is possible to determine this value from observable properties of waves travelling through a medium. Use the following problem-solving model to find the relationship.

The Wave Equation

1. A wave has an amplitude, A, frequency, f, and wavelength, λ. How can you find the speed of the wave using these variables?

Frame the Problem

- A source *vibrating* with a *frequency*, f, takes a time interval, $\Delta t = T$, to complete one cycle.
- During that *time*, the *wave* that it produced *moves* a *distance*, λ, along the medium.
- The average speed of any entity is the quotient of the distance it travelled and the time interval that it was travelling. This is true for waves as well as for moving objects.



While the hand moves through one cycle, the wave moves one wavelength.

Identify the Goal

The speed, v, of a wave

Variables and Constants

Involved in the problem		Known	Unknown
Δd	A	$\Delta t = T = \frac{1}{f}$	v
v	Δt	$\Delta d = \lambda$	
		A	

Strategy / Calculations

Strategy	Calculations
Use the formula for the velocity (or speed) of any entity.	$v = \frac{\Delta d}{\Delta t}$
Substitute in known values.	$v = \frac{\lambda}{T}$
Substitute $\frac{1}{f}$ for T.	$v = \frac{\lambda}{\frac{1}{f}}$
Simplify.	$v = \lambda f$

The speed of a wave is the product of its wavelength and its frequency: $v = \lambda f$.

Validate

The equation $v = f\lambda$ is called the **wave equation**. The wave equation can be seen simply as the form of the equation $v = \frac{\Delta d}{\Delta t}$ for waves, because we know that waves travel one wavelength in one period.

continued

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2. A physics student vibrates the end of a spring at 2.8 Hz. This produces a wave with a wavelength of 0.36 m. Calculate the speed of the wave.

Frame the Problem

- *Vibrating* the end of a spring creates a *wave* in the spring.
- The *frequency* of the wave is the same as the *frequency* of the vibrating source.
- The *wave equation* applies to this situation.

Identify the Goal

The speed, v, of the wave

Variables and Constants

Involved in the problem	Known	Unknown
f	$f = 2.8$ Hz	v
λ	$\lambda = 0.36$ m	
v		

Strategy

Use the wave equation.

All needed variables are known, so substitute.

The speed of the wave is 1.0 m/s.

Calculations

$v = f\lambda$

$v = (2.8 \text{ Hz})(0.36 \text{ m})$

$v = 1.0 \text{ ms}^{-1}$

$v = 1.0 \dfrac{\text{m}}{\text{s}}$

Validate

The units reduced to m/s which is correct for speed.
A reasonable speed for a wave in a spring is 1.0 m/s.

3. Water waves with wavelength 2.8 m, produced in a wave tank, travel with a speed of 3.80 m/s. What is the frequency of the straight vibrator that produced them?

Frame the Problem

- A vibrator in a water tank is producing waves.
- The *frequency* of a wave is the same as the *frequency* of the vibrating source.
- The *wave equation* applies to this situation.

Identify the Goal

The frequency, f, of the vibrator

Variables and Constants

Involved in the problem	Known	Unknown
f	$\lambda = 2.8$ m	f
λ	$v = \dfrac{3.80\ \text{m}}{\text{s}}$	
v		

Strategy	Calculations	
Use the wave equation to find the frequency of the wave.	$v = f\lambda$	
All needed values are known, so substitute into the equation.	**Substitute first**	**Solve for *f* first**
Divide by the coefficient of f.	$\dfrac{3.80\ \text{m}}{\text{s}} = f(2.8\ \text{m})$	$v = f\lambda$
Simplify.	$\dfrac{3.80\ \cancel{\text{m}}/\text{s}}{2.8\ \cancel{\text{m}}} = f$ $f = 1.4\ \text{s}^{-1}$ $f = 1.4$ Hz	$\dfrac{v}{\lambda} = \dfrac{f\cancel{\lambda}}{\cancel{\lambda}}$ $f = \dfrac{v}{\lambda}$ $f = \dfrac{\frac{3.80\ \cancel{\text{m}}}{\text{s}}}{2.8\ \cancel{\text{m}}}$ $f = 1.4\ s^{-1}$ $f = 1.4$ Hz

The frequency of the wave and, therefore, the frequency of the vibrator is 1.4 Hz.

Validate

Since the wavelength (~3 m) is shorter than the distance the wave travels in 1 s (~4 m/s), you would expect that the period would be less than 1 s. If the period is less than 1 s, then the frequency should be more than 1 s, which it is.

PRACTICE PROBLEMS

5. A longitudinal wave in a 6.0 m long spring has a frequency of 10.0 Hz and a wavelength of 0.75 m. Calculate the speed of the wave and the time that it would take to travel the length of the spring.

6. Interstellar hydrogen gas emits radio waves with a wavelength of 21 cm. Given that radio waves travel at 3.00×10^8 m/s, what is the frequency of this interstellar source of radiation?

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7. Tsunamis are fast-moving ocean waves typically caused by underwater earthquakes. One particular tsunami travelled a distance of 3250 km in 4.6 h and its wavelength was determined to be 640 km. What was the frequency of this tsunami?
8. An earthquake wave has a wavelength of 523 m and travels with a speed of 4.60 km/s through a portion of Earth's crust.
   - **(a)** What is its frequency?
   - **(b)** If it travels into a different portion of Earth's crust, where its speed is 7.50 km/s, what is its new wavelength?
   - **(c)** What assumption(s) did you make to answer part (b)?
9. The speed of sound in air at room temperature is 343 m/s. The sound wave produced by striking middle C on a piano has a frequency of 256 Hz.
   - **(a)** Calculate the wavelength of this sound.
   - **(b)** Calculate the wavelength for the sound produced by high C, one octave higher than middle C, with a frequency of 512 Hz.

Web Link

www.school.mcgrawhill.ca/resources/

To learn more about tsunamis, go to the above web site. Follow the links for **Science Resources** and **Physics 11** to find out where to go next.

THE WAVE EQUATION

The speed of a wave is the product of the wavelength and the frequency.

$$v = f\lambda$$

Quantity	Symbol	SI unit
speed	v	m/s (metres per second)
frequency	f	Hz (or s^{-1})(hertz)
wavelength	λ	m (metres)

Unit Analysis

(frequency)(wavelength) = Hz m = s^{-1} m = m/s

Think It Through

A student is holding one end of two different ropes, A and B. The other end of each rope is tied to a wall. Rope A is heavier than rope B, causing the speed of a wave in B to be twice as fast as the speed of a wave in A ($v_B = 2v_A$). The student initiates a wave pulse in both ropes by shaking the two ends at the same time. This gives the wave pulses identical amplitudes and time intervals. The diagram shows the shape and position of the wave pulse in rope A moments after the student initiated the pulses. Copy this figure into your notebook and, below it, sketch the appearance of rope B. Carefully consider the size, shape, and position of the wave pulse in rope B compared to rope A.

Waves at Boundaries: Reflection and Transmission

When a wave moves from one medium into another, its *frequency remains the same* but its *speed changes*. As you have learned, the speed of a wave depends on the properties of the medium through which it is travelling.

Figure 7.9 shows what happens when a wave crosses the boundary between two springs joined end to end. The spring on the left is heavy and larger; thus, the wave pulse travels slowly. Once the wave pulse moves into the lighter, smaller spring on the right, it travels faster. You could call the heavy spring the "slow medium" and the light spring the "fast medium." Notice in the figure that, in addition to a transmitted wave pulse, there is also a reflected pulse. Notice, also, that the reflected pulse is on the same side of the spring as the incident and transmitted pulse. When a wave travels from a slow medium to a fast medium, the reflected wave is always on the same side of the rest position as the incoming wave.

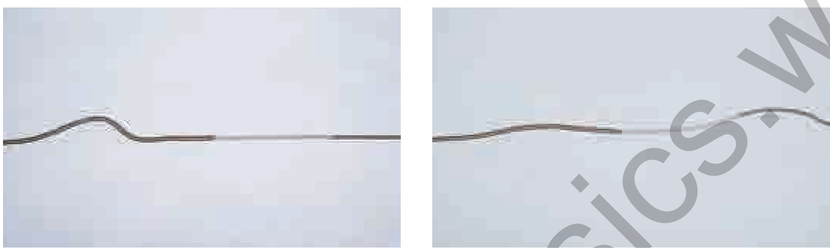


Figure 7.9 At a slow-to-fast interface between two media, the transmitted and reflected pulses are on the same side of the spring.

When a wave pulse travels from a fast medium, such as a light spring, to a slow medium, such as a heavy spring, both transmitted and reflected wave pulses result. However, the reflected pulse is inverted, that is, on the opposite side of the spring, as shown in Figure 7.10.

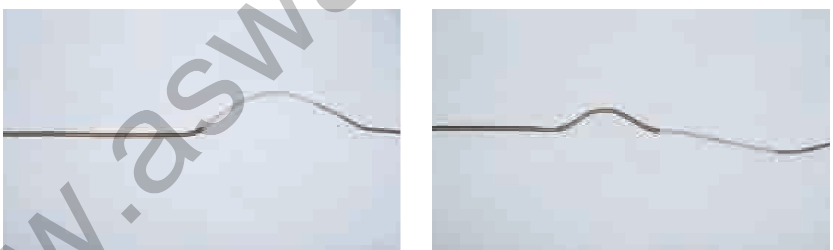


Figure 7.10 At a fast-to-slow interface, the transmitted pulse is on the same side of the spring as the original pulse, but the reflected pulse is inverted.

TRY THIS...

Attach two ropes of different thicknesses together at one end. You and your lab partner should hold the free ends of the combined ropes. First, let one partner initiate one wave pulse. Observe what happens to the pulse as it reaches and passes through the point of attachment. Then, let the other partner initiate a pulse in the opposite end. Observe the behaviour of this second pulse. Discuss any differences you observed between the behaviour of a wave pulse going from a heavy rope to a light rope in relation to a pulse travelling in the opposite direction.

When one end of a spring is attached firmly to a wall, for example, the reflected pulse is inverted as well (see Figure 7.11). You can consider reflection from an end attached to something solid to be a special case of transmission at a fast/slow boundary. The speed of the wave in the massive wall is much slower than in the spring.

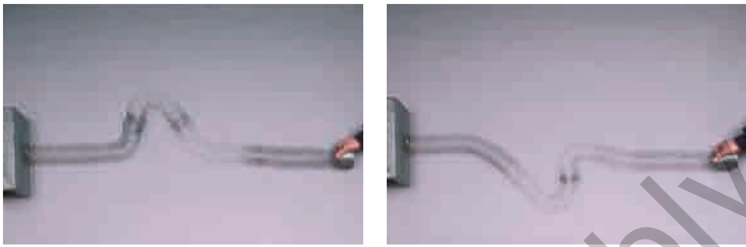


Figure 7.11 When a wave pulse is reflected from a fixed end, the reflected wave pulse is inverted.

Similarly, when a pulse travels down a spring toward an end that is not attached to anything, the free end will reflect the pulse. As shown in Figure 7.12, the reflected pulse will not be inverted. You can consider reflection from a free end as a special case of transmission at a slow-to-fast boundary.

Figure 7.12 When a wave pulse is reflected from a free end, the reflected pulse is on the same side as the original pulse.

Think It Through

- A good model accurately predicts observations from the widest possible set of related phenomena. Assume that the wave model presented here is a good model and also applies to water waves.

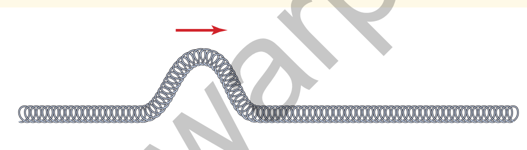
  1. If a water wave travels through water, what changes might occur that will simulate a different medium?

  2. Discuss the types of boundaries that water waves might encounter.

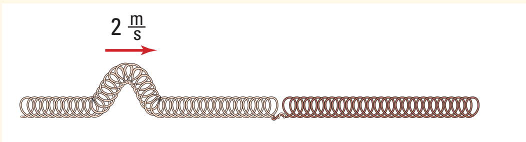
  3. A water wave moves from the deep ocean to the much shallower waters of the Grand Banks off the coast of Newfoundland. Use the wave model to predict how the waves will behave as they cross this boundary.

7.2 Section Review

1. K/U What are the essential characteristics of a wave?
2. K/U How do transverse and longitudinal waves differ? Give an example of each.
3. C Sketch a diagram of a transverse wave. Mark the amplitude and wavelength of the wave on your diagram. Also, mark two points, P1 and P2, that are in phase.
4. C Do the following:
   (a) State the wave equation relating the speed, frequency, and wavelength of a wave.
   (b) Explain how the wave equation can be derived from the fact that a wave travels a distance of one wavelength in a time of one period.
5. K/U A wave pulse is travelling down a spring from left to right as shown. Sketch what the spring would look like after the pulse had been reflected if
   (a) the opposite end of the spring was firmly held to the floor by another student.
   (b) the opposite end of the spring was held by a light thread so that it was free to move.



6. K/U After a transverse wave pulse has travelled 2.5 m through a medium, it has a speed of 0.80 m/s. How would this speed have differed if
   (a) the pulse had been twice the size?
   (b) the pulse had had twice the energy?
   (c) the pulse had travelled twice the distance?
7. C Explain the meaning of the statement, "The speed of a wave is a characteristic property of the medium through which it is travelling."
8. K/U A wave pulse is travelling down a spring with a speed of 2 m/s toward a second spring attached to its opposite end. Sketch what the two springs would look like after the pulse has passed into the second spring if
   (a) the speed of a wave in the second spring is 1 m/s.
   (b) the speed of a wave in the second spring is 4 m/s.
   (c) the speed of a wave in the second spring is 2 m/s.



7.3 Interference of Waves

SECTION EXPECTATIONS

- Explain and illustrate the principle of interference of waves.
- Communicate and graphically illustrate the principle of superposition.
- Analyze, measure, and interpret the components of standing waves.

KEY TERMS

- resultant wave
- component wave
- constructive interference
- destructive interference
- node
- antinode
- standing wave
- fundamental frequency
- fundamental mode
- overtone

When material objects such as billiard balls collide, they bounce off each other. One usually gains energy, while the other loses energy. In any case, they move off in different directions. In some cases, when an object has a large amount of energy and collides with another, the shape of the object undergoes a drastic change. It might break apart into many pieces or it might collapse or be crushed into an unrecognizable form. How do waves react when they meet?

The students in Figure 7.13 are sending wave pulses toward each other along the same spring. What will happen when the wave pulses meet? Will they collide and bounce off each other? Will the waves become distorted and unrecognizable? Will they simply pass through each other unchanged? Complete the following Quick Lab to find out for yourself.

Figure 7.13 How do collisions between wave pulses compare to collisions between material objects?

QUICK LAB: Do Waves Pass Through or Bounce Off Each Other?

TARGET SKILLS

- **Predicting**
- **Analyzing and interpreting**

Predict what will happen when two wave pulses meet. Give the reasoning behind your predictions. With a partner, stretch a large spring out along the floor, to a length of about 8 m. Start wave pulses from each end at the same time and observe what happens. Test all of the following combinations.

- pulses of the same size on the same side of the spring
- pulses of different sizes on the same side of the spring
- pulses on the opposite sides of the spring

Discuss with your partner what you perceive to be happening. If you do not agree, design more experiments until you feel that you have a clear understanding of what happens when wave pulses meet.

Analyze and Conclude

1. Did your final conclusion agree with your prediction? Explain any contradictions.
2. Describe your final conclusion about whether waves bounce off or pass through each other.
3. How did the design of your experiments help you to draw a firm conclusion?

Superposition of Waves

You no doubt concluded from the Quick Lab that waves *do* pass through each other. During the time that the two waves overlap, they interact in a manner that temporarily produces a different-shaped wave. This **resultant wave** is quite unlike either of the two **component waves**. Each component wave affects the medium *independently*. Consequently, at any one time, the displacement of each point in the medium is the *sum* of the displacements of each component wave. Note that the displacements of the component waves can be either positive (+) or negative (–). These signs must be included when adding them. If one wave would have moved a particular point in the medium up three centimetres (+3 cm), and a second wave would have moved that point down six centimetres (–6 cm), then the resultant displacement would be three centimetres down (+3 cm + (–6 cm) = –3 cm). This behaviour of waves is known as the "principle of superposition."

When two waves displace the medium in the same direction, either up or down, the resultant displacement is larger than the displacement produced by either component wave alone. This interaction is called **constructive interference** (see Figure 7.15). As the wave pulses pass through each other and the peaks of each wave overlap, one point (A) in the medium will experience the maximum displacement.

Figure 7.14 As these water waves move through each other, you can readily see the details of each individual wave.

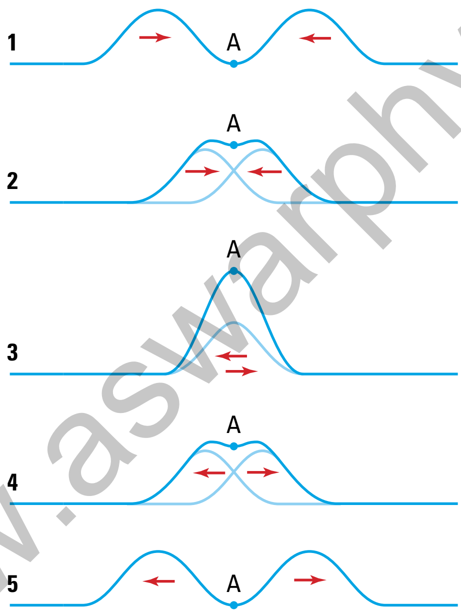


Figure 7.15 Constructive interference results in a wave pulse that is larger than either individual pulse.

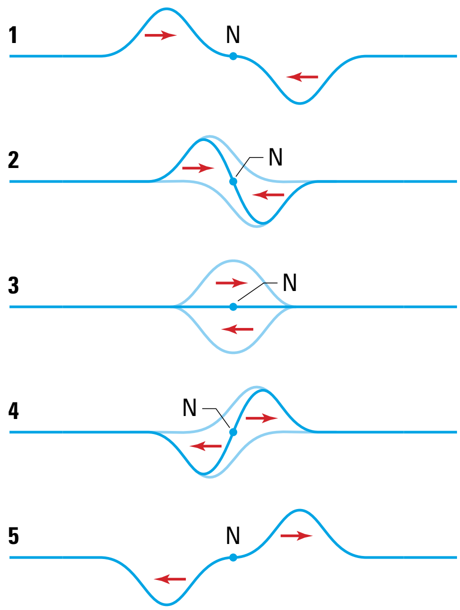


Figure 7.16 Destructive interference results in a pulse that is smaller than the larger of the component waves. When the component pulses are identical in size but one is inverted, there is one moment when no pulse can be seen.

When two waves displace the medium in opposite directions, the resultant displacement is less than one, and sometimes both, of the component waves. This interaction is called **destructive interference**, and is illustrated in Figure 7.16 on the previous page. If the two pulses are identical in size, the point where they first meet (N) will not move at all as the waves interfere.

Standing Waves

When periodic waves with the same shape, amplitude, and wavelength travel in opposite directions in a linear medium such as a rope or spring, they produce a distinct pattern in the medium that appears to be standing still. At intervals that are a half wavelength apart, the waves destructively interfere and create points, called **nodes**, that never move. Between each node, a point in the medium, called an **antinode**, vibrates maximally. Because the nodes do not move, the sense of movement of the two-component wave is lost and the resultant wave is called a **standing wave**.

Figure 7.17 illustrates how using the principle of superposition yields the pattern of fixed nodes, spaced half a wavelength apart, and points of maximum disturbance, or antinodes, also spaced half a wavelength apart. The antinodes are located at the midpoints between adjacent nodes. As you can see in part (A) of Figure 7.17, when the two identical component waves line up with troughs opposite crests, there is complete destructive interference and, momentarily, the medium is undisturbed.

A quarter of a period later, the yellow wave will have moved a quarter of a wavelength to the right and the blue wave will have moved a quarter of a wavelength to the left. Part (B) of Figure 7.17 shows how the two component waves are superimposed, producing constructive interference. This interference produces a resultant wave with an amplitude that is the sum of the component waves.

A quarter of a period after the situation depicted in part (B), the waves will again be lined up in opposition, so as to produce destructive interference in part (C). A quarter of a period later, the component waves will again be superimposed so as to produce constructive interference, as illustrated in part (D). This sequence will repeat over each period.

Part (E) of the figure represents the image you would see over a period of time. At the nodes, the medium does not move at all. In between the nodes, the standing wave appears as a blur, because the medium is moving up and down constantly. The resulting movement is characterized by a series of nodes spaced half a wavelength apart along the medium and a series of antinodes located at the midpoints between the nodes.

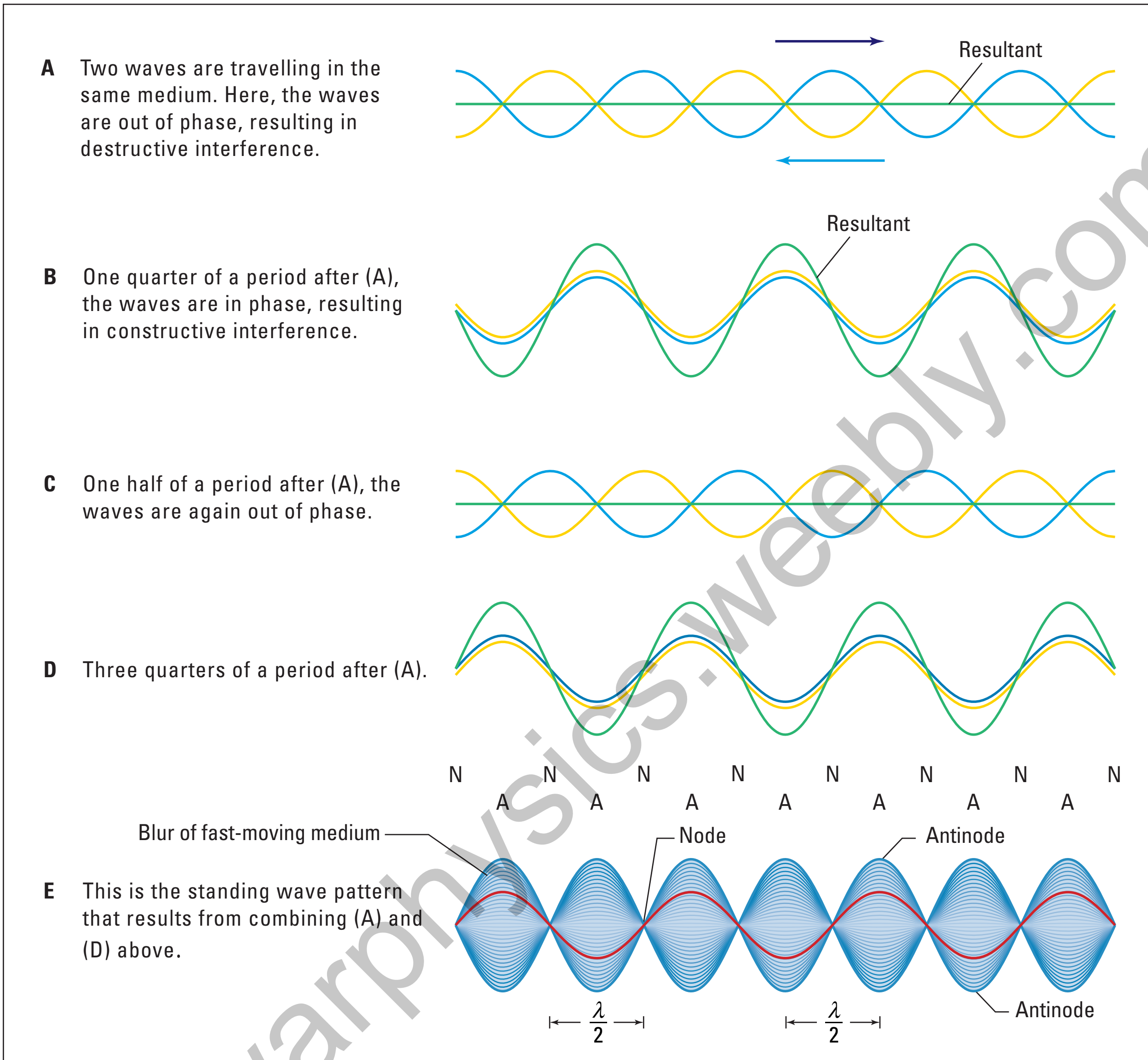


Figure 7.17 As identical travelling waves proceed one quarter of a wavelength in opposite directions, the resultant wave goes from complete destructive interference to maximal constructive interference. Part (E) shows how the wave appears over a period of time. The red wave shows the wave at one instant in time.

A standing wave can also be produced in a linear medium using only one vibrating source. The second wave is produced by the reflection of the first wave from the far end of the medium. Because the second wave is a reflection, it will have essentially the same frequency, wavelength, and amplitude as the first. Whether or not resonance and, consequently, a standing wave will occur depends on the match between the frequency of vibration and the length of the linear medium.

Figure 7.18 The position of a violinist's finger determines the effective length of the string and, therefore, determines which wavelengths will form a standing wave.

For example, consider a bow drawn across a violin string. The friction of the bow causes the string to vibrate at many different frequencies. Waves move in both directions away from the bow toward the fixed ends of the string. When they reach the ends, the waves reflect back. The propagated waves and the reflected waves interfere, sometimes constructively. Whether or not standing waves of a given frequency can form depends on the end points of the string where the string is fixed. Since the ends of the strings cannot move, standing waves can form only if nodes occur at the ends of the strings. When the string is vibrating at its resonance frequencies, it causes the body of the violin to vibrate and amplify the tone.

For every medium of a fixed length, there are many **natural frequencies** of vibration that produce resonance. Figure 7.19 shows a rope vibrating at three of its natural frequencies. The lowest natural frequency (corresponding to the longest wavelength) that will produce resonance on the rope is called the **fundamental frequency**. The standing wave pattern for a medium vibrating at its fundamental frequency displays the fewest number of nodes and antinodes and is called its **fundamental mode** of vibration. All natural frequencies higher than the fundamental frequency are called **overtones**. For example, the natural frequency that corresponds to a pattern with one node in the centre of the rope is called the "first overtone." The pattern continues with the addition of one node at a time. A rope or string may vibrate at several natural frequencies at the same time.

MISCONCEPTION

You can't get something for nothing!

Some people might think that constructive interference creates energy, or that destructive interference destroys energy. However, the law of conservation of energy still holds. Energy can neither be created nor destroyed. A standing wave simply redistributes the energy so that there is less energy near the nodes and more of it near the antinodes.

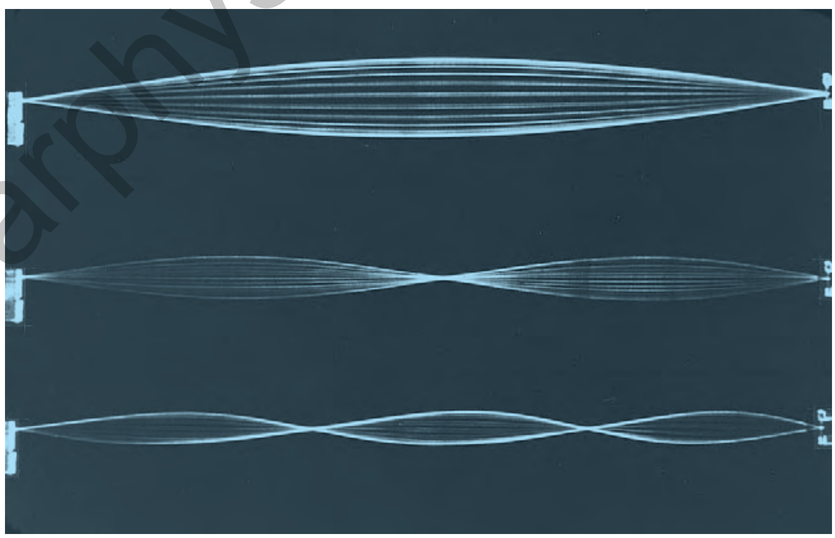


Figure 7.19 Resonance will occur in a vibrating rope for wavelengths that create nodes at the ends of the rope. There may be any number of nodes within the rope.

INVESTIGATION 7-B

Wave Speed in a Spring

TARGET SKILLS

- Performing and recording
- Analyzing and interpreting

If you know the speed of a wave, you can use it to determine the time it takes a wave to travel a given distance, or the distance a wave will travel in a given time. You can also use the speed to determine the wavelength of a wave when the frequency is known, or the frequency when the wavelength is known. The precision of any of these calculations depends on the precision with which the speed is known. Consequently, it is important to determine the speed as precisely and accurately as possible.

In this investigation, you will measure the speed of a wave using two different methods. Then, you will evaluate the methods and decide which is the more accurate. In order to make the best measurements, you will need at least three people in each group.

Problem

To determine the speed of a wave in a stretched spring as precisely as possible, and to evaluate the accuracy of the result.

Equipment

- long spring
- stopwatch
- metre stick or measuring tape

Procedure

Direct Measurement

1. Stretch the spring out between two partners. The third partner will carefully measure the length of the spring. Ensure that you maintain this length throughout the investigation.
2. Determine the optimum number of times that you can allow the pulse to reflect back and forth and still see the pulse clearly enough to make good time measurements. Send several test pulses down the spring to determine the optimum number of reflections to allow for one time measurement. (**Note:** You can increase the precision of your measurements by allowing the pulse to travel longer distances. However, as the pulse reflects back and forth, friction causes the amplitude to decrease. The amplitude eventually becomes so small that it is hard to follow and thus decreases the precision of your measurements.)
3. Devise a method for determining the exact distance that a pulse has travelled when you make a measurement.
4. Prepare a data table with the following headings: Distance, Time, Speed. Allow enough rows for at least five trials.
5. Carry out at least five trials for measuring the time and distance data for a moving pulse.
6. Calculate the speed of the pulse and determine the average speed for the five or more trials that you performed.

Indirect Measurement

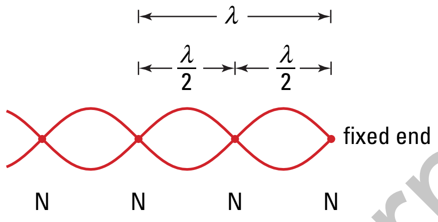
7. To carry out an indirect measurement, you need to create standing waves in the spring. Practise the creation of standing waves by performing the following steps.
   (a) Stretch the spring out to about 8 m.
   (b) While one partner holds the end of the spring fixed, another should vibrate the opposite end back and forth.
   (c) Start with a very low frequency and try to get the spring to vibrate in its fundamental mode. You should see only one node at the end held in place and one more node very close to the end that is being vibrated.
   (d) Slowly increase the frequency of vibration until you can produce other standing wave patterns.
   (e) Determine the values of all of the natural frequencies that you were able to find.

continued ▶

continued from previous page

time for 20 vibrations Δt	$f = \frac{20}{\Delta t}$	λ = distance from fixed end to second node	$v = f\lambda$

8. Stretch the spring to exactly the same distance that you used when making the first set of measurements.
9. Prepare a data table like the one shown above. Allow for at least five trials.
10. One partner should hold one end of the spring firmly in place, while a second partner creates a standing wave by vibrating the other end of the spring. Find a frequency that creates at least two nodes in the spring.



11. Let the third partner determine the wavelength by measuring the distance from the stationary end to the second node. Record the value in the data table.
12. Determine the time for 20 vibrations. Record the value in the data table.
13. Repeat steps 10 through 12 for at least five trials.
14. Calculate the speed of the wave for each trial. Determine the average of the speeds for all trials.

Analyze and Conclude

1. Compare the precision of measurement for the two methods for determining the speed of a wave. (**Note:** The range of the speeds in individual trials for each method is an indicator of precision. A narrow range of values indicates greater precision. If the calculated speeds were quite different from one trial to the next, the precision is low.) If you are unsure about the difference between precision and accuracy, review the meanings of these terms in Skill Set 2.
2. Compare the values of the speed of the wave for the two different methods. Do the ranges of values of speed for the two methods overlap? Are the values of average speed of the wave similar or quite different for the two different methods?
3. List the factors that might have contributed to any lack of compatibility of the two methods.
4. From your observations and analyses, which average speed do you think is the most accurate? Explain the reasoning on which you based your conclusion.
5. What is the relationship between the natural frequencies of the spring and its fundamental frequency?
6. How could you tell if you had missed one of the natural frequencies when you were finding natural frequencies above the fundamental?

Standing wave patterns can be set up in a variety of objects. If you carefully examine the photograph of the Tacoma Narrows Bridge collapse on page 326, you should see evidence of the standing wave that was set up in the bridge. You can also observe standing wave patterns in the radio antenna of a car as you travel at different speeds along a highway.

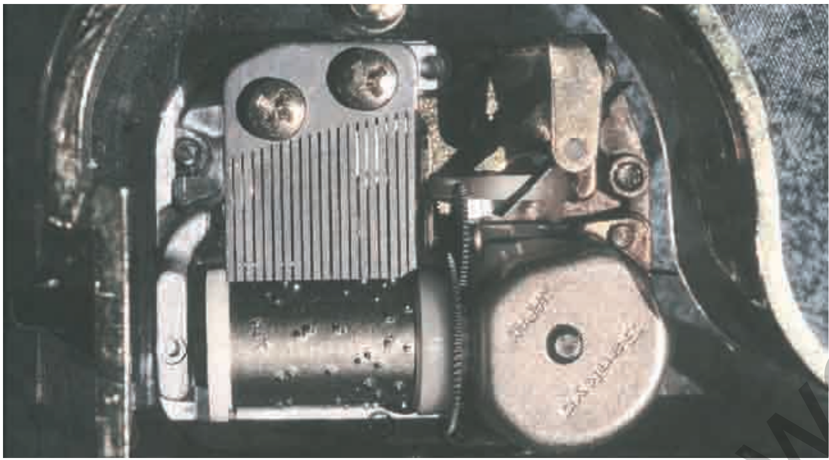


Figure 7.20 The tones of a music box are created by the natural frequencies of tiny strips cut from a small sheet of metal. As the drum turns, pegs on the drum flip the metal strips and cause them to vibrate.

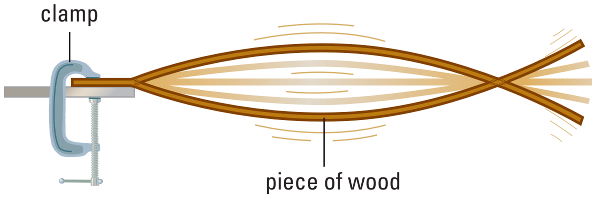
QUICK LAB

Standing Waves in a Thin Piece of Wood

TARGET SKILLS

- Analyzing and interpreting
- Communicating results

Standing wave patterns can easily be set up in a long piece of wood moulding. Obtain a piece of quarter-round moulding 2 m to 3 m long and 0.50 cm thick. With the moulding oriented horizontally or vertically, vibrate one end of the moulding back and forth through a range of frequencies. You should be able to "feel" the resonance that is produced when you are vibrating the moulding at a natural frequency.



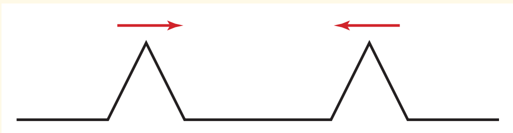
How is the wavelength associated with the fundamental frequency related to the length of the moulding?

Analyze and Conclude

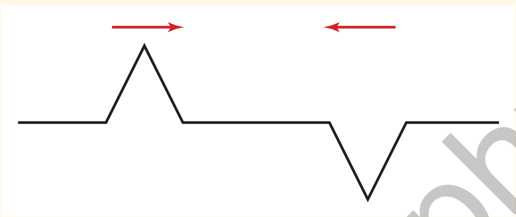
1. How do the standing wave patterns produced in the moulding differ from those produced in the spring?
2. Describe the standing wave pattern produced by the fundamental frequency.

7.3 Section Review

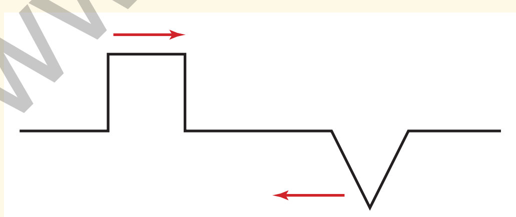
1. K/U Two triangular pulses, each 2 cm high and 1 cm wide, were directed toward each other on a spring, as shown. Sketch the appearance of the spring at the instant that they met and completely overlapped. What kind of interference is this?



2. K/U Two triangular pulses, each 2 cm high and 1 cm wide, were directed toward each other along the same spring. However, the pulse approaching from the left was upright and the one approaching from the right was inverted. Sketch the appearance of the spring at the instant that the two pulses met and completely overlapped. What kind of interference is this?



3. K/U An upright square pulse and an inverted triangular pulse were directed toward each other on a spring, as shown in the illustration. Sketch the appearance of the spring at the instant the two pulses met and completely overlapped. What principle did you use in constructing the shape of the spring for the instant at which the two pulses met? What does this principle state about how waves combine?

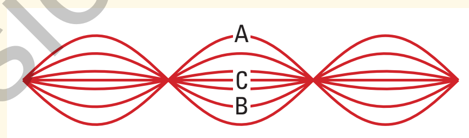


4. C Describe what you would see when a standing wave was set up in a spring. Why is it called a standing wave?

5. K/U What is a node? What is an antinode? Describe how the nodes and antinodes are distributed along the length of the standing wave pattern.

6. C Sketch the appearance of the standing wave pattern set up in a spring when it is fixed at one end and the other end is vibrated at (a) its fundamental frequency, (b) a frequency twice its fundamental frequency, and (c) a frequency three times its fundamental frequency.

7. K/U The figure shown here represents a spring vibrating at its second overtone. The points labelled (A), (B), and (C) represent the location of the central point of the string at various times.



(a) At which location is the central point of the string moving at its maximum speed?

(b) At which location is its instantaneous speed zero?

(c) At which location is the point on the string moving with an intermediate speed?

(d) Explain the reasoning you used to answer the above questions.

7.4 Waves in Two Dimensions

Have you ever taken a stroll near a river, either in woodland or perhaps along a city street, and heard the splashing sounds of moving water before you could actually see the river?

Figure 7.21 A river generates sound that often can be heard long before the river is in view. This phenomenon highlights some special properties of sound waves that result from their three-dimensional nature.

So far in this chapter, you have explored the behaviour of waves in linear media such as springs and ropes. However, many wave phenomena that you will be studying, such as sound and light, are not confined to a single dimension. In fact, sound waves can travel around corners, as you can tell whenever you hear a sound before you can see its source. To understand such phenomena, you need to learn about waves in more than one dimension. In this section, you will briefly explore some wave behaviours that emerge when waves travel in two-dimensional media.

Behaviour of Two-Dimensional Waves

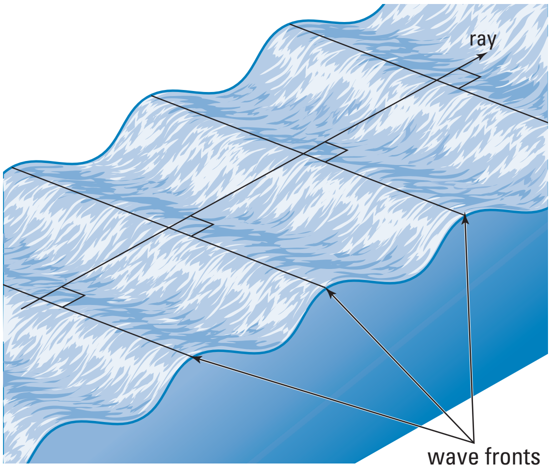
The most visible two-dimensional waves are water waves. Observing and describing water waves will help you to understand sound and light waves, as well as many other types of waves. Water waves can take on a variety of shapes. Two examples, straight and circular waves, are shown in Figure 7.22 on the next page. The lines drawn across the crests are called **wavefronts**. Since the distance from one crest to the next is one wavelength, the distance between wavefronts is one wavelength. To indicate the direction of the motion of the wave, lines called **rays** are drawn perpendicular to the wavefronts. Rays are not physically ***part of*** the wave, but they do help to model it scientifically.

SECTION EXPECTATIONS

- Investigate the properties of mechanical waves through experimentation.
- Define and describe the concepts and units related to constructive and destructive interference.
- Draw and interpret interference of waves during transmission through a medium.

KEY TERMS

- wavefront
- ray
- normal line
- angle of incidence
- angle of reflection
- refraction
- diffraction
- nodal line
- antinodal line



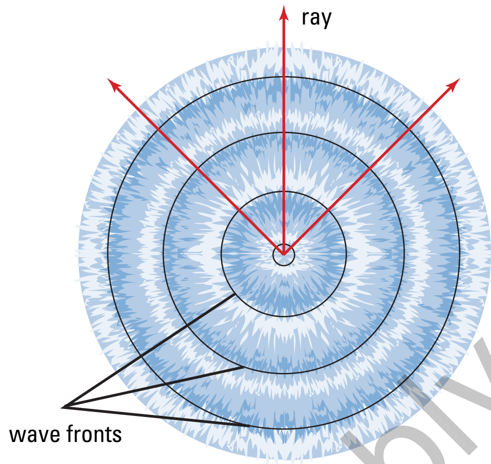


Figure 7.22 **(A)** A straight object rocking back and forth can disturb the water's surface and create waves with straight wavefronts.

(B) A stone or pebble dropped into water can create circular waves. The crests move out in all directions from a central disturbance to water.

When a water wave encounters a solid barrier, it reflects in a way that is similar to a wave in a rope reflecting from an end that is firmly attached to a wall. However, water waves are not constrained to reflect directly backward. To quantitatively describe the way a two-dimensional wave reflects off a barrier, physicists define specific angles, as shown in Figure 7.23. At the point where a ray strikes the barrier, a line, called a **normal line**, is drawn perpendicular to the barrier surface. The **angle of incidence** is the angle between the normal line and the ray representing the incoming wave. The **angle of reflection** is the angle between the normal line and the ray representing the reflected wave.

PHYSICS FILE

A ripple tank consists of a shallow tank with a glass bottom that allows a light to shine through the water onto a screen as shown in the investigation on the following page. When waves form on the surface of the water, bright and dark regions, corresponding to the crests and troughs of the waves, are produced on the screen.

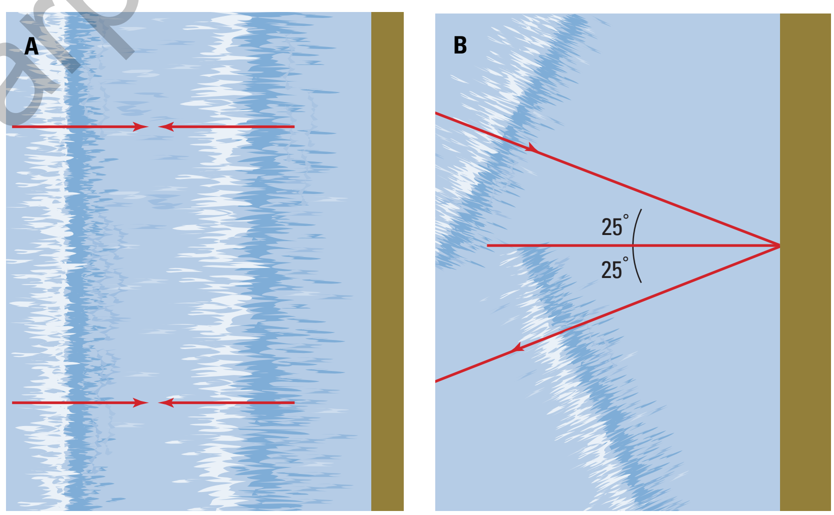


Figure 7.23 **(A)** Waves travelling directly toward a straight barrier reflect straight back. **(B)** Waves arriving at a barrier at an angle reflect off the barrier at an angle.

INVESTIGATION 7-C

Waves on the Surface of Water

TARGET SKILLS
- Identifying variables
- Performing and recording
- Analyzing and interpreting

Patterns occur in a ripple tank because the crests of waves act as lenses (see Chapter 12) that focus the light and produce bright regions on the screen. The troughs act as lenses that spread the light out and produce dark regions.

Problem

How can a ripple tank be used to study waves?

Equipment

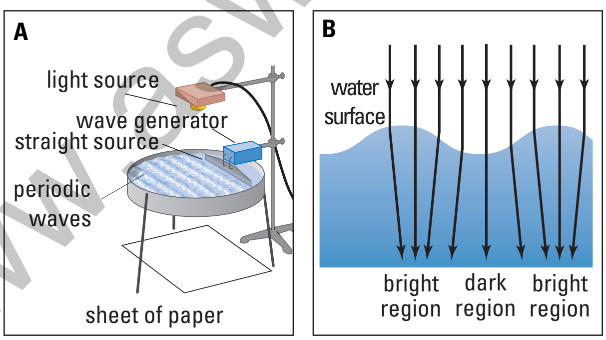
- ripple tank
- wooden dowel
- wave generator
- plastic or paraffin block (about 1 cm thick)

CAUTION

Care must be taken with any electrical equipment near ripple tanks. Firmly attach lights and wave generators to the tank or lab bench, and keep all electrical wiring away from the water.

Procedure

1. Assemble a ripple tank similar to the one shown below. Add water and level the tank so that the depth of the water is approximately 2 cm at all points in the tank.
2. Place a solid barrier in the tank. Use a dowel to generate single wave pulses, one at a time.



(A) You can see the details of water waves by using a ripple tank with a light shining directly onto the surface of the water. **(B)** The curves on the water's surface focus light, creating bright and dark regions.

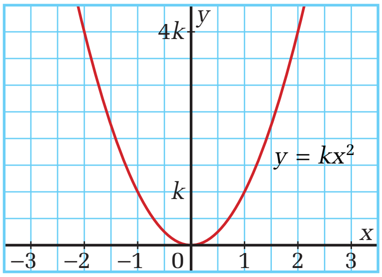
3. First, send a straight wave pulse directly toward the barrier. Then send straight wave pulses toward the barrier at a variety of angles. Draw diagrams of the wavefronts, with rays showing their direction of motion.
4. Next, send straight wave pulses toward a concave barrier roughly the shape of a parabola. Adjust the shape of the barrier until the reflected wave appears to converge toward a point. Keeping the shape of the barrier the same, start a circular wave from the point you just found, using your finger. Observe what happens when these circular waves reflect from the parabolic barrier.
5. To record your observations, draw diagrams of the shape of the wavefronts and include rays to illustrate the path of their motion.
6. Place a block of plastic (or paraffin), approximately 1 cm thick, on the bottom of the tank at one end. With the dowel, make straight wave pulses. First, send the pulses directly toward the edge of the plastic. Then, send straight wave pulses toward the plastic at various angles with the edge of the plastic. Observe any changes in wavelength or direction after the waves pass over the plastic.

Analyze and Conclude

1. Compare the angle of reflection to the angle of incidence when straight waves reflect from a straight barrier. State any general relationship that you observed.
2. How does a straight wave reflect from a parabolic barrier?
3. If a circular wave is started at the point where a parabola focusses a straight wave, what is the shape of the reflected wavefront?
4. How did the wavelength and direction of straight waves change when the waves passed from deeper water into more shallow water?

Math Link

The equation $y = kx^2$ is the equation of a parabola. The vertex of this parabola is located at the origin (0,0) and it opens upward. The rate at which it opens is determined by the value of k. Radar antennas and satellite dishes for television are constructed with parabolic cross sections. They collect waves coming straight in and focus them into a small receiver. Carefully sketch a parabola with equation $y = x^2$, and use ray paths to form a hypothesis about the location of the focus.



Reflection and Refraction of Water Waves

In Investigation 7–C, you probably discovered that, when a straight wave moves directly toward a straight barrier, the wave will be reflected directly backward. If a straight wave meets a barrier at an angle, it will reflect off at an angle. The angle of reflection will equal the angle of incidence.

Barriers with different shapes reflect waves in unique ways. For example, a concave barrier in the shape of a parabola will reflect straight waves so they become curved waves. The waves will converge toward, then pass through, a single point. As they continue through the point, they curve outward, or diverge.

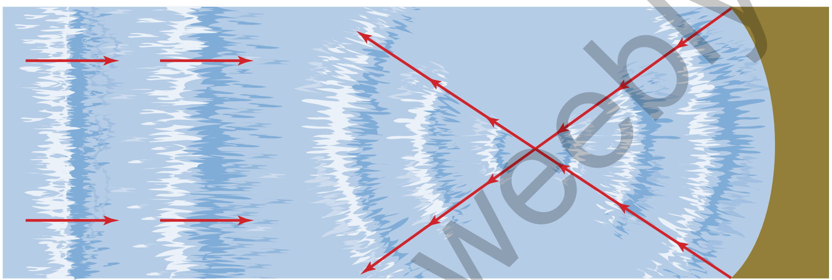


Figure 7.24 A parabolic barrier will reflect straight waves through a single focal point.

QUICK LAB Diffracting Water Waves

TARGET SKILLS
- **Identifying variables**
- **Analyzing and interpreting**

CAUTION Use extreme care when working with electrical equipment near ripple tanks. Ensure that lights and wave generators are firmly attached. Keep all electrical wiring away from the water.

Use a straight wave generator with a ripple tank to generate periodic water waves. Obtain a barrier with an opening that can be varied in size. Place the barrier in the tank, parallel to the straight wave generator. Position the barrier so that you have a good view of the wavefronts after they have passed through the opening. Observe the behaviour of the waves passing through the barrier under the following conditions.

- Vary the size, D, of the opening in the barrier.
- Vary the wavelength, λ, of the waves.

The property of waves that causes them to "bend around corners" is called "diffraction." Choose the size of opening that caused the greatest amount of diffraction and make two openings of that size that are quite close together. Observe the behaviour of straight waves as they reach and pass through the two openings.

Analyze and Conclude

1. Do small or large openings in the barrier cause more diffraction of the water waves?
2. Are small or large wavelengths diffracted more?
3. Describe the pattern you observed that was caused by two openings located close together.

When waves travel from one medium into another, their speed changes. This phenomenon is called **refraction**. As a result of the change in speed, the direction of two-dimensional waves changes. You can demonstrate this effect in water waves without even changing from water to another medium. Refraction occurs in water because the speed of waves in water is influenced by the depth of the water. You probably observed refraction occurring in the ripple tank when you placed the thick sheet of plastic in the tank. Did the waves change direction when they went from the deeper water to the shallower water? You will study refraction of light waves in more depth in Chapter 11.

Biology Link

Scientists who study bird vocalizations use parabolic reflectors to collect sounds from a distance and focus the sound waves to a point where they have placed a microphone. By aiming the reflector at a distant bird, they can "capture" the sound of that bird and nearly eliminate other sounds. Use print resources and the Internet to find out what researchers have discovered about how songs and calls are learned, and if they have "meaning."

Bending Around Corners: Diffraction of Waves

Waves and particles behave quite differently when they travel past the edge of a barrier or through one or more small openings in a barrier. Moving particles either reflect off the barrier or pass through the opening and continue in a straight line. What do waves do when they encounter the edge of a barrier or openings in a barrier?

In the previous Quick Lab, you probably discovered that when waves pass through small openings in barriers they do not continue straight through. Instead, they bend around the edges of the barrier. This results in circular waves that radiate outward. This behaviour of waves at barriers is called **diffraction**. The amount of diffraction is greatest when the size of the opening is nearly the same as the size of one wavelength.

Figure 7.25 When straight water waves reach a small opening in a barrier, the tiny part of the wave at the opening acts as a point source, similar to the effect of putting your finger in the water; thus, the waves move out in semicircles. This phenomenon is an example of the diffraction of waves.