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Dear Student,

I am also a student. I like to learn how things work then use what I know to show others. As one student to another, I hope you enjoy this course! I hope you learn how electricity works and how light and color are created. I hope you learn some secrets of nature that lie deep within the tiny atoms that make up our universe and yourself. I hope you learn what it means to accelerate and how to apply force to cause things to stop and go. Most of all, I hope you learn how to take a new situation and figure out how things work for yourself.

The secret to success is not in knowing the answers, but in knowing how to find the answers. Someday, each of you will come across many problems that are not in this book or any other book. I hope this course will teach you how to begin solving any problem involving the man-made or natural world. My knowledge of physics has allowed me to solve problems as simple as why my car will not start, and as complex as making a nuclear fusion reactor work.

I love learning new things. From one student to another, I hope you have fun in this course and that you will also come to love learning new things about the wonderful universe we live in.

[Signature]

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**Unit Pages and Chapter Pages**

**UNIT PAGE**
- Unit icon and number
- Topic of unit
- Chapters and titles in unit
- Color that identifies unit
- Illustration that represents concepts presented in the unit

**CHAPTER PAGE**
- Chapter number
- Chapter title
- Color that identifies unit
- Introduction to the chapter
- Thought-provoking questions

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*Chapter 4: Machines, Work, and Energy*

The Egyptian pyramids were built about 4000 years ago. It took workers approximately 80 years to build the pyramids of Giza. The largest, called the Great Pyramid, contains about 1 million stone blocks, each weighing about 2.5 tons! No one knows exactly how the Egyptians were able to build such an incredible monument. What did the ancient Egyptians use to help them build the pyramids? Egyptians, men and women who study ancient Egypt, disagree about the details of how the gigantic structures were built, but most agree that a system of ramps and levers (simple machines) was necessary for moving and placing the blocks. The fact that they could move such enormous massive blocks of limestone to build the Great Pyramid (and that the roads were 12 miles long, and the Great Pyramid is 1.5 miles high—just try to imagine a 48 story building) is fascinating, don't you think? Perhaps the most amazing fact of all the story is that the Great Pyramid of Giza still stands, and is visited by tens of thousands of people each year.

**Key Questions**
- Why does elevator use a cable system to transport people?
- How much power can a highly trained athlete have?
- What is one of the most perfect machines ever invented?
- Why does time always move forward, and never backwards?
Chapter Review Pages

Vocabulary words to fill in the sentences below

These questions help you check your understanding of concepts you have learned in the chapter

Section numbers identify where you can find the information to answer the questions

Chapter number with icon and color that identifies unit

These questions help you practice solving problems found in the chapter

Colorful illustrations to support the questions

Unit number and title
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On June 21, 2004, SpaceShipOne became the first private aircraft to leave Earth's atmosphere and enter space. What is the future of this technology? Private companies are hoping to sell tickets to adventurous people who want to take a trip beyond Earth's atmosphere. Our study of physics can help us understand how such a trip is possible.

Many people, when asked the question “What is physics?” respond with “Oh, physics is all about complicated math equations and confusing laws to memorize.” This response may describe the physics studied in some classrooms, but this is not the physics of the world around us, and this is definitely not the physics that you will study in this course! In this chapter you will be introduced to what studying physics is REALLY all about, and you will begin your physics journey by studying motion and speed.

Key Questions
- Does air have mass and take up space? What about light?
- How can an accident or mistake lead to a scientific discovery?
- What is the fastest speed in the universe?
1.1 What Is Physics?

What is physics and why study it? Many students believe physics is a complicated set of rules, equations to memorize, and confusing laws. Although this is sometimes the way physics is taught, it is not a fair description of the science. In fact, physics is about finding the simplest and least complicated explanation for things. It is about observing how things work and finding the connections between cause and effect that explain why things happen.

Three aspects of physics

1. Describing the organization of the universe
   - The universe is defined as everything that exists. Everything in the universe is believed to be either matter or energy (Figure 1.1). Matter is all of the “stuff” in the universe that has mass. You are made of matter, and so is a rock and so is the air around you. Energy is a measure of the ability to make things change. Energy flows any time something gets hotter, colder, faster, slower, or changes in any other observable way.

2. Understanding natural laws
   - A natural law is a rule that tells you how (or why) something happens the particular way it does. We believe that all events in nature obey natural laws that do not change. For example, one natural law tells you a ball rolling down a ramp of a certain height will have a certain speed at the bottom. If the same ball rolls down the same ramp again, it will have the same speed again. Physics is concerned with understanding the natural laws that relate matter and energy.

3. Deducing and applying natural laws
   - A third important part of physics is the process of figuring out the natural laws. The natural laws are human explanations based on human experience. A ball will still roll down a ramp regardless of whether you know why or how. It is up to us to figure out how and why. This part of physics often uses experiments and analysis. An experiment is a situation you carefully set up to see what happens under controlled conditions. Analysis is the detailed thinking you do to interpret and understand what you observe. Both of these activities lead to the development and refinement of natural laws. You will learn many natural laws in this course. We don’t yet know all the natural laws. There is a lot left for us to learn.

Vocabulary
- natural law, experiment, analysis, mass, system, variable, macroscopic, scientific method, independent variable, dependent variable, hypothesis, control variable, experimental variable, model

Objectives
- ✓ Explain what makes up the universe.
- ✓ Describe how the scientific method is used.
- ✓ Explain the effects of energy on a system.

Figure 1.1: The universe contains matter and energy.
Matter and energy

Matter and mass  Matter is defined as anything that has mass and takes up space. Mass is the measure of the amount of matter that makes up an object. A car has more mass than a bicycle. But why does the car have more mass? The answer is that the car contains more matter. Steel, plastic, and rubber are different forms of matter and the car has a lot more than the bicycle.

Is air matter?  How can you tell if something takes up space? Does the air around you take up space? Think about how you could test whether or not air takes up space. An “empty” glass contains air. Imagine a cylinder you could push into the empty glass. If the cylinder formed a seal so that the air inside couldn’t escape, you wouldn’t be able to push the cylinder all the way to the bottom. Why? Because air is matter and takes up space (Figure 1.2). You don’t always notice the mass of air because it is spread thinly, but the mass of air in an average classroom is about equal to the mass of one student.

Is light matter?  Just as an empty glass is actually filled with air, it also fills with light in front of a window. Is light a kind of matter? Because light does not take up space and has no mass, it does not fit the definition of matter. Imagine pumping all of the air out of that empty glass while the cylinder is pulled back. Even if the glass were near a light source and filled with light, you could push the cylinder all the way down because light does not take up space (Figure 1.3). The glass also has the same mass in a dark room and a room full of sunlight. Later in the course we will see that light is a pure form of energy.

Energy  Imagine dropping a stone. In your hand, the stone is described by its mass and height off the ground. Once it is falling, the stone speeds up and its height changes. If you investigate, you learn that you cannot get any speed by dropping the stone. You cannot make the stone go 100 miles per hour by dropping it only one meter from your hand to the floor. But why not? What limits how much speed the stone can have? The answer is energy. Energy is how we measure the amount of change that is possible. Changing the speed of the stone from zero to 100 mph takes a certain amount of energy. Lifting the stone up (changing its height) also takes energy. Change takes energy and the amount of change you can have is limited by the amount of energy available.

Figure 1.2: Air is matter because it has mass and takes up space.

Figure 1.3: Light is not matter because it has no mass and does not take up space.
Systems and variables

Defining a system
The universe is huge and complex. The only way to make sense of it is to think about only a small part at a time. If you want to understand a car rolling down a ramp, you don’t need to confuse yourself with the sun, or the Milky Way galaxy or even the room next door. When you want to understand something, you focus your attention on a small group called a system. A system is a group of objects, effects, and variables that are related. You choose the system to include the things you wish to investigate and exclude the things you think are not relevant.

Variables
A variable is a factor that affects the behavior of the system. When you are trying to find out how a system works, you look for relationships between the important variables of the system. For example, imagine you are doing an experiment with a car rolling down a ramp. The car and ramp are the system. The car’s speed is one important variable. Time, position, and mass are other variables.

What to include
The ideal choice of a system includes all the objects, effects, and variables that affect what you are trying to understand (Figure 1.4). To understand the motion of a car on a ramp you might include the car, the ramp, and the mass, angle, and speed. The fewer the variables, the easier it is to find important relationships. You can include more variables, like friction from the wheels, after you understand how the more important variables fit together (Figure 1.5).

Figure 1.4: Choose variables that are important to your investigation.

First investigation
System includes:
car, ramp, angle, speed, time, mass

Discover relationship between angle and speed

Second investigation
System includes:
car, ramp, angle, speed, time, mass and friction

Figure 1.5: You may change the system later to include new objects, effects, or variables. You may also remove things if they are not necessary to explain what you observe.
The scale of a system

An example of different scales
A system almost always shows different and important behavior at different scales. Figure 1.6 shows a road at three different scales. To calculate driving time between cities, you use the largest scale. To design the road to be wide enough to fit a car, you use the middle scale. To understand how water drains through cracks in the road, you need to look on the smallest scale. In a similar way the universe can be understood differently on different scales. It depends on what you are trying to understand.

The macroscopic scale
Observations are on the macroscopic scale when they are large enough for us to see or directly measure. The mass of a car and the temperature of a pot of water are macroscopic variables. Virtually all the things you measure in experiments in this course are macroscopic. Many of the natural laws you learn will relate macroscopic variables, such as speed, temperature, and mass.

Variables that can be observed and measured directly are on the macroscopic scale.

The scale of atoms
Temperature is related to energy but it is not possible to understand how on the macroscopic scale. To understand temperature we must investigate the composition of matter. To understand the connection between temperature and energy we must look on the scale of atoms and molecules.

Atoms
Almost all of the matter you experience is made of atoms. Atoms are tiny particles, far too small to see directly. However, many of the macroscopic properties of matter you can observe depend on the behavior of atoms. Physics shows us that to understand certain aspects of the macroscopic world (such as temperature) we need to understand the behavior of atoms. We will use the term “atomic” to mean “on the scale of atoms.”

Variables that are on the scale of atoms and are far too small to be observed are on the atomic scale.

Figure 1.6: Three different scales for looking at a road.
1.1 What Is Physics?

Investigating systems

Experiments
An experiment is a situation set up to investigate the relationship between variables in a system. The process used to conduct an experiment is called the scientific method (Figure 1.7). Experiments usually have a question associated with them. An example would be: “How does the steepness of a ramp affect the speed of a ball at the bottom?”

Types of variables
To answer the question you do an experiment to measure the cause-and-effect relationship between the ramp’s angle and the speed of the ball. The variable that is the cause of change in the system is called the independent variable. This is the variable that you change in an experiment. The ramp’s angle is the independent variable in this example. The variable that shows (or may show) the effect of those changes is called the dependent variable. The speed of the ball is the dependent variable.

Making a hypothesis
A hypothesis is an educated guess that predicts the relationship between the independent and dependent variables in an experiment. Coming up with a good hypothesis means you must have some experience with the system you are investigating. However, don’t worry if you are unsure about what will happen in an experiment. Scientists often make hypotheses that they end up proving to be incorrect. The first hypothesis is just a starting point for developing a correct understanding.

Designing experiments
In an ideal experiment you change only one variable at a time. You keep ALL of the other variables the same. This way you can be certain any change you see in the system must be associated with the one variable you changed. A variable that is kept the same is called a control variable, and the variable that is changed is called the experimental variable. In a ball and ramp experiment, the ramp angle, the ball’s mass, and the starting point are all important variables that affect the speed. In a well-designed experiment you choose only one variable at a time.

The scientific method
1. Ask a question.
2. Formulate a hypothesis.
3. Design a procedure to test the hypothesis.
4. Conduct the experiment and collect the data.
5. Analyze the data.
6. Use the data to make a conclusion.
7. If necessary, refine the question and go through each step again.

Figure 1.7: How does the angle of the ramp affect the ball’s speed?

Figure 1.8: Follow these steps when conducting an experiment.
Energy and systems

Energy  
*Energy* is an important concept that is difficult to define. Energy is a measure of a system’s ability to change or create change in other systems. A car at the top of a ramp is able to move because it has energy due to its height on the ramp. The car’s increase in speed as it moves is a change in the system that could not occur without energy.

Energy can appear in many forms, such as heat, motion, height, pressure, electricity, and chemical bonds between atoms. The key to understanding how systems change is to trace the movement of energy between objects and also between the various forms of energy.

![Image of energy forms](image)

The stability of systems  
Systems in nature tend to go from higher energy to lower energy. A system at higher energy is often unstable, while a system at lower energy is stable. The car is unstable at the top of the ramp where its energy is greatest. It will naturally move to a more stable position at the bottom of the ramp.

Creating change  
The stretched bowstring on a bow is another example of a system that has energy (Figure 1.9). Released, the string springs back to its unstretched, stable position. The bow uses its energy to change its own shape. It also can create change in the arrow. While the bow and bowstring move from high to low energy, the arrow moves from low to high energy. The energy originally in the bowstring is used to change the speed of the arrow.

Macroscopic and atomic changes  
Energy can create macroscopic and microscopic changes to systems. The changes in the bow and arrow are macroscopic because they can be directly observed. If you shoot many arrows one after another, the bowstring gets warm from the heat of friction. The warmth comes from energy flowing between atoms on the atomic scale.

Figure 1.9: A stretched bowstring on a bent bow has energy, so it is able to create change in itself and in the arrow.
Models

Consider the following system. A stretched rubber band is used to launch a car along a track that is straight for a distance and then turns uphill. If the rubber band is stretched more, the car has more speed. If the car has more speed it gets higher on the hill. How do we explain the relationship between the height the car reaches and the speed it has at the bottom of the hill?

What is a model?
Explanations in physics typically come in the form of models. In physics, a **model** is an explanation that links the variables in a system through cause and effect relationships.

Figure 1.10 shows a model of the car and ramp system. Launching the car gives it energy due to its speed. Climbing the hill takes energy. The car climbs only so high because it only has so much energy. Making the car go faster gives it more energy and that is why it goes higher. This explanation is a model that links the height and speed through the idea of energy. This model is known as the **law of conservation of energy** and is one of the natural laws of physics. The model in Figure 1.10 is conceptual because it is not precise enough to predict exactly how much height the car gets for a given speed. In chapter 3 you will encounter a more detailed version of the law of conservation of energy.

1.1 Section Review

1. What are the main activities involved in studying physics?
2. Which has more mass: a dollar bill or a quarter? Why?
3. Imagine that you are doing an experiment to find out if more expensive batteries will run your radio for a longer amount of time than cheaper batteries will. List a question, a hypothesis, the independent variable, the dependent variable, and the control variables for this experiment. Then write a procedure that would allow you to test your hypothesis.
4. What is needed to create change in a system?
1.2 Distance and Time

To do science you need a precise way to describe the natural world. In physics, many things are described with measurements. For example, two meters is a measurement of length that is a little more than the height of an average person. Measurements such as length, mass, speed, and temperature are important in science because they are a language which allows us to communicate information so that everyone understands exactly what we mean. In this section you will learn about measuring distance and time.

**Measuring distance**

- **Measurements**: A measurement is a precise value that tells how much. How much *what*, you ask? That depends on what you are measuring. The important concept in measurement is that it communicates the amount in a way that can be understood by others. For example, two meters is a measurement because it has a *quantity*, 2, and gives a *unit*, meters.

- **Units**: All measurements must have units. Without a unit, a measurement cannot be understood. For example, if you asked someone to walk 10, she would not know how far to go: 10 feet, 10 meters, 10 miles, and 10 kilometers are all 10, but the units are different and therefore the distances are also different. Units allow people to communicate amounts. For communication to be successful, physics uses a set of units that have been agreed upon around the world.

- **What is distance?**: Distance is the amount of space between two points (Figure 1.11). You can also think of distance as how far apart two objects are. You probably have a good understanding of distance from everyday experiences, like the distance from one house to another, or the distance between California and Massachusetts. The concept of distance in physics is the same, but the actual distances may be much larger and much smaller than anything you normally refer to as a distance.

- **Distance is measured in units of length**: Distance is measured in units of *length*. Some of the commonly used units of length include inches, miles, centimeters, kilometers, and meters. It is important to always specify which length unit you are using for a measurement.
The two common systems for measuring distance

**Systems of units**
There are two common systems of standardized (or agreed upon) units that are used for measuring distances, the **English system** and the International System of Units, commonly called the **metric system** in the United States. The English system uses inches (in.), feet (ft), yards (yd), and miles (mi). The metric system uses millimeters (mm), centimeters (cm), meters (m), and kilometers (km). The names of units in the metric system use prefixes that are based on powers of ten (Figure 1.12).

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>giga</td>
<td>1 billion</td>
<td>1,000,000,000</td>
</tr>
<tr>
<td>mega</td>
<td>1 million</td>
<td>1,000,000</td>
</tr>
<tr>
<td>kilo</td>
<td>1 thousand</td>
<td>1,000</td>
</tr>
<tr>
<td>centi</td>
<td>1 one-hundredth</td>
<td>0.01</td>
</tr>
<tr>
<td>milli</td>
<td>1 one-thousandth</td>
<td>0.001</td>
</tr>
<tr>
<td>micro</td>
<td>1 one-millionth</td>
<td>0.000001</td>
</tr>
</tbody>
</table>

**Scientists use metric units**
Almost all fields of science use metric units because they are easier to work with. In the English system, there are 12 inches in a foot, 3 feet in a yard, and 5,280 feet in a mile. In the metric system, there are 10 millimeters in a centimeter, 100 centimeters in a meter, and 1,000 meters in a kilometer. Factors of 10 are easier to remember than 12, 3, and 5,280. The diagram below will help you get a sense for the metric units of distance.

**You will use both systems of measurement**
To solve problems by applying science in the real world, you will need to know both sets of units, English and metric. For example, a doctor will measure your height and weight in English units. The same doctor will prescribe medicine in milliliters (mL) and grams (g), which are metric units. Plywood is sold in 4-by-8-foot sheets — but the thickness of many types of plywood is given in millimeters. Some of the bolts on an automobile have English dimensions, such as $\frac{1}{2}$ inch. Others have metric dimensions, such as 13 millimeters. Because both units are used, it is a good idea to know both metric and English units.
Measuring time

Two ways to think about time
In physics, just as in your everyday life, there are two ways to think about time (Figure 1.13). One way is to identify a particular moment in time. The other way is to describe a quantity of time. The single word, “time,” means two different things.

What time is it? If you ask, “What time is it?” you usually want to identify a moment in time relative to the rest of the universe and everyone in it. To answer this question, you would look at a clock or your watch at one particular moment. For example, 3 P.M. Eastern Time on April 21, 2004, tells the time at a certain place on Earth.

How much time? If you ask, “How much time?” (did something take to occur, for instance), you are looking for a quantity of time. To answer, you need to measure an interval of time that has both a beginning and an end. For example, you might measure how much time has passed between the start of a race and when the first runner crosses the finish line. A quantity of time is often called a time interval. Whenever you see the word time in physics, it usually (but not always) means a time interval. Time intervals in physics are almost always in seconds, and are represented by the lower case letter t.

Units for measuring time
You are probably familiar with the common units for measuring time: seconds, hours, minutes, days, and years. But you may not know how they relate to each other. Table 1.1 gives some useful relationships between units of time. In everyday life, time is often expressed in mixed units rather than with a single unit (Figure 1.14).

Table 1.1: Time relationships

<table>
<thead>
<tr>
<th>Time unit</th>
<th>... in seconds ...</th>
<th>... and in days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second</td>
<td>1</td>
<td>0.0001157</td>
</tr>
<tr>
<td>1 minute</td>
<td>60</td>
<td>0.00694</td>
</tr>
<tr>
<td>1 hour</td>
<td>3,600</td>
<td>0.0417</td>
</tr>
<tr>
<td>1 day</td>
<td>86,400</td>
<td>1</td>
</tr>
<tr>
<td>1 year</td>
<td>31,557,600</td>
<td>365.25</td>
</tr>
<tr>
<td>1 century</td>
<td>3,155,760,000</td>
<td>36,525</td>
</tr>
</tbody>
</table>
Time scales in physics

One second  The second (sec) is the basic unit of time in both the English and metric systems. One second is about the time it takes to say “thousand.” There are 60 seconds in a minute and 3,600 seconds in an hour. The second was originally defined in terms of one day: There are 86,400 seconds in an average day of 24 hours (24 hr × 3,600 sec/hr).

Time in physics  Things in the universe happen over a huge range of time intervals. Figure 1.15 gives a few examples of time scales that are considered in physics and in other sciences. The average life span of a human being is 2.2 billion seconds. The time it takes a mosquito to beat its wings once is 0.0005 second. The time it takes light to get from this page to your eyes is 0.000000002 seconds.

Time in experiments  In many experiments, you will observe how things change with time. For example, when you drop a ball, it falls to the ground. You can make a graph of the height of the ball versus the time since it was released. The time is the time interval measured from when the ball was released. This graph shows how the height of the ball changes with time. The graph shows that it takes the ball about 0.45 seconds to fall a distance of 1 meter. Many of the experiments you will do involve measuring times between 0.0001 seconds and a few seconds. When making graphs of results from experiments, the time almost always goes on the horizontal (or x) axis.

Figure 1.15: Some time intervals in physics.
Unit conversions

Measuring time When doing an experiment or solving a physics problem, you often need to convert from one unit to another. This happens a lot with time. If you used a stopwatch to measure the time it took a runner to finish a marathon, the stopwatch would display the time in hours, minutes, and seconds (Figure 1.16). The measurements of hours, minutes, and seconds are usually separated with colons. Accurate timers, such as those used for races, usually also have a decimal that shows fractions of a second.

Converting units Hours, minute, and seconds are mixed units, but people are used to hearing time this way. However, if you want to do any calculations with the race time, such as figuring out the runner’s average speed, you must convert the time into a single unit. When converting to seconds the first thing you do is convert each quantity of hours and minutes to seconds. Then you add up all the seconds to get the total. Seconds are often used as the unit of time for experiments.

Convert the time 2:30:45 into seconds.

1. Looking for: You are asked for the time in seconds.
2. Given: You are given the time in mixed units.
3. Relationships: There are 60 seconds in one minute and 3,600 seconds in one hour.
4. Solution:

\[
2 \text{ hr} \times 3600 \text{ sec/hr} = 7200 \text{ sec} \quad 30 \text{ min} \times 60 \text{ sec/min} = 1800 \text{ sec}
\]

Add all of the seconds: 7200 sec + 1800 sec + 45 sec = 9045 seconds

Your turn...

a. Convert 3:45:10 into seconds. \textbf{Answer:} 13,510 seconds
b. One year equals 365.25 days. How many seconds are in 5 years? \textbf{Answer:} 157,790,000 seconds

Figure 1.16: Digital timers have displays that show time in mixed units.
Distance and time graphs

**Graphs**

A graph is a picture that shows how two variables are related. Graphs are easier to read than tables of numbers, so they are often used to display data collected during an experiment. The graph to the right shows distance and time measurements taken during a long trip in a car.

**The independent variable**

By convention, or common agreement, graphs are drawn with the independent variable on the horizontal or x-axis. In the graph above, time is the independent variable. We say it is independent because we are free to decide the times when we take measurements. The graph shows that measurements were taken every hour.

**The dependent variable**

The dependent variable goes on the vertical or y-axis. Distance is the dependent variable because the distance depends on the time. If a time interval other than one hour had been chosen, the distance measurements would be different.

### 1.2 Section Review

1. List two common systems of units and give examples of distance measurements for each.
2. Explain the two meanings in physics of the word “time.”
3. If you wait in a long line for 1 hour and 10 minutes, how many seconds have you waited?
4. List the steps you should follow when making a graph.

---

**How to make a graph**

1. Decide which variable to put on the x-axis and which to put on the y-axis.
2. Make a scale for each axis by counting boxes to fit your largest value for each axis. Count by multiples of 1, 2, 5, 10, or a larger number if needed. Write the numbers on each axis at evenly spaced intervals and label each axis with its corresponding variable and unit.
3. Plot each point by finding the x-value and tracing the graph upward until you get to the right y-value. Draw a dot for each point.
4. Draw a smooth curve that shows the pattern of the points.
5. Create a title for your graph.
1.3 Speed

Nothing in the universe stays still. A book on a table appears to be sitting still, but Earth is moving in its orbit around the sun at a speed of 66,000 miles per hour. You and the book move with Earth. Speed is an important concept in physics and saying that something is “fast” is not descriptive enough to accurately convey its speed. A race car may be fast compared with other cars, but it is slow compared with a jet airplane. In this section, you will learn a precise definition of speed.

**Speed**

Consider a bicycle moving along the road. The diagrams below show the positions of two bicycles at different times. To understand the concept of speed, think about the following two questions.

- How many meters does the bicycle move in each second?
- Does the bicycle move the same number of meters every second?

The precise meaning of speed

The **speed** of a bicycle is the distance it travels divided by the time it takes. At 1 m/sec, a bicycle travels one meter each second. At 3 m/sec, it travels three meters each second. Both bicycles in the diagram are moving at **constant speed**. Constant speed means the same distance is traveled every second.
Calculating speed

Speed is a measure of the distance traveled in a given amount of time. Therefore, to calculate the speed of an object, you need to know two things:

- The distance traveled by the object.
- The time it took to travel the distance.

Average speed

Speed is calculated by dividing the distance traveled by the time taken. For example, if you drive 150 kilometers in 1.5 hours (Figure 1.17), then the average speed of the car is 150 kilometers divided by 1.5 hours, which is equal to 100 kilometers per hour.

What does “per” mean?

The word “per” means “for every” or “for each.” The speed of 100 kilometers per hour is short for saying 100 kilometers for each hour. You can also think of “per” as meaning “divided by.” The quantity before the word per is divided by the quantity after it. For example, 150 kilometers divided by 1.5 hours (or per every 1.5 hours) equals 100 miles per hour.

Units for speed

Since speed is a ratio of distance over time, the units for speed are a ratio of distance units over time units. In the metric system, distance is measured in centimeters, meters, or kilometers. If distance is in kilometers and time in hours, then speed is expressed in kilometers per hour (km/h). Other metric units for speed are centimeters per second (cm/sec) and meters per second (m/sec). Speed is also commonly expressed in miles per hour (mph). Table 1.2 shows different units commonly used for speed.

Table 1.2: Common units for speed

<table>
<thead>
<tr>
<th>Distance</th>
<th>Time</th>
<th>Speed</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>meters</td>
<td>seconds</td>
<td>meters per second</td>
<td>m/sec</td>
</tr>
<tr>
<td>kilometers</td>
<td>hours</td>
<td>kilometers per hour</td>
<td>km/h</td>
</tr>
<tr>
<td>centimeters</td>
<td>seconds</td>
<td>centimeters per second</td>
<td>cm/sec</td>
</tr>
<tr>
<td>miles</td>
<td>hours</td>
<td>miles per hour</td>
<td>mph</td>
</tr>
<tr>
<td>inches</td>
<td>seconds</td>
<td>inches per second</td>
<td>in/sec, ips</td>
</tr>
<tr>
<td>feet</td>
<td>minutes</td>
<td>feet per minute</td>
<td>ft/min, fpm</td>
</tr>
</tbody>
</table>

Figure 1.17: A driving trip with an average speed of 100 km/h.
Relationships between distance, speed, and time

Mixing up distance, speed, and time

A common type of question in physics is: “How far do you go if you drive for two hours at a speed of 100 km/h?” You know how to get speed from time and distance. How do you get distance from speed and time? The answer is the reason mathematics is the language of physics. A mathematical description of speed in terms of distance and time can easily be rearranged while preserving the original connections between variables.

Calculating speed

Let the letter \( v \) stand for “speed,” the letter \( d \) stand for “distance traveled,” and the letter \( t \) stand for “time taken.” If we remember that the letters stand for those words, we can now write a mathematically precise definition of speed.

\[
\text{Speed (m/sec)} \rightarrow v = \frac{d}{t} \quad \text{Distance traveled (meters)}
\]

There are three ways to arrange the variables that relate distance, time, and speed. You should be able to work out how to get any one of the three variables if you know the other two (Figure 1.18).

Using formulas

Remember that the words or letters stand for the values that the variables have. For example, the letter \( t \) will be replaced by the actual time when we plug in numbers for the letters. You can think about each letter as a box that will eventually hold a number. Maybe you do not know yet what the number will be. Once we get everything arranged according to the rules, we can fill the boxes with the numbers that belong in each one. The last box left will be our answer. The letters (or variables) are the labels that tell us which numbers belong in which boxes.

Why \( v \) is used to represent speed

When we represent speed in a formula, we use the letter \( v \). If this seems confusing, remember that \( v \) stands for velocity. It is not important for this chapter, but there is a technical difference between speed and velocity. Speed is a single measurement that tells how fast you are going, such as 80 kilometers per hour. Velocity means you know both your speed and the direction you are going. If you tell someone you are going 80 km/h directly south, you are telling them your velocity. If you say only that you are going 60 mph, you are telling them your speed.

Forms of the speed equation

<table>
<thead>
<tr>
<th>Equation</th>
<th>gives you</th>
<th>if you know</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v = \frac{d}{t} )</td>
<td>speed</td>
<td>distance and time</td>
</tr>
<tr>
<td>( d = vt )</td>
<td>distance</td>
<td>speed and time</td>
</tr>
<tr>
<td>( t = \frac{d}{v} )</td>
<td>time</td>
<td>distance and speed</td>
</tr>
</tbody>
</table>

Figure 1.18: Different forms of the speed equation.
How to solve physics problems

Physics problems

You will be asked to analyze and solve many problems in this course. In fact, learning physics will make you a better problem-solver. This skill is important in all careers. For example, financial analysts are expected to look at information about businesses and determine which companies are succeeding. Doctors collect information about patients and must figure out what is causing pain or an illness. Mechanics gather information about a car and have to figure out what is causing a malfunction and how to fix it. All these examples use problem-solving skills.

A four-step technique

The technique for solving problems has four steps. Follow these steps and you will be able to see a way to the answer most of the time and will at least make progress toward the answer almost every time. Figure 1.19 illustrates these steps, and the table below explains them.

Table 1.3: Steps to solving physics problems

<table>
<thead>
<tr>
<th>Step</th>
<th>What to do</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identify clearly what the problem is asking for. If you can, figure out exactly what variables or quantities need to be in the answer.</td>
</tr>
<tr>
<td>2</td>
<td>Identify the information you are given. Sometimes this includes numbers or values. Other times it includes descriptive information you must interpret. Look for words like constant or at rest. In a physics problem, saying something is constant means it does not change. The words “at rest” in physics mean the speed is zero. You may need conversion factors to change units.</td>
</tr>
<tr>
<td>3</td>
<td>Identify any relationships that involve the information you are asked to find and the information you are given. For example, suppose you are given a speed and time and asked to find a distance. The relationship ( v = d/t ) relates what you are asked for to what you are given.</td>
</tr>
<tr>
<td>4</td>
<td>Combine the relationships with what you know to find what you are asked for. Once you complete steps 1-3, you will be able to see how to solve most problems. If not, start working with the relationships you have and see where they lead.</td>
</tr>
</tbody>
</table>

Figure 1.19: Follow these steps and you will be able to see a way to the answer most of the time.
Example problems

Solved example problems are provided

Throughout this book you will find example problems that have been solved for you. Following each solved example, there are two practice problems. The answers to the practice problems are provided so that you can check your work while practicing your problem-solving skills. Always remember to write out the steps when you are solving problems on your own. If you make a mistake, you will be able to look at your work and determine where you went wrong. Here is the format for example problems:

Calculating speed

An airplane flies 450 meters in 3 seconds. What is its speed in meters per second?

1. Looking for: You are asked for the speed in meters/second.
2. Given: You are given the distance in meters and the time in seconds.
3. Relationships: Use this version of the speed equation:

   \[ v = \frac{d}{t} \]

4. Solution: \[ v = \frac{450 \text{ m}}{3 \text{ sec}} = 150 \text{ m/sec} \]

Your turn...

a. A snake moves 20 meters in 5 seconds. What is the speed of the snake in meters per second? Answer: 4 m/sec
b. A train is moving at a speed of 50 kilometers per hour. How many hours will it take the train to travel 600 kilometers? Answer: 12 hours

1.3 Section Review

1. List three commonly used units for speed.
2. State the steps used to solve physics problems.
3. Calculate the average speed (in km/h) of a car that drives 140 kilometers in two hours.
4. How long (in seconds) will it take you to swim 100 meters if you swim at 1.25 m/sec?
5. How far (in meters) will a dog travel if he runs for 1 minute at a constant speed of 5 m/sec?
Scientific Method and Serendipity

Have you ever made a mistake that resulted in something very positive happening? Usually, we try to avoid mistakes. However, sometimes making a mistake — like taking a wrong turn — leads to a place you would not have seen if you had taken a right turn!

Serendipity is a term used to describe an event that happens by accident that results in an unexpected discovery. An example of an accident might be losing your keys. An example of a serendipitous event would be that looking for your keys causes you to find the watch that you lost a week ago.

Scientists tend to follow the scientific method or some version of it to “do science.” However, while searching for answers to nature’s mysteries or looking for a cure to a disease, many important discoveries have come about unexpectedly. Sometimes small chance events or observations are just enough for a curious person to begin to unravel an important mystery.

A scientist made famous by serendipity

In 1928, Alexander Fleming, a British bacteriologist, was investigating the influenza virus as well as his own interests in the antibacterial properties of mucus. He was working at St. Mary’s Hospital in London.

In one experiment, Fleming smeared mucus in a petri dish that had a culture of a harmful strain of bacteria called staphylococcus. Infections of staphylococcus would spread uncontrollably, and often caused the death of the infected person.

Important observation brings fame and saves lives

At one point in his research, Fleming took a two-week vacation. He happened by chance to leave a petri dish containing staphylococcus on his laboratory bench. What happened next is a good example of serendipity.

When Fleming returned from his vacation he noticed that mold had grown in the plate. The growth was a simple mold that grows as green and white, fuzzy masses on food that is left out too long and exposed to the air. In Fleming’s case, a mold spore had entered his lab from another lab in his building. This mold spore had traveled through the air and had landed by chance on the petri dish.

When Fleming examined the plate he saw that the staphylococcus was growing on the plate, but it was not growing near the mold. At this point, Fleming came up with a hypothesis that brought him great fame and helped save the lives of many people. His hypothesis was that a substance produced by the mold could kill harmful bacteria.

A miracle drug

After Fleming made his important hypothesis, that mold has antibiotic properties, he investigated the mold on the petri dish. He grew a pure sample of the mold and learned that it produced a substance that stopped some of the bacteria from growing. Fleming named the substance penicillin after the fungus (or mold) growing in the plate, *Penicillin notatum*. You may be familiar with the drug, penicillin. It is a very common and effective antibiotic.
Although Fleming was not able to purify penicillin enough for use as an antibiotic, he published his findings so others could. In 1945, Fleming received the Nobel Prize along with two other scientists (Ernst B. Chain and Sir Howard Florey) who helped develop penicillin. Ernst B. Chain and Sir Howard Florey were very important in developing the techniques needed to make large quantities of penicillin. During World War II penicillin saved the lives of thousands of injured soldiers and civilians. Not surprisingly, penicillin became known as a “miracle drug.”

More discoveries
Alexander Fleming made an important discovery by recognizing the importance of mold in a petri dish. He took advantage of a serendipitous event and opened the door for a life-saving medical breakthrough!

It is through education, and a strong sense of curiosity, tempered with a bit of creativity, (and yes, sometimes a little luck) that people can make great scientific discoveries. So, the next time you make a mistake or something does not seem to be working as you think it should, be patient and think about it. You may discover something yourself!

Here are some other serendipitous events that resulted in scientific breakthroughs. Take the time to research these important events and get inspired. Maybe one day you will make an important discovery!

- An apple falling from a tree inspires Isaac Newton to develop the idea of gravity.
- An unusual, accidental photograph revealing the bone structure of a hand leads to the discovery of X rays by Wilhelm Rontgen.
- Two photographs of the same star field, taken a few days apart by astronomy student Clyde Tombaugh, reveal that one of the “stars” moved during that time. The “star” turned out to be the previously undiscovered planet, Pluto.
- After developing safely-stored photographic film, Henri Becquerel discovers a “ghostly” image on new photographic paper. That something turned out to be coming from uranium salts stored in the same drawer. The accidental exposure of the film led to the pioneering work of Marie and Pierre Curie on “radioactivity”—a term coined by Marie Curie.
- Background radio noise coming from space led technicians Arno Penzias and Robert Wilson to the realization that they were actually listening to the Big Bang, an event that formed the universe billions of years ago.

Questions:
1. What serendipitous event led to the discovery of penicillin?
2. Lewis Thomas, a medical research scientist and former president of Memorial Sloan-Kettering Cancer Center, once stated “You create the lucky accidents.” What do you think he meant by this statement?
3. Why is the scientific method important to follow when confirming an accidental discovery?
4. Do some research to find three additional serendipitous events (besides the ones mentioned in this reading) that led to important scientific discoveries.
# Understanding Vocabulary

Select the correct term to complete the sentences.

<table>
<thead>
<tr>
<th>experiment</th>
<th>dependent</th>
<th>speed</th>
<th>time interval</th>
<th>metric system</th>
<th>length</th>
<th>natural laws</th>
<th>English system</th>
<th>mass</th>
<th>seconds</th>
<th>hypothesis</th>
<th>constant speed</th>
<th>atomic</th>
</tr>
</thead>
</table>

## Section 1.1

1. It is believed all events in nature obey a set of ____ that do not change.
2. _____ is the measure of the amount of matter in an object.
3. A(n) ____ can help you understand the natural laws that relate matter and energy.
4. When you formulate a(n) ____, you make an educated guess or prediction that can be tested by an experiment.
5. ____ properties are too small to be directly observed.
6. The ____ variable goes with the y-axis of a graph.

## Section 1.2

7. Distance is measured in units of ____.
8. A quantity of time is known as a(n) ____.
9. The ____ uses length measurements of millimeters, centimeters, meters, and kilometers.
10. In physics, time is usually measured in units of ____.
11. The ____ uses length measurements of inches, feet, yards and miles.

## Section 1.3

12. ____ is the distance traveled divided by the time taken.
13. A car traveling the same distance every second is moving at ____.

# Reviewing Concepts

## Section 1.1

1. List and define the two categories we use to classify everything in the universe.
2. How have physicists come to understand the natural laws?
3. What property does matter have that energy does not?
4. Is light matter? Why or why not?
5. Define the term system as it relates to experiments.
6. When designing an experiment, how do you choose the system to investigate?
7. Explain the main difference between the macroscopic scale and the atomic scale.
8. List the steps of the scientific method.
9. A hypothesis is a random guess. True or false? Explain your answer.
10. What do you call variables that are kept the same in an experiment?
11. Why is it important to only change one experimental variable at a time in an experiment?
12. You wish to do an experiment to determine how a ball’s radius affects how fast it rolls down a ramp. List the independent and dependent variables in this experiment.
13. Explain the role of energy in a system that is changing.

## Section 1.2

14. Why are units important when measuring quantities?
15. State whether you would measure each quantity in kilometers, meters, centimeters, or millimeters.
   a. The length of a car
   b. A single grain of rice
   c. The thickness of your textbook
   d. The distance from your house to school
16. Why is it important to understand both English and metric units?
17. Give an example of a quantity that is often measured in metric units and a quantity that is often measured in English units.

18. What are the two different meanings of the word time?

19. Summarize how to make a graph by listing the steps you would follow.

20. You wish to make a graph of the height of the moon above the horizon every 15 minutes between 9:00 p.m. and 3:00 a.m during one night.
   a. What is the independent variable?
   b. What is the dependent variable?
   c. On which axis should you graph each variable?

Section 1.3

21. Write the form of the speed equation that you would use in each of the following scenarios. Let \( v = \text{speed}, t = \text{time}, \) and \( d = \text{distance}: \)
   a. You know distance and speed and want to find the time.
   b. You know time and distance and want to find the speed.
   c. You know speed and time and want to find the distance.

22. What is the speed of an object that is standing still?

23. Your friend rides her bicycle across town at a constant speed. Describe how you could determine her speed.

24. Fill in the missing information in the table showing common units for speed below:

<table>
<thead>
<tr>
<th>Distance</th>
<th>Time</th>
<th>Speed</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>meters</td>
<td>seconds</td>
<td>km/h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>centimeters per second</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

25. Summarize the four steps for solving physics problems mentioned in the text.

Solving Problems

Section 1.1

1. You want to find out whether the birds near your school prefer thistle seed or sunflower seed. You have a bag of thistle seed, a bag of sunflower seed, and two bird feeders. Describe the experiment you would do to see which type of seed birds prefer. Write down your question, your hypothesis, and the procedure you would follow when doing your experiment.

2. You are doing an experiment to determine whether a dropped ball’s mass affects the rate at which it falls. Describe the system you are studying. Write down your question, your hypothesis, and the procedure you would follow when doing your experiment.

Section 1.2

3. Order the following lengths from shortest to longest.
   a. 400 millimeters
   b. 22 kilometers
   c. 170 meters
   d. 3.3 centimeters

4. Convert:
   a. 3 kilometers = ___ meters
   b. 1.5 meters = ___ centimeters
   c. 110 centimeters = ___ meters
   d. 2.5 centimeters = ___ millimeters

5. Convert:
   a. 3 minutes = ___ seconds
   b. 200 seconds = ___ minutes, ___ seconds
   c. 2 days = ___ minutes
   d. 1,000 minutes = ___ hours

6. Determine your age in each of the following units.
   a. months
   b. days
   c. hours
   d. seconds
7. Luis rides his new bike while his brother records his position and time. They create the data table shown below.

<table>
<thead>
<tr>
<th>Position (m)</th>
<th>0</th>
<th>105</th>
<th>270</th>
<th>400</th>
<th>540</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (sec)</td>
<td>0</td>
<td>30</td>
<td>60</td>
<td>90</td>
<td>120</td>
<td>150</td>
</tr>
</tbody>
</table>

a. Which is the dependent variable?
b. Which is the independent variable?
c. On which axis should you graph each variable?
d. Construct a graph of Luis’ bike ride.

Section 1.3

8. A bicyclist, traveling at 22 miles per hour, rides a total of 44 miles. How much time (in hours) did it take?
9. A mouse is moving in a straight line at a steady speed of 2 m/sec for 10 seconds. How far (in meters) did the mouse travel?
10. The gray wolf is a threatened animal that is native to the United States. A wildlife biologist tracks a gray wolf that moves 250 meters in 100 seconds. Calculate the wolf’s speed in meters per second.
11. It takes Brooke 10 minutes to run 1 mile. What is her speed in miles per minute?
12. If it takes 500 seconds for the light from the sun to reach Earth, what is the distance to the sun in meters? (The speed of light is 300,000,000 meters/second).
13. Use the data from Luis’ bike ride in question 7 to answer the following questions:
   a. What was Luis’ speed (in meters per second) for the entire ride, from 0 to 150 seconds?
   b. What was Luis’ speed (in meters per second) between 60 and 90 seconds?
   c. During which 30 second interval did Luis have the greatest speed? Calculate this speed in meters per second.

Applying Your Knowledge

Section 1.1

1. Read an article in a science magazine and identify how scientists have used the scientific method in their work.
2. Given a ruler, a stopwatch, a tennis ball, a 1-meter long piece of string, a rubber band, tape, and 10 pieces of paper, design an experiment. List a question, a hypothesis, the independent variable, the dependent variable, the control variables, and the procedure for your experiment.

Section 1.2

3. Research the number system and length units of an ancient civilization. What types of things did this ancient group of people need to measure? What were the smallest and largest units of length used? Write a short report on what you learn.
4. Research what the time standard is for the United States. What determines the correct time? Where is this national clock kept and how can you set your clocks at home to it? Write a short report on what you learn.
5. Find an example of a graph used to model a system in your everyday life. You might check magazines, newspapers, or the internet. Copy the graph, describe what it is modeling, and list the dependent variable, independent variable, and measurement scales used.

Section 1.3

6. Research the speeds of many kinds of animals and make a table showing slowest to fastest.
7. Determine your average walking speed. How long would it take you to walk 2,462 miles (3,962 km) from New York to Los Angeles?
8. Prepare a short report on important speeds in your favorite sport.
9. Use the Internet to find the world record times for running races of different lengths (100-meter, 200-meter, mile, marathon, etc.). Calculate and compare speeds for the different races.
Chapter 2

Laws of Motion

In January 1993, the 53rd space shuttle mission crew, in addition to their usual science experiments, brought some toys on board! During the flight, crew members took the toys out and played with them to see how they would work in what NASA calls “microgravity.” Many people think astronauts float because there is no gravity in space. Not true! If there were no gravity, the space shuttle would not stay in orbit around Earth. So why do astronauts float?

This chapter will help you explain many aspects of motion as it occurs here on Earth, and even how things like simple toys would act in microgravity. You will be able to use Newton's laws of motion to explain why it's possible to throw a basketball through a hoop. What if that hoop and basketball were on the space shuttle? Would the crew members be able to shoot baskets in a microgravity environment?

Sir Isaac Newton, who lived from 1642-1727, attempted to answer similar questions and soon you will know the answers too!

Key Questions

- Why do thrown objects fall to Earth instead of flying through the air forever?
- Is it possible for a feather and a hammer to hit the ground at the same time when dropped?
- What does a graph of motion look like?
2.1 Newton’s First Law

Sir Isaac Newton (1642-1727), an English physicist and mathematician, was one of the most brilliant scientists in history. Before age 30, he had made several important discoveries in physics and had invented a new kind of mathematics called calculus. Newton’s three laws of motion are probably the most widely used natural laws in all of science. The laws explain the relationships between the forces acting on an object, the object’s mass, and its motion. This section discusses Newton’s first law of motion.

**Changing an object’s motion**

Suppose you are playing miniature golf and it is your turn. What action must you take to make the golf ball move toward the hole? Would you yell at the ball to make it move? Of course not! You would have to hit the ball with the golf club to get it rolling. The club applies a force to the ball. This force is what changes the ball from being at rest to being in motion (Figure 2.1).

**What is force?**

A **force** is a *push* or *pull*, or any action that has the ability to change motion. The golf ball will stay at rest until you apply force to set it in motion. Once the ball is moving, it will continue to move in a straight line at a constant speed, unless another force changes its motion. You need force to start things moving and also to make any change to their motion once they are moving. Forces can be used to increase or decrease the speed of an object, or to change the direction in which an object is moving.

**How are forces created?**

Forces are created in many different ways. For example, your muscles create force when you swing the golf club. Earth’s gravity creates forces that pull on everything around you. On a windy day, the movement of air can create forces. Each of these actions can create force because they all can change an object’s motion.

**Force is required to change motion**

Forces create changes in motion, and *there can be no change in motion without the presence of a force*. Anytime there is a change in motion a force must exist, even if you cannot immediately recognize the force. For example, when a rolling ball hits a wall and bounces, its motion changes rapidly. That change in motion is caused by the wall exerting a force that changes the direction of the ball’s motion.

---

**Vocabulary**

- force, Newton’s first law, inertia, newton, net force

**Objectives**

- Recognize that force is needed to change an object’s motion.
- Explain Newton’s first law.
- Describe how inertia and mass are related.

---

**Figure 2.1:** Force is the action that has the ability to change motion. Without force, the motion of an object cannot be started or changed.
**Forces, mass, and inertia**

**Stopping a moving object**  
Let’s keep playing golf. Once the golf ball is moving, how can you stop it? The only way to stop the ball is to apply a force in a direction opposite its motion. In general, objects continue doing what they are already doing. This idea is known as Newton’s first law of motion.

**Newton’s first law** states that objects tend to continue the motion they already have unless they are acted on by forces. In the absence of forces an object at rest will stay at rest. An object that is moving will keep moving at the same speed and in the same direction. In other words, objects resist changes in their motion.  

*An object at rest will stay at rest and an object in motion will continue in motion with the same speed and direction UNLESS acted on by a force.*

**Inertia**  
Some objects resist changes in motion better than others. Inertia is the property of an object that resists changes in its motion. To understand inertia, imagine trying to move a bowling ball and a golf ball. Which requires more force? Of course, the bowling ball needs more force to get it moving at the same speed as the golf ball (assuming the forces act for the same length of time). The bowling ball also requires more force to stop. A bowling ball has more inertia than a golf ball. The greater an object’s inertia, the greater the force needed to change its motion. Because inertia is an important idea, Newton’s first law is sometimes called the law of inertia.

**Mass**  
Inertia comes from mass. Objects with more mass have more inertia and are more resistant to changes in their motion. Mass is measured in kilograms (kg). A golf ball has a mass of 0.05 kilograms, and the average bowling ball has a mass of 5 kilograms (Figure 2.2). A bowling ball is 100 times as massive, so it has 100 times the inertia. For small amounts of mass, the kilogram is too large a unit to be convenient. One gram (g) is one-thousandth of a kilogram. A dollar bill has a mass of about a gram, so 1,000 dollar bills have a mass of approximately 1 kilogram.
Units of force

Pounds
If you are mailing a package at the post office, how does the clerk know how much to charge you? The package is placed on a scale and you are charged based on the package’s weight. For example, the scale shows that the package weighs 5 pounds. The pound is a unit of force commonly used in the United States. When you measure weight in pounds on a scale, you are measuring the force of gravity acting on the object (Figure 2.3).

The origin of the pound
The pound measurement of force is based on the Roman unit libra, which means “balance” and is the source for pound’s abbreviation, “lb.” The word “pound” comes from the Latin word pondus, which means “weight.” The definition of a pound has varied over time and from country to country.

The newton
Although the pound is commonly used to express force, scientists prefer to use the newton. The newton (N) is the metric unit of force. A force of one newton is the exact amount of force needed to cause a mass of one kilogram to speed up by one meter per second each second (Figure 2.3). We call the unit of force the newton because force in the metric system is defined by Newton’s laws. The newton is a useful way to measure force because it connects force directly to its effect on mass and speed.

Converting newtons and pounds
The newton is a smaller unit of force than the pound. One pound of force equals 4.448 newtons. How much would a 100-pound person weigh in newtons? Remember that 1 pound = 4.448 newtons. Therefore, a 100-pound person weighs 444.8 newtons.

The force unit of newtons
When physics problems are presented in this book, forces will almost always be expressed in newtons. In the next section, on Newton’s second law, you will see that the newton is closely related to the metric units for mass and distance.

Figure 2.3: The definition of the pound and the newton.
The net force

**Multiple forces**
When you hit a golf ball, the force from the club is not the only force that acts. Gravity also exerts a force on the ball. Which force causes the change in the ball’s motion: gravity or the force from the golf club? Does gravity stop while the golf club exerts its force?

**Forces act together**
You are right if you are thinking “all forces together.” The motion of objects changes in response to the total force acting on the object, including gravity and any other force that is present. In fact, it is rare that only one force acts at a time since gravity is always present.

**Net force**
Adding up forces can be different from simply adding numbers because the directions of the forces matter. For this reason the term net force is used to describe the total of all forces acting on an object. When used this way, the word “net” means total but also implies that the direction of the forces has been taken into account when calculating the total.

**Forces in the same direction**
When two forces are in the same direction, the net force is the sum of the two. For example, think about two people pushing a box. If each person pushes with a force of 300 newtons in the same direction, the net force on the box is 600 N (Figure 2.4 top). The box speeds up in the direction of the net force.

**Forces in opposite directions**
What about gravity acting on the box? Gravity exerts a force downward on the box. However, the floor holds the box up. In physics, the term “holds up” means “applies a force.” In order to “hold up” the box, the floor exerts a force upward on the box. The net force on the box in the “up-down” direction is zero because the force from the floor is opposed to the force of gravity. When equal forces are in the opposite direction they cancel (Figure 2.4 bottom). The motion of the box in the up-down (vertical) direction does not change because the net force in this direction is zero.

2.1 Section Review

1. State Newton’s first law in your own words.
2. How is mass related to inertia?
3. What is the net force and how is it determined?
2.2 Acceleration and Newton’s Second Law

Newton’s first law says that a force is needed to change an object’s motion. But what kind of change happens? The answer is acceleration. Acceleration is how motion changes. The amount of acceleration depends on both the force and the mass according to Newton’s second law. This section is about Newton’s second law, which relates force, mass, and acceleration. The second law is probably the most well-used relationship in all of physics.

**Acceleration**

**Definition of acceleration**

What happens if you coast on a bicycle down a long hill without pedaling? At the top of the hill, you move slowly. As you go down the hill, your speed gets faster and faster—you accelerate. **Acceleration** is the rate at which your speed increases. If speed increases by 1 kilometer per hour (km/h) each second, the acceleration is 1 km/h per second.

**Steeper hills**

Your acceleration depends on the steepness of the hill. If the hill is a gradual incline, you have a small acceleration, such as 1 km/h per second. If the hill is steeper, your acceleration will be greater, perhaps 2 km/h per second. On the gradual hill, your speedometer increases by 1 km/h every second. On the steeper hill, it increases by 2 km/h every second.

**Car acceleration**

Advertisements for sports cars often discuss acceleration. A typical ad might boast that a car can go “from zero to 60 in 10 seconds.” This means the car’s speed begins at zero and reaches 60 miles per hour (96 km/h) after accelerating for 10 seconds. The car’s acceleration is therefore 6 miles per hour per second (Figure 2.5).

![Figure 2.5: It takes 10 seconds for a car to go from zero to 60 mph if it has an acceleration of 6 mph per second. In metric units the car goes from zero to 96 km/h in 10 seconds. The acceleration is 9.6 km/h per second.](image)
Units of acceleration

Speed units and time units

Acceleration is the rate of change of an object’s speed. To calculate acceleration, you divide the change in speed by the amount of time it takes for the change to happen. In the example of the sports car, acceleration was given in kilometers per hour per second. This unit can be abbreviated as km/h/sec. Notice that two time units are included in the unit for acceleration. One unit of time is part of the speed unit, and the other is the time over which the speed changed.

Metric units

If the change in speed is in meters per second and the time is in seconds, then the unit for acceleration is m/sec/sec or meters per second per second. An acceleration of 10 m/sec/sec means that the speed increases by 10 m/sec every second. If the acceleration lasts for three seconds, then the speed increases by a total of 30 m/sec (3 seconds × 10 m/sec/sec). This is approximately the acceleration of an object allowed to fall free after being dropped.

What do units of seconds squared mean?

An acceleration in m/sec/sec is often written m/sec² (meters per second squared). If you apply the rules for simplifying fractions on the units of acceleration (m/sec/sec), the denominator ends up having units of seconds times seconds, or sec². Saying seconds squared is just a math-shorthand way of talking. It is better to think about acceleration in units of speed change per second (that is, meters per second per second).

Acceleration in m/sec²

Nearly all physics problems will use acceleration in m/sec² because these units agree with the units of force (newtons). If you measure speed in centimeters per second, you may have to convert to meters/second before calculating acceleration. This is especially true if you do any calculations using force in newtons.

Acceleration and direction

The velocity of an object includes both its speed and the direction it is moving. A car with a velocity of 20 m/sec north has a speed of 20 m/sec and is moving north. An object accelerates if its velocity changes. This can occur if its speed changes or if its direction changes (or both). Therefore, a car driving at a constant speed of 40 mph around a bend is actually accelerating. The only way a moving object can have an acceleration of zero is to be moving at constant speed in a straight line.

This chapter covers acceleration that involves only changes in speed. In chapter 6, you will learn about the acceleration of moving objects that change direction as well.
Calculating acceleration

The equation for acceleration

To calculate acceleration, you divide the change in speed by the time over which the speed changed. To find the change in speed, subtract the starting (or initial) speed from the final speed. For example, if a bicycle’s speed increases from 2 m/sec to 6 m/sec, its change in speed is 4 m/sec. Because two speeds are involved, subscripts are used to show the difference. The initial speed is \( v_1 \), and the final speed is \( v_2 \).

\[
\text{Acceleration (m/sec}^2) = \frac{v_2 - v_1}{t}
\]

Positive and negative acceleration

If an object speeds up, it has a positive acceleration. If it slows down, it has a negative acceleration. In physics, the word acceleration is used to refer to any change in speed, positive or negative. However, people sometimes use the word deceleration to describe the motion that is slowing down.

Calculating acceleration

A sailboat moves at 1 m/sec. A strong wind increases its speed to 4 m/sec in 3 seconds (Figure 2.6). Calculate the acceleration.

1. Looking for: You are asked for the acceleration in meters per second.
2. Given: You are given the initial speed in m/sec (\( v_1 \)), final speed in m/sec (\( v_2 \)), and the time in seconds.
3. Relationships: Use the formula for acceleration: \( a = \frac{v_2 - v_1}{t} \)
4. Solution:

\[
a = \frac{4 \text{ m/sec} - 1 \text{ m/sec}}{3 \text{ sec}} = \frac{3 \text{ m/sec}}{3 \text{ sec}} = 1 \text{ m/sec}^2
\]

Your turn...

a. Calculate the acceleration of an airplane that starts at rest and reaches a speed of 45 m/sec in 9 seconds. Answer: 5 m/sec²
b. Calculate the acceleration of a car that slows from 50 m/sec to 30 m/sec in 10 seconds. Answer: -2 m/sec²
Force, mass, and acceleration

**Newton’s second law** relates the net force on an object, the mass of the object, and acceleration. It states that the stronger the net force on an object, the greater its acceleration. If twice the net force is applied, the acceleration will be twice as great. The law also says that the greater the mass, the smaller the acceleration for a given net force (Figure 2.7). An object with twice the mass will have half the acceleration if the same force is applied.

**Direct and inverse proportions** In mathematical terms, the acceleration of an object is directly proportional to the net applied force and inversely proportional to the mass. These two relationships are combined in Newton’s second law (below).

**NEWTON’S SECOND LAW**

\[ a = \frac{F}{m} \]

*Acceleration (m/sec²) → \( a \) → Force (N) → Mass (kg)*

**Changes in motion involve acceleration** Force is not necessary to keep an object in motion at constant speed. A moving object will keep going at a constant speed in a straight line until a force acts on it. Once a skater is moving, she will coast for a long time without any force to push her along. However, she does need force to speed up, slow down, turn, or stop. Changes in speed or direction always involve acceleration. Force causes acceleration, and mass resists acceleration.

**Figure 2.7:** Increasing the force increases the acceleration, and increasing the mass decreases the acceleration.
Applying the second law

Some guidelines
To use Newton’s second law properly, keep the following important ideas in mind. They are a good guideline for how to apply the second law to physics problems.

1. The net force is what causes acceleration.
2. If there is no acceleration, the net force must be zero.
3. If there is acceleration, there must also be a net force.
4. The force unit of newtons is based on kilograms, meters, and seconds.

Net force
When two forces are in the same direction, the net force is the sum of the two forces. When two forces are in opposite directions the net force is the difference between them. To get the direction right we usually assign positive values to one direction and negative values to the other direction. Figure 2.8 shows how to calculate the net force for different forces.

Examples with and without acceleration
Objects at rest or moving with constant speed have zero acceleration. This means the net force must also be zero. You can calculate unknown forces by using the knowledge that the net force must be zero. The motion of a kicked ball or a car turning a corner are examples where the acceleration is not zero. Both situations have net forces that are not zero.

Using newtons in calculations
The newton is defined by the relationship between force, mass, and acceleration. A force of one newton is the exact amount of force needed to cause a mass of one kilogram to accelerate at one m/sec² (Figure 2.9). The newton is a useful way to measure force because it connects force directly to its effect on matter and motion. A net force of one newton will always accelerate a 1-kilogram mass at 1 m/sec² no matter where you are in the universe. In terms of solving problems, you should always use the following units when using force in newtons:

- mass in kilograms
- distance or position in meters
- time in seconds
- speed in m/sec
- acceleration in m/sec²
Doing calculations with the second law

Writing the second law

The formula for the second law of motion uses $F$, $m$, and $a$ to represent force, mass, and acceleration. The way you write the formula depends on what you want to know. Three ways to write the law are summarized below.

Table 2.1: Three forms of the second law

<table>
<thead>
<tr>
<th>Use</th>
<th>if you want to find</th>
<th>and you know</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a = \frac{F}{m}$</td>
<td>acceleration $(a)$</td>
<td>force $(F)$ and mass $(m)$</td>
</tr>
<tr>
<td>$F = ma$</td>
<td>force $(F)$</td>
<td>acceleration $(a)$ and mass $(m)$</td>
</tr>
<tr>
<td>$m = \frac{F}{a}$</td>
<td>mass $(m)$</td>
<td>acceleration $(a)$ and force $(F)$</td>
</tr>
</tbody>
</table>

Net force

Remember, when using the second law, the force that appears is the net force. Consider all the forces that are acting and add them up to find the net force before calculating any accelerations. If you work in the other direction, calculating force from mass and acceleration, it is the net force that you get from the second law. You may have to do additional work if the problem asks for a specific force and there is more than one force acting.

A car has a mass of 1,000 kg. If a net force of 2,000 N is exerted on the car, what is its acceleration?

1. **Looking for:** You are asked for the car’s acceleration.
2. **Given:** You are given its mass in kilograms and the net force in newtons.
3. **Relationships:**

   $a = \frac{F}{m}$

4. **Solution:**

   $a = \frac{2000\ \text{N}}{1000\ \text{kg}} = \frac{2\text{kg} \cdot \text{m/ sec}^2}{\text{kg}} = 2\ \text{m/ sec}^2$

**Your turn...**

a. What is the acceleration of a 1,500-kilogram car if a net force of 1,000 N is exerted on it? **Answer:** 1.5 m/sec²
b. As you coast down the hill on your bicycle, you accelerate at 0.5 m/sec². If the total mass of your body and the bicycle is 80 kg, with what force is gravity pulling you down the hill? **Answer:** 40 kg m/sec² or 40 N
c. You push a grocery car with a force of 30 N and it accelerates at 2 m/sec². What is its mass? **Answer:** 15 kg
2.2 ACCELERATION AND NEWTON’S SECOND LAW

**Force and energy**

**Energy moves through force**

Force is the action through which energy moves. This important idea will help you understand why forces occur. Consider a rubber band that is stretched to launch a car. The rubber band has energy because it is stretched. When you let the car go, the energy of the rubber band is transferred to the car. The transfer of energy from the stretched rubber band to the car occurs through the force that the rubber band exerts on the car (Figure 2.10).

**Energy differences create force**

Forces are created any time there is a difference in energy. A stretched rubber band has more energy than a rubber band lying relaxed. The difference in energy results in a force that the rubber band exerts on whatever is holding it in the stretched shape.

**An example of energy difference**

Energy differences can be created in many ways. A car at the top of a hill has more energy than when the car is at the bottom. This tells you there must be a force that pulls the car toward the bottom of the hill. You can predict that a downhill force must exist even though you may not know the cause of that force.

**An important idea**

Suppose there is an energy difference between one arrangement of a system (car at the top) and another arrangement (car at the bottom). Some force will always act to bring the system from the higher energy arrangement to the lower energy one. We will find many examples of this important principle throughout the course. The principle is true in all of science, not just physics. It is true in chemistry, earth science, and biology, too.

**Figure 2.10:** Energy differences cause forces to be created. The forces can transfer energy from one object to another.

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### 2.2 Section Review

1. List three units in which acceleration can be measured.
2. According to Newton’s second law, what causes acceleration? What resists acceleration?
3. An 8,000 kg helicopter’s speed increases from 0 m/sec to 25 m/sec in 5 seconds. Calculate its acceleration and the net force acting on it.
4. Define the term “net force.”
5. Describe the conceptual relationship between energy and force.
2.3 Gravity and Free Fall

Imagine dropping a baseball out of a second-floor window. What happens? Of course, the ball falls toward the ground. Is the speed constant or does the ball accelerate? If it accelerates, at what rate? Do all objects fall at the same rate? You will learn the answers to these questions in this section.

The acceleration due to gravity

An object is in free fall if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped baseball is in free fall from the instant it leaves your hand until it reaches the ground. A ball thrown upward is also in free fall after it leaves your hand. Although you might not describe the ball as “falling,” it is still in free fall. Birds, helicopters, and airplanes are not normally in free fall because forces other than gravity act on them.

Objects in free fall on Earth accelerate downward at 9.8 m/sec², the acceleration due to gravity. Because this acceleration is used so frequently in physics, the letter g is used to represent its value. When you see the letter g in a physics question, you can substitute the value 9.8 m/sec².

If you know the acceleration of an object in free fall, you can predict its speed at any time after it is dropped. The speed of a dropped object will increase by 9.8 m/sec every second (Figure 2.11). If it starts at rest, it will be moving at 9.8 m/sec after one second, 19.6 m/sec after two seconds, 29.4 m/sec after three seconds, and so on. To calculate the object’s speed, you multiply the time it falls by the value of g. Because the units of g are m/sec², the speed must be in m/sec and the time must be in seconds.

Vocabulary
free fall, acceleration due to gravity, velocity, weight, air resistance, terminal speed

Objectives
✓ Describe the motion of an object in free fall.
✓ Calculate speed and distance for an object in free fall.
✓ Distinguish between mass and weight.
✓ Explain how air resistance affects the motion of objects.

Figure 2.11: The speed of a ball in free fall increases by 9.8 m/sec every second.
Upward launches

Throwing a ball upward

When an object is in free fall, it accelerates downward at 9.8 m/sec². Gravity causes the acceleration by exerting a downward force. So what happens if you throw a ball upward? The ball will slow down as it moves upward, come to a stop for an instant, and then fall back down. As it moves upward, the speed decreases by 9.8 m/sec every second until it reaches zero. The ball then reverses direction and starts falling down. As it falls downward, the speed increases by 9.8 m/sec every second.

Velocity

When an object’s direction is important, we use the velocity instead of the speed. Velocity is speed with direction. In Figure 2.12, the ball’s initial velocity is +19.6 m/sec and its velocity four seconds later is -19.6 m/sec. The positive sign means upward and the negative sign means downward.

Speed

The acceleration of the ball is -9.8 m/sec² (-g). That means you subtract 9.8 m/sec from the speed every second. Figure 2.12 shows what happens to a ball launched upward at 19.6 m/sec. The speed decreases for two seconds, reaches zero, and then increases for two seconds. The acceleration is the same all the time (-9.8 m/sec²) even though the ball is slowing down as it goes up and speeding up as it comes back down. The acceleration is the same because the change in speed is the same from one second to the next. The speed always changes by -9.8 m/sec every second.

Stopping for an instant

Notice the ball’s speed is 0 m/sec at the top of its path. If you watch this motion, the ball looks like it stops, because it is moving so slowly at the top of its path. To your eye it may look like it stops for a second, but a slow-motion camera would show the ball’s speed immediately reverses at the top and does not stay zero for any measurable amount of time.

Acceleration

You may want to say the acceleration is zero at the top, but only the speed is zero at the top. Speed and acceleration are not the same thing, remember — just like 60 miles and 60 miles per hour are not the same thing. The force of gravity causes the ball’s acceleration. The force of gravity stays constant; therefore, the acceleration is also constant and cannot be zero while the ball is in the air.
Free fall and distance

Changing speeds

In chapter 1, you used \( d = vt \) to calculate distance. You cannot calculate distance in the same simple way when speed is not constant, as happens in free fall. An object in free fall increases its speed by 9.8 m/sec each second (or 9.8 m/sec\(^2\)), so it moves a greater distance each second.

Average speed

One way to calculate distance is to use the average speed. In free fall and other situations of constant acceleration, the average speed is the average of the starting or initial speed (\( v_i \)) and the final speed (\( v_f \)). Taking the average accounts for the fact that the speed is not constant. Be careful when doing this calculation. The average speed may not be \( \frac{v_f + v_i}{2} \), if the acceleration is not constant.

\[
V_{avg} = \frac{v_f + v_i}{2}
\]

Figure 2.13: What is the average speed of a rock that falls for 5 seconds?

A rock falls off a cliff and splashes into a river 5 seconds later (Figure 2.13). What was the rock’s average speed during its fall?

1. **Looking for:** You are asked for the average speed in meters per second. You need to find the final speed in meters per second.

2. **Given:** You may assume zero initial speed and are given the air time in seconds.

3. **Relationships:**

\[
v_f = gt \quad \text{and} \quad v_{avg} = \frac{v_i + v_f}{2}
\]

where \( g = 9.8 \text{ m/sec}^2 \)

4. **Solution:**

\[
v_f = (9.8 \text{ m/sec}^2)(5 \text{ sec}) = 49 \text{ m/sec} \quad v_{avg} = \frac{0 + 49 \text{ m/sec}}{2} = 24.5 \text{ m/sec}
\]

Your turn...

a. What is the average speed of a baseball dropped from rest that falls for 2 seconds? **Answer:** 9.8 m/sec  
b. What is the average speed of a ball with an initial downward speed of 10 m/sec that falls for 2 seconds? **Answer:** 14.8 m/sec
Calculating distance  

Now that you know how to calculate the average speed for an object in free fall, you can use the average speed to find out the distance it falls.

**FREE FALL DISTANCE**

\[
\text{Distance (m)} \rightarrow d = \frac{v_{avg}}{2} \times t \rightarrow \text{Time (sec)}
\]

**Calculating free-fall speed and distance**

A skydiver falls for 6 seconds before opening her parachute. Calculate her actual speed at the 6-second mark and the distance she has fallen in this time.

1. **Looking for:** You are asked to find the final speed and the distance.
2. **Given:** You may assume zero initial speed and are given the time in seconds.
3. **Relationships:**
   \[
   v_f = gt \quad \frac{v_f + v_i}{2} = \frac{v_{avg}}{2} \quad d = v_{avg}t
   \]
4. **Solution:**
   \[
   v_f = (9.8 \text{ m/sec}^2)(6 \text{ sec}) = 58.8 \text{ m/sec}
   \]
   The speed after 6 seconds is 58.8 m/sec.

   \[
   v_{avg} = \frac{0 + 58.8 \text{ m/sec}}{2} = 29.4 \text{ m/sec}
   \]
   \[
   d = (29.4 \text{ m/sec})(6 \text{ sec}) = 176.4 \text{ m}
   \]
   The skydiver falls 176.4 meters.

**Your turn...**

a. Calculate the final speed and distance for a skydiver who waits only 4 seconds to open his parachute. **Answer:** 39.2 m/sec and 78.4 m

b. An apple falls from the top branch of a tree and lands 1 second later. How tall is the tree? **Answer:** 4.9 m

**Another way to calculate free-fall distance**

Using the average speed to calculate the distance traveled by an object in free fall requires multiple steps. If you are only given the air time, you must first find the final speed, then you must calculate the average speed, and finally you can find the distance. These three steps can all be combined into one formula. The general version of the formula is more complicated than the scope of this book, but can be simplified if the object starts at rest \((v_i = 0)\).

1) If the initial speed is zero and the object falls for \(t\) seconds, then the final speed is \(gt\).
2) The average speed is half the final speed or \(\frac{1}{2}gt\).
3) The distance is the average speed multiplied by the time or \(\frac{1}{2}gt^2\).

The general formula is therefore:

\[
d = \frac{1}{2} gt^2
\]

Remember, this formula only works when the object starts at rest and is in free fall.
Gravity and weight

Gravity’s force depends on mass

The force of gravity on an object is called **weight**. The symbol \( F_g \) stands for “force of gravity” and is used to represent weight. At Earth’s surface, gravity exerts a force of 9.8 N on every kilogram of mass. That means a 1-kilogram mass has a weight of 9.8 N, a two-kilogram mass has a weight of 19.6 N, and so on. On Earth’s surface, the weight of any object is its mass multiplied by 9.8 N/kg. Because weight is a force, it is measured in units of force such as newtons and pounds.

Weight and mass

We all tend to use the terms **weight** and **mass** interchangeably. Heavy objects have lots of mass and light objects have little mass. People and things such as food are “weighed” in both kilograms and pounds. If you look on the label of a bag of flour, it lists the “weight” in two units: 5 pounds in the English system and 2.3 kilograms in the metric system. As long as we are on Earth, where \( g = 9.8 \text{ N/kg} \) a 2.3-kilogram object will weigh 5 pounds. But on the moon, \( g = 1.6 \text{ N/kg} \), so a 2.3 kilogram object will weigh only 0.8 pounds (Figure 2.14).

Weight and the second law

You should recognize that the value of 9.8 N/kg is the same as \( g \) (9.8 m/sec\(^2\)) but with different units. This is no coincidence. According to the second law, a force of 9.8 newtons acting on one kilogram produces an acceleration of 9.8 m/sec\(^2\). For this reason the value of \( g \) can also be used as 9.8 N/kg. Which units you choose depends on whether you want to calculate acceleration or the weight force. Both units are actually identical: 9.8 N/kg = 9.8 m/sec\(^2\).

---

**Figure 2.14**: An object that weighs 5 pounds on Earth weighs only 0.8 pounds on the moon. It has the same mass but different weights because gravity is stronger on Earth.
Mass is fundamental

Although mass and weight are related quantities, always remember the difference when doing physics. Mass is a fundamental property of an object measured in kilograms (kg). Weight is a force measured in newtons (N) that depends on mass and gravity. A 10-kilogram object has a mass of 10 kilograms no matter where it is in the universe. A 10-kilogram object’s weight, however, can vary greatly depending on whether the object is on Earth, on the moon, or in outer space.

Weight and mass

Legend has it that around 1587 Galileo dropped two balls from the Leaning Tower of Pisa to see which would fall faster. Suppose the balls had masses of 1 kilogram and 10 kilograms.

a. Use the equation for weight to calculate the force of gravity on each ball.

b. Use your answers from (a) and Newton’s second law to calculate each ball’s acceleration.

1. Looking for: You are asked to find the force of gravity (weight) and the acceleration.

2. Given: You are given each ball’s mass in kilograms.

3. Relationships: $W=mg$ $a=F/m$

4. Solution:

   a. For the 1-kg ball:
      a) $W = (1 \text{ kg})(9.8 \text{ m/sec}^2)$ $W = 9.8 \text{ N}$
      b) $a = (9.8 \text{ N})/(1 \text{ kg})$ $a = 9.8 \text{ m/sec}^2$

   b. For the 10-kg ball:
      a) $W = (10 \text{ kg})(9.8 \text{ m/sec}^2)$ $W = 98 \text{ N}$
      b) $a = (98 \text{ N})/(10 \text{ kg})$ $a = 9.8 \text{ m/sec}^2$  Both balls have the same acceleration.

Your turn...

a. Calculate the weight of a 60-kilogram person (in newtons) on Earth and on Mars ($g = 3.7 \text{ m/sec}^2$). Answer: 588 N, 222 N

b. A 70-kg person travels to a planet where he weighs 1,750 N. What is the value of $g$ on that planet? Answer: 25 m/sec$^2$

Why accelerations are the same

The example problem shows the weight of a 10-kilogram object is 10 times the weight of a 1-kilogram object. However, the heavier weight produces only one-tenth the acceleration because of the larger mass. The increase in force (weight) is exactly compensated by the increase in inertia (mass). As a result, the acceleration of all objects in free fall is the same.
Air resistance

We just said the acceleration of all objects in free fall is the same. So why does a feather fall slower than a baseball? The answer is that objects on Earth are not truly in free fall because gravity is not the only force acting on falling objects. When something falls through air, the air exerts an additional force. This force, called air resistance, acts against the direction of the object’s motion.

Factors affecting air resistance

The size and shape of an object affect the force of air resistance. A feather has its weight spread out over a comparatively large area, so it must push a lot of air out of the way as it falls. The force of air resistance is large compared with the weight. According to the second law of motion of motion, acceleration is caused by the net force. The net force is the weight minus the force of air resistance. The feather accelerates at much less than 9.8 m/sec² because the net force is very small.

Why the baseball falls faster

A baseball’s shape allows it to move through the air more easily than a feather. The force of air resistance is much smaller relative to the baseball’s weight. Since the net force is almost the same as its weight, the baseball accelerates at nearly 9.8 m/sec² and falls much more rapidly than the feather.

Terminal speed

If you observe a falling feather it stops accelerating after a short distance and then falls at constant speed. That is because air resistance increases with speed. A feather only accelerates until the force of air resistance equals the force of gravity. The net force then becomes zero and the feather falls at a constant speed called the terminal speed. The terminal speed depends on the ratio of an object’s weight to its air resistance. A tightly crumpled ball of paper has a faster terminal speed than a flat piece of paper because the flat sheet has more air resistance even though the papers’ weights are the same.

2.3 Section Review

1. Describe the motion of a freely falling object. Use the words speed, acceleration, and distance in your answer.
2. What is the difference between mass and weight?
3. If you drop a feather and a baseball in a place where there is no air (a vacuum), how will their motions compare? Why?
2.4 Graphs of Motion

Motion graphs are an important tool used to show the relationships between distance, speed, acceleration, and time. For example, meteorologists use graphs to show the motion of hurricanes and other storms. Graphs can show the location and speed of a storm at different points in time to help in predicting its path and the time when it will reach a certain location. In this section, you will use graphs of position versus time and speed versus time to represent motion.

The position vs. time graph

Position versus time

The position versus time graph in Figure 2.15 shows the constant-speed motion of two cars, A and B. Using the numbers on the graph, you see that both cars move for 5 seconds. Car A moves 10 meters while car B moves only 5 meters. Using the equation \( v = \frac{d}{t} \) the speed of car A is 2 m/sec. The speed of car B is 1 m/sec. Notice that line A is steeper than line B. A steeper slope on a position versus time graph means a faster speed.

The definition of slope

The slope of a line is the ratio of the “rise” (vertical change) to the “run” (horizontal change). The diagram below shows you how to calculate the slope of a line. The rise is equal to the height of the triangle. The run is equal to the length along the base of the triangle. Here, the \( x \)-values represent time and the \( y \)-values represent distance. The slope of a position versus time graph is therefore a distance divided by a time, which equals speed.

Vocabulary

slope

Objectives

✓ Describe motion with position versus time and speed versus time graphs.
✓ Use a position versus time graph to calculate speed from the slope.
✓ Use a speed versus time graph to calculate acceleration and distance traveled.

Figure 2.15: Both cars have constant speed, but Car A is moving faster than Car B.
Position graphs of accelerated motion

**Graphing free fall**  A position versus time graph can tell you whether an object’s speed is constant or changes. If the speed is constant, the graph is a straight line with a constant slope. If the speed is changing, the slope changes, so the graph curves. Consider the speed of an accelerating ball in free fall. As time passes, the ball’s speed increases. Because the slope equals the speed, the slope must also become greater with time. The graph is a curve that gets steeper as you move along the x-axis (time). A position versus time graph for a ball in free fall is shown below.

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Position (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>4.9</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>44.1</td>
</tr>
<tr>
<td>4</td>
<td>78.4</td>
</tr>
<tr>
<td>5</td>
<td>122.5</td>
</tr>
</tbody>
</table>

**Slowing down**  The graph of an object slowing down is also curved. One example might be a car gradually coming to a stop at a red light. As time passes, the car’s speed decreases. The slope of the graph must therefore decrease as you trace the line to the right. Figure 2.16 shows the graph of a car coming to a stop.

*Figure 2.16: The position versus time graph for a car coming to a gradual stop at a red light.*
The speed vs. time graph for constant speed

The speed versus time graph has speed on the y-axis and time on the x-axis. The graph in Figure 2.17 shows the speed versus time for a ball rolling at constant speed on a level floor. On this graph, constant speed is shown with a straight horizontal line. If you look at the speed on the y-axis, you see that the ball is moving at 1 m/sec for the entire 10 seconds. Figure 2.18 is the position versus time graph for the ball. Both of the graphs in the sidebar show the exact same motion. If you calculate the slope of the lower graph, you will find that it is 1 m/sec, the same as the speed in Figure 2.17.

Calculating distance

A speed versus time graph also can be used to find the distance the object has traveled. Remember, distance is equal to the speed multiplied by the time. Suppose we draw a rectangle on the speed versus time graph between the x-axis and the line showing the speed. The area of the rectangle (shown below) is equal to its length times its height. On the graph, the length is equal to the time and the height is equal to the speed. Therefore, the area of the graph is the speed multiplied by the time. This is the distance the ball traveled.
The speed vs. time graph for accelerated motion

The speed versus time graph

If an object is accelerating it is easier to work with the speed versus time graph instead of the position versus time graph. The speed versus time graph is the best tool for understanding acceleration because it clearly shows how an object’s speed changes with time.

Constant acceleration

The speed versus time graph below is for a ball in free fall. Because the graph is a straight line, the speed increases by the same amount each second. This means the ball has a constant acceleration. Make sure you do not confuse constant speed with constant acceleration. As long as it is moving in one direction, an object at constant speed has zero acceleration (Figure 2.19, bottom). Constant speed means an object’s position changes by the same amount each second. Constant acceleration means an object’s speed changes by the same amount each second.

Calculating acceleration

The slope of a speed versus time graph represents the object’s acceleration. Figure 2.19 shows some examples of graphs with and without acceleration. Note that there is acceleration any time the speed versus time graph is not perfectly horizontal (or zero slope). If the graph slopes down, it means the speed is decreasing. If the graph slopes up, the speed is increasing.

Figure 2.19: Examples of graphs showing different accelerations.
Calculating acceleration from the speed vs. time graph

Slope
You know that the slope of a graph is equal to the ratio of rise to run. On the speed versus time graph, the rise and run have special meanings, as they did for the distance versus time graph. The rise is the amount the speed changes. The run is the amount the time changes.

Acceleration and slope
Remember, acceleration is the change in speed over the change in time. This is exactly the same as the rise over run for the speed versus time graph. The slope of an object’s speed versus time graph is equal to its acceleration. Figure 2.20 shows how to find the acceleration of a ball in free fall from a speed versus time graph.

Make a triangle to get the slope
To determine the slope of the speed versus time graph, take the rise (change in speed) and divide by the run (change in time). It is helpful to draw a triangle on the graph to help figure out the rise and run. The rise is the height of the triangle. The run is the length of the base of the triangle. The graph is for a ball in free fall, so you should not be surprised to see that the slope is 9.8 m/sec^2, the acceleration due to gravity.

Calculate the acceleration shown by the speed versus time graph at right.

1. Looking for: You are asked for the acceleration in meters per second per second.
2. Given: You are given a graph of speed versus time.
3. Relationships: The acceleration is equal to the slope of the line.
4. Solution: The rise is 40 m/sec, and the run is 10 sec. Dividing the two gives an acceleration of 4 m/sec^2.

Your turn...
a. Calculate the acceleration shown by the graph in Figure 2.21. Answer: 1.0 m/sec^2
b. Calculate the acceleration shown by the graph in Figure 2.17. Answer: 0 m/sec^2 because the rise is 0 m/sec.

Figure 2.20: The slope of a speed versus time graph equals the acceleration.
**Distance on an accelerated motion graph**

**A ball rolling downhill**
Consider an experiment with a ball rolling downhill. The speed of the ball increases as it rolls downward. The speed versus time graph looks like Figure 2.21. This graph shows a speed that starts at zero. Two seconds later, the speed is two meters per second. A speed versus time graph that shows any slope (like this one does) tells you there is acceleration because the speed is changing over time.

**The distance traveled when speed is changing**
The speed versus time graph gives us a way to calculate the distance an object moves even when its speed is changing. The distance is equal to the area on the graph, but this time the area is a triangle instead of a rectangle. The area of a triangle is one-half the base times the height. The base is equal to the time, just as before. The height is equal to the speed of the ball at the end of two seconds. For the graph in the example, the ball moves two meters from zero to two seconds.

![The speed versus time graph for a ball rolling down a hill.](image)

**2.4 Section Review**

1. Explain how to calculate the slope of a graph.
2. What does the slope of a position versus time graph represent?
3. Draw the position versus time graph and the speed versus time graph for an object moving at a constant speed of 2 m/sec.
4. How can you use a speed versus time graph to find an object’s acceleration?
Revealing the secrets of motion

How can a tiny hummingbird fly backward? How does it manage to hover in mid-air as it sips nectar from a flower? For years, answers to these questions eluded naturalists, because a hummingbird’s wings beat an average of sixty times per second, so fast that their movement appears blurred to our eyes.

In 1936, a young MIT professor unlocked the secrets of hummingbird flight using a tool he invented to study rotating engines. Harold Edgerton, Ph.D., created a system for taking high-speed photographs of moving objects using a strobe light in a darkened room. Edgerton left his camera shutter open while his strobe light flashed quick, bright pulses of light that lasted only 1/100,000 of a second, with a period of darkness 1/500 of a second between each flash. He invented a device to pull film at a constant speed through his camera, enabling him to take about 540 separate pictures in a single second. The resulting photos revealed that hovering hummingbirds don’t beat their wings up and down like other birds. Instead, they move them forward and backward, tracing a figure-eight. This pattern allows them to generate lift during both parts of their wings’ beat making hovering possible.

Newton’s laws caught on film

“Doc” Edgerton spent a lifetime using his strobe light to illuminate aspects of motion that we aren’t normally able to see. His famous photo, Newton’s apple, is a striking demonstration of acceleration due to gravity. To create this photo, he set his strobe light to flash sixty times per second, and had an assistant drop the apple in a darkened room. By capturing all of the resulting images on a single piece of film, he shows very clearly how the apple accelerates as it falls.

Capturing the moment of impact

Prior to World War II, Edgerton studied another of Newton’s laws, an action-reaction pair—the firing of a bullet and the “kickback” of the pistol. Edgerton proved that the pistol’s upward “kick” did not affect the bullet’s path as was previously thought. Edgerton’s photos showed that the gun did not begin its upward motion until after the bullet had left the barrel.

When U.S. Army officials learned of Edgerton’s work, they asked him to assist in testing the effects of various types of shells on armor. They wanted to photograph the exact moment of impact. Edgerton invented a new way to trigger the flash—he placed a microphone in front of the target and connected it to his flash unit. The sound wave from the bullet set off the flash and Edgerton obtained clear photos of the moment the bullet pierced the armor. Edgerton’s work helped the Army develop better materials for fighting World War II.

Edgerton also developed a strobe flash that allowed Allied troops to take aerial reconnaissance photos of nighttime movements of enemy troops. His strobos were used in the nights immediately preceding the D-Day invasion of Normandy. In 1946, Edgerton was awarded the Medal of Freedom for this work.

Finding the perfect swing

Edgerton’s photographic techniques are also used to analyze motion in sports. In this photograph of a golfer’s swing, you can see that the head of the golf club gets faster toward the bottom of the swing because it moves a greater distance between flashes of the strobe. Photographs like these can help an athlete evaluate and improve his or her technique and performance. For example, a high-speed photograph records a player’s stance and timing through a swing so that improvements can be made.

An irrepressible curiosity

Although Edgerton is perhaps best remembered as a photographer, he saw himself primarily as a scientist. He wanted to know what could be revealed about motion in all sorts of contexts. Strobe photography was his tool for doing that. His curiosity extended beyond studies of birds, falling apples, ammunition, and sports. In his lifetime, he showed us how red blood cells move through capillaries, how tiny marine animals dart about, and how an atomic bomb explodes. Yet he never lost his appreciation for the beauty of the simplest motions like the splash of a milk drop on a table.

Questions:

1. What did Edgerton’s photos reveal about hummingbird flight?
2. Describe how Edgerton’s photo of an apple’s falling motion shows that the apple is accelerating.
3. Make a list of other examples where high-speed photography could be used to better understand what is happening in a situation involving motion.
Chapter 2 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

<table>
<thead>
<tr>
<th>velocity</th>
<th>force</th>
<th>acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton’s first law</td>
<td>inertia</td>
<td>net force</td>
</tr>
<tr>
<td>newton</td>
<td>free fall</td>
<td>terminal speed</td>
</tr>
<tr>
<td>Newton’s second law</td>
<td>weight</td>
<td>acceleration due to gravity</td>
</tr>
</tbody>
</table>

Section 2.1

1. A ____ is required to change motion.
2. “Objects want to keep doing the same thing” is a way of stating ____.
3. An object with more mass also has more ____.
4. The total of all the forces acting on an object is called the ____.
5. The ____ is the metric unit of force.

Section 2.2

6. The rate at which speed changes is called ____.
7. ____ relates force, mass, and acceleration in the equation \( F = ma \).

Section 2.3

8. A falling object under the influence of only gravity is in ____.
9. The ____ on Earth is equal to 9.8 m/sec².
10. Speed with direction is called ____.
11. The force of gravity on an object is its ____.
12. When the force due to gravity equals the force due to air resistance, the speed of a falling object is called its ____.

Section 2.4

13. The ____ of a line is found by dividing the rise by the run.

Reviewing Concepts

Section 2.1

1. Define the term force and give three examples of forces.
2. Give an example of Newton’s first law in everyday life.
3. Explain why Newton’s first law is also known as the law of inertia.
4. List two units for measuring mass and two units for measuring force.
5. One newton is the _____ it takes to change the _____ of a _____ mass by _____ in one second.

Section 2.2

6. If an object has an acceleration of 20 cm/sec², what do you know about how its speed changes over time?
7. Give two ways the unit “meter per second per second” can be abbreviated.
8. An object accelerates if its speed changes. What is the other way an object can accelerate (without changing speed)?
9. Write the equation for Newton’s second law that you would use in each of the following scenarios. Let \( F = \) force, \( m = \) mass, and \( a = \) acceleration:
   a. You know mass and acceleration and want to find the force.
   b. You know mass and force and want to find the acceleration.
   c. You know force and acceleration and want to find the mass.
10. What is the acceleration of a car moving at a steady speed of 50 mph?
11. Give an example of Newton’s second law in everyday life.
12. Explain how the unit of 1 newton is defined.

Section 2.3

13. By how much does the speed of an object in free fall change each second?
14. A ball is thrown straight up into the air. As it moves upward, its speed ____ by ____ each second. As it falls back down, its speed ____ by ____ each second.
15. What is the difference between speed and velocity?
16. Can an object have a negative speed? Can it have a negative velocity?
17. Can an object have a speed of zero while it has an acceleration that is not zero? Explain.
18. An astronaut carries a rock from the moon to Earth. Is the rock’s mass the same on Earth as on the moon? Is its weight the same? Explain.
19. What is the direction of air resistance on a falling object?
20. Which two forces are equal when an object is at its terminal speed?

Section 2.4
21. Explain how to calculate the slope of a line.
22. The slope of a position vs. time graph is equal to the object’s ____.
23. Sam rolls down his driveway on a skateboard while Beth keeps track of his position every second for 15 seconds. When they make a graph of the data, the position vs. time graph is a curve that gets steeper as time increases. What does this tell you about Sam’s speed?
24. A graph is made of the speed vs. time of a plane as it flies from San Francisco to the Kahului Airport on Maui. How could the distance traveled by the plane be calculated from the graph?
25. The slope of a speed vs. time graph is equal to the object’s ____.
26. Sketch the speed vs. time graph for an object moving at a constant speed of 3 m/sec.

Solving Problems

Section 2.1
1. Order the following mass measurements from smallest to largest: 0.5 kilograms, 1,000 grams, 5 kilograms, 50 grams.
2. Dani and Gina are pushing on a box. Dani pushes with 250 N of force and Gina pushes with 100 N of force.
   a. What is the net force if they both push in the same direction?
   b. What is the net force if they push in opposite directions?

Section 2.2
3. A car accelerates from 0 to 20 m/sec in 10 seconds. Calculate its acceleration.
4. During a race, you speed up from 3 m/sec to 5 m/sec in 4 seconds.
   a. What is your change in speed?
   b. What is your acceleration?
5. Marcus is driving his car at 15 km/hr when he brakes suddenly. He comes to a complete stop in 2 seconds. What was his acceleration in km/hr/sec? Was his acceleration positive, negative, or zero?
6. You start from rest and ski down a hill with an acceleration of 2 m/sec². Find your speed at the following times:
   a. 1 second
   b. 2 seconds
   c. 3 seconds
   d. 10 seconds
7. Use your knowledge of Newton’s second law to answer the following questions:
   a. What is the net force required to accelerate a 1,000-kg car at 3 m/sec²?
   b. You pull your little cousin in a wagon. You must pull with a net force of 50 N to accelerate her at 2 m/sec². What’s her mass?
   c. When a 10-kg object is in free fall, it feels a force of 98 N. What is its acceleration?

Section 2.3
8. You drop a ball from the edge of a cliff. It lands 4 seconds later.
   a. Make a table showing the ball’s speed each second for 4 seconds.
   b. What is the ball’s average speed during the first second it is in free fall?
   c. What is the ball’s average speed for the whole 4 second?
   d. What distance does the ball fall during the 4 seconds?
9. During a science experiment, your teacher drops a tennis ball out of a window. The ball hits the ground 3 seconds later.
   a. What was the ball’s speed when it hit the ground? Ignore air resistance.
   b. What was the ball’s average speed during the 3 seconds?
   c. How high is the window?
10. Answer the following questions about mass and weight:
   a. How many newtons does a 5-kg backpack weigh on Earth?
   b. How many newtons does a 5-kg backpack weigh on the moon?
   c. Aya’s mass is 45 kg. What is her weight in newtons on Earth?
   d. What is Aya’s mass on the moon?
   e. What is Aya’s weight in Newtons on the moon?

Section 2.4

11. Rank the four points on the position vs. time graph in order from slowest to fastest.

12. Draw the position vs. time graph for a person walking at a constant speed of 1 m/sec for 10 seconds. On the same axes, draw the graph for a person running at a constant speed of 4 m/sec.

13. Calculate speed from the position vs. time graph to the right. Show your work.

14. Draw the position vs. time graph for an object that is not moving.

15. Why is the position vs. time graph for an object in free fall a curve?

16. Draw the speed vs. time graph showing the same motion as the position vs. time graph to the right.

17. Draw a speed vs. time graph for a car that starts at rest and steadily accelerates until it is moving at 40 m/sec after 20 seconds. Then calculate the car’s acceleration and the distance it traveled during the 20 seconds.

18. Draw a speed vs. time graph for an object accelerating from rest at 2 m/sec².

Applying Your Knowledge

Section 2.1

1. Aristotle, Galileo Galilei, and Sir Isaac Newton all developed their own theories about motion. Research to find out how each scientist changed what people believed about motion. Were all of their theories correct?

2. Write about Newton’s three laws of motion, giving examples from your own life. If you have ever ridden in an automobile, taken a bike ride, played a sport, or walked down the street you have experienced Newton’s laws. Be sure to describe the effects of all three of Newton’s laws on the activities you choose.

Section 2.2

3. Research the accelerations from 0-60 mph for ten different car models and make a table showing: the model of car, the mass of the car, the amount of time to go from 0-60 mph (in seconds), and the acceleration (in mph/sec). Is there any relationship between the masses of the cars and their accelerations? Explain possible reasons.

4. Research the following: What is the fastest acceleration of a human in a sprint race? What is the fastest acceleration of a race horse? Which animal using only its muscles is capable of the fastest acceleration?

Section 2.3

5. A falling object reaches terminal speed when the force of gravity is balanced by the air resistance of the object. Explain this in terms of Newton’s first and second laws.

6. Imagine what it would be like if there suddenly were no air resistance. Explain three differences you might notice in the world around you.

Section 2.4

7. As Joseph starts to ride his bike, he accelerates at a constant 1 m/sec² from rest to final speed of 10 m/sec.
   a. Make a table of his speed each second from zero to ten seconds. Make a speed vs. time graph from your table.
   b. Make a table of his position each second from zero to ten seconds. Make a position vs. time graph from your table.
Look around you. Do you see any changes taking place? Is a light bulb giving off heat and light? Is the sun shining? Are your eyes moving across the page while you read this introduction? When an object falls toward Earth, when you play a sport or a musical instrument, when your alarm clock wakes you up in the morning, and when a bird flies through the air, there are changes taking place that could not occur without the effects of energy.

Energy is everywhere! Energy is responsible for explaining “how the world works”. As you read this chapter think about the examples and see if you can identify the forms of energy that are responsible for the changes that take place in each. Skateboarding, astronauts, car crashes, ball throwing, billiards, and tennis are just some of the physical systems you will encounter. Studying physics also requires energy, so always eat a good breakfast!

Key Questions

✓ Do objects at rest ever have any forces acting on them?
✓ Why does a faster skateboarder take more force to stop than a slower one with the same mass?
✓ How can energy be so important when it cannot be smelled, touched, tasted, seen, or heard?
3.1 Newton’s Third Law and Momentum

For every action there is an equal and opposite reaction. This section is about the true meaning of this statement, known as Newton’s third law of motion. In the last section, you learned that forces cause changes in motion. However, this does not mean that objects at rest experience no forces! What is it that keeps your book perfectly still on the table as you read it even though you know gravity exerts a force on the book (Figure 3.1)? “Force” is a good answer to this question and the third law is the key to understanding why.

Newton on a skateboard

Imagine a skateboard contest between Newton and an elephant. They can only push against each other, not against the ground. The fastest one wins. The elephant knows it is much stronger and pushes off Newton with a huge force thinking it will surely win. But who does win?

The winner

Newton wins — and will always win. No matter how hard the elephant pushes, Newton always moves away at a greater speed. In fact, Newton doesn’t have to push at all and he still wins. Why?

Forces always come in pairs

You already know it takes force to make both Newton and the elephant move. Newton wins because forces always come in pairs. The elephant pushes against Newton and that action force pushes Newton away. The elephant’s force against Newton creates a reaction force against the elephant. Since the action and reaction forces are equal in strength and because of Newton’s second law of motion \( a = F/m \), Newton accelerates more because his mass is smaller.

Figure 3.1: There are forces acting even when things are not moving.
The third law of motion

The first and second laws
The first and second laws of motion apply to single objects. The first law says an object will remain at rest or in motion at constant velocity unless acted upon by a net force. The second law says the acceleration of an object is directly proportional to force and inversely proportional to the mass \((a = F/m)\).

The third law operates with pairs of objects
In contrast to the first two laws, the third law of motion deals with pairs of objects. This is because all forces come in pairs. Newton’s third law states that every action force creates a reaction force that is equal in strength and opposite in direction.

For every action force, there is a reaction force equal in strength and opposite in direction.

Forces only come in action-reaction pairs. There can never be a single force, alone, without its action-reaction partner. The force exerted by the elephant (action) moves Newton since it acts on Newton. The reaction force acting back on the elephant is what moves the elephant.

The labels “action” and “reaction”
The words action and reaction are just labels. It does not matter which force is called action and which is reaction. You choose one to call the action and then call the other one the reaction (Figure 3.2).

A skateboard example
Think carefully about moving the usual way on a skateboard. Your foot exerts a force backward against the ground. The force acts on the ground. However, you move, so a force must act on you. Why do you move? What force acts on you? You move because the action force of your foot against the ground creates a reaction force of the ground against your foot. You “feel” the ground because you sense the reaction force pressing on your foot. The reaction force is what makes you move because it acts on you (Figure 3.3).
**Action and reaction forces**

**Action and reaction forces do not cancel**

It is easy to get confused thinking about action and reaction forces. Why don’t they cancel each other out? The reason is that action and reaction forces act on different objects. For example, think about throwing a ball. When you throw a ball, you apply the action force to the ball, creating the ball’s acceleration. The reaction is the ball pushing back against your hand. The action acts on the ball and the reaction acts on your hand. The forces do not cancel because they act on different objects. You can only cancel forces if they act on the same object (Figure 3.4).

**Draw diagrams**

When sorting out action and reaction forces it is helpful to draw diagrams. Draw each object apart from the other. Represent each force as an arrow in the appropriate direction.

**Identifying action and reaction**

Here are some guidelines to help you sort out action and reaction forces:

- Both are always there whenever any force appears.
- They always have the exact same strength.
- They always act in opposite directions.
- They always act on different objects.
- Both are real forces and either (or both) can cause acceleration.

A woman with a weight of 500 N is sitting on a chair. Describe an action-reaction pair of forces.

1. **Looking for:** You are asked for a pair of action and reaction forces.
2. **Given:** You are given one force in newtons.
3. **Relationships:** Action-reaction forces are equal and opposite, and act on different objects.
4. **Solution:** The force of 500 N exerted by the woman on the chair seat is an action. The chair seat acting on the woman with an upward force of 500 N is a reaction.

**Your turn...**

a. A baseball player hits a ball with a bat. Describe an action-reaction pair of forces. **Answer:** The force of the bat on the ball accelerates the ball. The force of the ball on the bat (reaction) slows down the swinging bat (action).

b. Earth and its moon are linked by an action-reaction pair. **Answer:** Earth attracts the moon (action) and the moon attracts Earth (reaction) in an action-reaction pair. Both action and reaction are due to gravity.
Momentum

Faster objects are harder to stop

Imagine two kids on skateboards are moving toward you (Figure 3.5). Each has a mass of 40 kilograms. One is moving at one meter per second and the other at 10 meters per second. Which one is harder to stop?

You already learned that inertia comes from mass. That explains why an 80-kilogram skateboarder is harder to stop than a 40-kilogram skateboarder. But how do you account for the fact that a faster skateboarder takes more force to stop than a slower one with the same mass?

Momentum

The answer is a new quantity called momentum. The momentum of a moving object is its mass multiplied by its velocity. Like inertia, momentum measures a moving object’s resistance to changes in its motion. However, momentum includes the effects of speed and direction as well as mass. The symbol \( p \) is used to represent momentum.

\[
p = mv
\]

Units of momentum

The units of momentum are the units of mass multiplied by the units of velocity. When mass is in kilograms and velocity is in meters per second, momentum is in kilogram-meters per second (kg·m/sec).

Calculating momentum

Momentum is calculated with velocity instead of speed because the direction of momentum is always important. A common choice is to make positive momentum to the right and negative momentum to the left (Figure 3.6).
**Impulse**

**Force changes momentum**  
Momentum changes when velocity changes. Since force is what changes velocity, that means that force is also linked to changes in momentum. The relationship with momentum gives us an important new way to look at force.

**Impulse**  
A change in an object’s momentum depends on the net force and also on the amount of time the force is applied. The change in momentum is equal to the net force multiplied by the time the force acts. A change in momentum created by a force exerted over time is called impulse.

**IMPULSE**

\[ Ft = mv_2 - mv_1 \]

**Units of impulse**  
Notice that the force side of the equation has units of N·sec, while the momentum side has units of momentum, kg·m/sec. These are the same units, since 1 N is 1 kg·m/s². Impulse can be correctly expressed either way.

---

A net force of 100 N is applied for 5 seconds to a 10-kg car that is initially at rest. What is the speed of the car at the end of the 5 seconds.

1. **Looking for:** You are asked for the speed.
2. **Given:** You are given the net force in newtons, the time the force acts in seconds, and the mass of the car in kilograms.
3. **Relationships:** impulse = force × time = change in momentum; momentum = mass × velocity.
4. **Solution:** The car’s final momentum = 100 N × 5 seconds = 500 kg·m/sec.  
   Speed is momentum divided by mass, or \( v = \frac{500 \text{ kg·m/sec}}{10 \text{ kg}} = 50 \text{ m/sec} \)

**Your turn...**

a. A 15-N force acts for 10 seconds on a 1-kg ball initially at rest. What is the ball’s final momentum? **Answer:** 150 kg·m/sec
b. How much time should a 100-N force take to increase the speed of a 10-kg car from 10 m/sec to 100 m/sec? **Answer:** 9 sec
The law of momentum conservation

**An important new law**

We are now going to combine Newton’s third law with the relationship between force and momentum. The result is a powerful new tool for understanding motion: the law of conservation of momentum. This law allows us to make accurate predictions about what happens before and after an interaction even if we don’t know the details about the interaction itself.

**Momentum in an action-reaction pair**

When two objects exert forces on each other in an action-reaction pair, their motions are affected as a pair. If you stand on a skateboard and throw a bowling ball, you apply force to the ball. That force changes the momentum of the ball.

The third law says the ball exerts an equal and opposite force back on you. Therefore, your momentum also changes. Since the forces are exactly equal and opposite, the changes in momentum are also equal and opposite. If the ball gains +20 kg·m/sec of forward momentum, you must gain -20 kg·m/sec of backward momentum (Figure 3.7).

**The law of conservation of momentum**

Because of the third law, the total momentum of two interacting objects stays constant. If one gains momentum, the other loses the same amount, leaving the total unchanged. This is the law of conservation of momentum. The law says the total momentum in a system of interacting objects cannot change as long all forces act only between the objects in the system.

*If interacting objects in a system are not acted on by outside forces, the total amount of momentum in the system cannot change.*

**Forces inside and outside the system**

Forces outside the system, such as friction and gravity, can change the total momentum of the system. However, if ALL objects that exert forces are included in the system, the total momentum stays perfectly constant. When you jump up, the reaction force from the ground gives you upward momentum. The action force from your feet gives the entire Earth an equal amount of downward momentum and the universe keeps perfect balance. No one notices the planet move because it has so much more mass than you so its increase in momentum creates negligible velocity (Figure 3.8).
An astronaut floating in space throws a 2-kilogram hammer to the left at 15 m/sec. If the astronaut’s mass is 60 kilograms, how fast does the astronaut move to the right after throwing the hammer?

1. **Looking for:** You are asked for the speed of the astronaut after throwing the hammer.

2. **Given:** You are given the mass of the hammer in kilograms and the speed of the hammer in m/sec and the mass of the astronaut in kilograms.

3. **Relationships:** The total momentum before the hammer is thrown must be the same as the total after. Momentum = mass \(\times\) velocity. A negative sign indicates the direction of motion is to the left.

4. **Solution:** Both the astronaut and hammer were initially at rest, so the initial momentum was zero. Use subscripts \((a\) and \(h)\) to distinguish between the astronaut and the hammer. 

\[m_av_a + m_hv_h = 0\]

Plug in the known numbers:

\[(60 \text{ kg})(v_a) + (2 \text{ kg})(-15 \text{ m/sec}) = 0\]

Solve:

\[(60 \text{ kg})(v_a) = +30 \text{ kg} \cdot \text{m/sec}\]

\[v_a = +0.5 \text{ m/sec}\]

The astronaut moves to the right at a speed of 0.5 m/sec.

**Your turn...**

a. Two children on ice skates start at rest and push off from each other. One has a mass of 30 kg and moves back at 2 m/sec. The other has a mass of 15 kg. What is the second child’s speed? **Answer:** 4 m/sec

b. Standing on an icy pond, you throw a 0.5 kg ball at 40 m/sec. You move back at 0.4 m/sec. What is your mass? **Answer:** 50 kg

### 3.1 Section Review

1. List three action and reaction pairs shown in the picture at right.
2. Why don’t action and reaction forces cancel?
3. Use impulse to explain how force is related to changes in momentum.
4. Explain the law of conservation of momentum and how it relates to Newton’s third law.
3.2 Energy and the Conservation of Energy

Energy is one of the fundamental quantities in our universe. Without energy, nothing could ever change. Yet pure energy itself cannot be smelled, tasted, touched, seen, or heard. However, energy does appear in many forms, such as motion and heat. Energy can travel in different ways, such as in light and sound waves and in electricity. The workings of the universe (including all of our technology) can be viewed from the perspective of energy flowing from one place to another and changing back and forth from one form to another.

What is energy?

A definition of energy

Energy is a quantity that measures the ability to cause change. Anything with energy can change itself or cause change in other objects or systems. Energy can cause changes in temperature, speed, position, momentum, pressure, or other physical variables. Energy can also cause change in materials, such as burning wood changing into ashes and smoke.

Energy is a quantity that measures the ability to cause change in a physical system.

Examples

- A gust of wind has energy because it can move objects in its path.
- A piece of wood in a fireplace has energy because it can produce heat and light.
- You have energy because you can change the motion of your own body.
- Batteries have energy because they can be used in a radio to make sound.
- Gasoline has energy because it can be burned in an engine to move a car.
- A ball at the top of a hill has energy because it can roll down the hill and move objects in its path.

Units of energy

The unit of measurement for energy is the joule (J). One joule is the energy needed to push with a force of one newton over a distance of one meter (Figure 3.9). The joule is an abbreviation for one newton multiplied by one meter. If you push on your calculator with a force of one newton while it moves a distance of one meter across a table, one joule of your energy is converted into the energy of the calculator’s motion.

Vocabulary

- energy
- joule
- work
- potential energy
- kinetic energy
- law of conservation of energy

Objectives

- Describe work and energy.
- Calculate potential energy.
- Calculate kinetic energy.
- Apply the law of conservation of energy to explain the motion of an object acted on by gravity.

Calories

The Calorie is a unit of energy often used for food. One Calorie equals 4,187 joules.
What is work?

“Work” means different things

The word “work” is used in many different ways.

• You should always check over your work before handing in a test.
• You go to work.
• Your toaster doesn’t work.
• You work with other students on a group project.

What “work” means in physics

In physics, work has a very specific meaning. Work is the transfer of energy that results from applying a force over a distance. To calculate work you multiply the force by the distance the object moves in the direction of the force. If you lift a block with a weight of one newton for a distance of one meter, you do one joule of work. One joule of energy is transferred from your body to the block, changing the block’s energy. Both work and energy are measured in the same units because work is a form of energy.

Work is done on objects

When thinking about work you should always be clear about which force is doing the work on which object. Work is done on objects. If you lift a block one meter with a force of one newton, you have done one joule of work on the block (Figure 3.10).

Energy is needed to do work

An object that has energy is able to do work; without energy, it is impossible to do work. In fact, one way to think about energy is as stored work. A falling block has kinetic energy that can be used to do work. If the block hits a ball, it will do work on the ball and change its motion. Some of the block’s energy is transferred to the ball during the collision.

Figure 3.10: When you lift a 1-newton block a height of 1 meter, you do 1 joule of work on the block.
Potential energy

**What is potential energy?**

Potential energy is energy due to position. The word “potential” means that something is capable of becoming active. Systems or objects with potential energy are able to exert forces (exchange energy) as they change to other arrangements. For example, a stretched spring has potential energy. If released, the spring will use this energy to move itself (and anything attached to it) back to its original length.

**Gravitational potential energy**

A block above a table has potential energy. If released, the force of gravity moves the block down to a position of lower energy. The term gravitational potential energy describes the energy of an elevated object. The term is often shortened to just “potential energy” because the most common type of potential energy in physics problems is gravitational. Unless otherwise stated, you can assume “potential energy” means gravitational potential energy.

**How to calculate potential energy**

How much potential energy does a raised block have? The block’s potential energy is exactly the amount of work it can do as it goes down. Work is force multiplied by distance. The force is the weight \((mg)\) of the block in newtons. The distance the block can move down is its height \((h)\) in meters. Multiplying the weight by the distance gives you the block’s potential energy at any given height (Figure 3.11).

\[
E_p = mgh
\]

Figure 3.11: The potential energy of the block is equal to the product of its mass, the strength of gravity, and the height the block can fall from.
**Kinetic energy**

**Kinetic energy is energy of motion**

Objects that are moving also have the ability to cause change. Energy of motion is called **kinetic energy**. A moving billiard ball has kinetic energy because it can hit another object and change its motion. Kinetic energy can easily be converted into potential energy. The kinetic energy of a basketball tossed upward converts into potential energy as the height increases.

**Kinetic energy can do work**

The amount of kinetic energy an object has equals the amount of work the object can do by exerting force as it stops. Consider a moving skateboard and rider (Figure 3.12). Suppose it takes a force of 500 N applied over a distance of 10 meters to slow the skateboard down to a stop (500 N × 10 m = 5,000 joules). The kinetic energy of the skateboard and rider is 5,000 joules since that is the amount of work it takes to stop the skateboard.

**Kinetic energy depends on mass and speed**

If you had started with twice the mass — say, two skateboarders — you would have to do twice as much work to stop them both. Kinetic energy increases with mass. If the skateboard board and rider are moving faster, it also takes more work to bring them to a stop. This means kinetic energy also increases with speed. Kinetic energy is related to both an object’s speed and its mass.

**The formula for kinetic energy**

The kinetic energy of a moving object is equal to one half its mass multiplied by the square of its speed. This formula comes from a combination of relationships, including Newton’s second law, the distance equation for acceleration \( d = \frac{1}{2}at^2 \), and the calculation of energy as the product of force and distance.

\[
E_k = \frac{1}{2}mv^2
\]

where

- \( E_k \) is kinetic energy (joules)
- \( m \) is mass (kg)
- \( v \) is speed (m/sec)

**Figure 3.12:** The amount of kinetic energy the skateboard has is equal to the amount of work the moving board and rider can do as they come to a stop.
Kinetic energy increases as the square of the speed. This means that if you go twice as fast, your energy increases by four times \( (2^2 = 4) \). If your speed is three times as fast, your energy is nine times bigger \( (3^2 = 9) \). A car moving at a speed of 100 km/h (62 mph) has *four times* the kinetic energy it had when going 50 km/h (31 mph). At a speed of 150 km/h (93 mph), it has *nine times* as much energy as it did at 50 km/h. The stopping distance of a car is proportional to its kinetic energy. A car going twice as fast has four times the kinetic energy and needs four times the stopping distance. This is why driving at high speeds is so dangerous.

Potential and kinetic energy

A 2 kg rock is at the edge of a cliff 20 meters above a lake. It becomes loose and falls toward the water below. Calculate its potential and kinetic energy when it is at the top and when it is halfway down. Its speed is 14 m/sec at the halfway point.

1. **Looking for:** You are asked for the potential and kinetic energy at two locations.

2. **Given:** You are given the mass in kilograms, the height at each location in meters, and the speed halfway down in m/sec. You can assume the initial speed is 0 m/sec because the rock starts from rest.

3. **Relationships:**

   \[ E_p = mgh \quad \text{and} \quad E_k = \frac{1}{2}mv^2 \]

4. **Solution:**

   Potential energy at the top: \( m = 2 \text{ kg}, \ g = 9.8 \text{ N/kg}, \ \text{and} \ h = 20 \text{ m} \)
   \[ E_p = (2 \text{ kg})(9.8 \text{ N/kg})(20 \text{ m}) = 392 \text{ J} \]

   Potential energy halfway down: \( m = 2 \text{ kg}, \ g = 9.8 \text{ N/kg}, \ \text{and} \ h = 10 \text{ m} \)
   \[ E_p = (2 \text{ kg})(9.8 \text{ N/kg})(10 \text{ m}) = 196 \text{ J} \]

   Kinetic energy at the top: \( m = 2 \text{ kg} \ \text{and} \ v = 0 \text{ m/sec} \)
   \[ E_k = \frac{1}{2}(2 \text{ kg})(0^2) = 0 \text{ J} \]

   Kinetic energy halfway down: \( m = 2 \text{ kg} \ \text{and} \ v = 14 \text{ m/sec} \)
   \[ E_k = \frac{1}{2}(2 \text{ kg})(14 \text{ m/sec})^2 = 196 \text{ J} \]

**Your turn...**

a. Calculate the potential energy of a 4 kilogram cat crouched 3 meters off the ground. **Answer:** 117.6 J
b. Calculate the kinetic energy of a 4 kilogram cat running at 5 m/sec. **Answer:** 50 J
Conservation of energy

Energy converts from potential to kinetic

What happens when you throw a ball straight up in the air (Figure 3.14)? The ball leaves your hand with kinetic energy it gained while your hand accelerated it from rest. As the ball goes higher, it gains potential energy. However the ball slows down as it rises so its kinetic energy decreases. The increase in potential energy is exactly equal to the decrease in kinetic energy. The kinetic energy converts into potential energy, and the ball’s total energy stays the same.

Law of conservation of energy

The idea that energy converts from one form into another without a change in the total amount is called the law of conservation of energy. The law states that energy can never be created or destroyed, just converted from one form into another. The law of conservation of energy is one of the most important laws in physics. It applies to not only kinetic and potential energy, but to all forms of energy.

Energy can never be created or destroyed, just converted from one form into another

Using energy conservation

The law of conservation of energy explains how a ball’s launch speed affects its motion. As the ball in Figure 3.14 moves upward, it slows down and loses kinetic energy. Eventually it reaches a point where all the kinetic energy has been converted to potential energy. The ball has moved as high as it will go and its upward speed has been reduced to zero. If the ball had been launched with a greater speed, it would have started with more kinetic energy. It would have had to climb higher for all of the kinetic energy to be converted into potential energy. If the exact launch speed is given, the law of conservation of energy can be used to predict the height the ball reaches.

Energy converts from kinetic to potential

The ball’s conversion of energy on the way down is opposite what it was on the way up. As the ball falls, its speed increases and its height decreases. The potential energy decreases as it converts into kinetic energy. If gravity is the only force acting on the ball, it returns to your hand with exactly the same speed and kinetic energy it started with — except that now it moves in the opposite direction.

Figure 3.14: When you throw a ball in the air, the energy transforms from kinetic to potential and then back to kinetic.
Using energy conservation to solve problems

Energy conservation is a direct way to find out what happens before and after a change (Figure 3.15) from one form of energy into another. The law of energy conservation says the total energy before the change equals the total energy after it. In many cases (with falling objects, for instance), you need not worry about force or acceleration. Applying energy conservation allows you to find speeds and heights very quickly.

**How to use energy conservation**

**Before change**

**Change**

**After change**

**Total energy = Total energy**

**Figure 3.15: Applying energy conservation.**

A 2 kg car moving with a speed of 2 m/sec starts up a hill. How high does the car roll before it stops?

1. **Looking for:** You are asked for the height.
2. **Given:** You are given the mass in kilograms, and starting speed in m/sec.
3. **Relationships:** From the law of conservation of energy, the sum of kinetic and potential energy is constant. The ball keeps going uphill until all its kinetic energy has been turned into potential energy.

\[
E_K = \frac{1}{2}mv^2, \quad E_P = mg \cdot h
\]

4. **Solution:**

Find the kinetic energy at the start:

\[
E_K = \frac{1}{2}(2 \text{ kg})(2 \text{ m/sec})^2 = 4 \text{ J}
\]

Use the potential energy to find the height

\[
mgh = 4 \text{ J} \quad \text{therefore:}
\]

\[
h = \frac{4 \text{ J}}{(2 \text{ kg})(9.8 \text{ N/kg})}
\]

\[
= 0.2 \text{ m}
\]

The car rolls upward to a height of 0.2 m above where it started.

**Your turn...**

a. A 500 kg roller coaster car starts from rest at the top of a 60-meter hill. Find its potential energy when it is halfway to the bottom. **Answer:** 147,000 J

b. A 1 kg ball is tossed straight up with a kinetic energy of 196 J. How high does it go? **Answer:** 20 m
“Using” and “conserving” energy in the everyday sense

“Conserving” energy
Almost everyone has heard that is good to “conserve energy” and not waste it. This is good advice because energy from gasoline or electricity costs money and uses resources. But what does it mean to “use energy” in the everyday sense? If energy can never be created or destroyed, how can it be “used up”? Why do smart people worry about “running out” of energy?

“Using” energy
When you “use” energy by turning on a light, you are really converting energy from one form (electricity) to other forms (light and heat). What gets “used up” is the amount of energy in the form of electricity. Electricity is a valuable form of energy because it is easy to move over long distances (through wires). In the “physics” sense, the energy is not “used up” but converted into other forms. The total amount of energy stays constant.

Power plants
Electric power plants don’t make electrical energy. Energy cannot be created. What power plants do is convert other forms of energy (chemical, solar, nuclear) into electrical energy. When someone advises you to turn out the lights to conserve energy, they are asking you to use less electrical energy. If people used less electrical energy, power plants would burn less oil, gas, or other fuels in “producing” the electrical energy they sell.

“Running out” of energy
Many people are concerned about “running out” of energy. What they worry about is running out of certain forms of energy that are easy to use, such as oil and gas. When you use gas in a car, the chemical energy in the gasoline mostly becomes heat energy. It is impractical to put the energy back into the form of gasoline, so we say the energy has been “used up” even though the energy itself is still there, only in a different form.

3.2 Section Review
1. What are the units of energy and what do they mean?
2. What is work in physics and what is the relationship between work and energy?
3. How can you increase an object’s potential or kinetic energy?
4. What happens to the kinetic and potential energy of a ball as it falls toward the ground?
5. Explain what it means to say energy is conserved.
3.3 Collisions

A collision occurs when two or more objects hit each other. When we hear the word collision, we often picture cars crashing. But a collision also takes place when a tennis ball hits a racket, your foot hits the ground, or your fingers press on a keyboard. During a collision, momentum and energy are transferred from one object to another. Different factors like mass, initial velocity, and the type of collision determine the velocity of objects after they collide. In this section, you will learn about the two types of collisions, elastic and inelastic, and the momentum and energy changes that result.

Elastic and inelastic collisions

Elastic collisions

There are two main types of collisions, elastic and inelastic. When an elastic collision occurs, objects bounce off each other with no loss in the total kinetic energy of the system. The total kinetic energy before the collision is the same as the total kinetic energy after the collision. The collision between billiard balls is very close to a perfectly elastic collision (Figure 3.16).

Inelastic collisions

In an inelastic collision, objects change shape or stick together, and the total kinetic energy of the system decreases. The energy is not destroyed, but it is transformed into forms other than kinetic energy, such as permanently changing shape. An egg hitting the floor is one example of an inelastic collision; two vehicles colliding is another. In both cases, some of the kinetic energy is used to permanently change an object’s shape.

Perfectly elastic collisions

Collisions you see in everyday life are mixed. When two billiard balls collide, it looks like they bounce without a loss of kinetic energy. But the sound of the collision tells you a small amount of kinetic energy is being changed into sound energy. However, we approximate the collision as elastic because it is more like an elastic collision than an inelastic one. The balls bounce and do not change shape. Perfectly elastic collisions do occur on a smaller scale. The collision between two individual atoms in the air is an example of a perfectly elastic collision. No kinetic energy is transformed into heat or sound. These collisions are responsible for the air pressure that keeps a balloon inflated.

Vocabulary

collision, elastic collision, inelastic collision

Objectives

✓ Distinguish between elastic and inelastic collisions.
✓ Use momentum conservation to solve collision problems.
✓ Explain how momentum, impulse, force, and time are related.

Figure 3.16: The collision of two billiard balls is elastic. The collision of an egg with the floor is inelastic.
Momentum conservation in collisions

Elastic and inelastic collisions

As long as there are no outside forces (such as friction), momentum is conserved in both elastic and inelastic collisions. This is true even when kinetic energy is not conserved. Conservation of momentum makes it possible to determine the motion of objects before or after colliding.

Problem-solving steps

Using momentum to analyze collisions takes practice. Use the steps below to help you find solutions to problems.

1. Draw a diagram.
2. Decide whether the collision is elastic or inelastic.
3. Assign variables to represent the masses and velocities of the objects before and after the collision.
4. Use momentum conservation to write an equation stating that the total momentum before the collision equals the total after. Then solve it.

Problem-solving steps

An 8,000-kg train car moves to the right at 10 m/sec. It collides with a 2,000-kg parked train car (Figure 3.17). The cars get stuck together and roll along the track. How fast do they move after the collision?

1. Looking for: You are asked for the velocity of the train cars after the collision.
2. Given: You are given both masses in kilograms and the initial velocity of the moving car in m/sec. You know the collision is inelastic because the cars get stuck together.
3. Relationships: Apply the law of conservation of momentum. Because the two cars get stuck together, consider them to be a single giant train car after the collision. The final mass is the sum of the two individual masses. initial momentum of car 1 + initial momentum of car 2 = final momentum of combined cars

\[ m_1v_1 + m_2v_2 = (m_1+m_2)v_3 \]

4. Solution: \[ (8,000 \text{ kg})(10 \text{ m/sec}) + (2,000 \text{ kg})(0 \text{ m/sec}) = (8,000 \text{ kg} + 2,000 \text{ kg})v_3 \]

\[ v_3 = 8 \text{ m/sec} \] The train cars move to the right together at 8 m/sec.

Your turn...
a. Repeat the above problem but with each car having a mass of 2000 kg. Answer: 5 m/sec
b. A 5-kg bowling ball with a velocity of +10 m/sec hits a stationary 2-kg bowling pin. If the ball’s final velocity is +8 m/sec, what is the pin’s final velocity? Answer: +5 m/sec
Forces in collisions

Collisions involve forces
Collisions create forces because the colliding objects change their motion. Since collisions take place quickly, the forces change rapidly and are hard to measure directly. However, momentum conservation can be used to estimate the forces in a collision. Engineers need to know the forces so they can design things not to break when they are dropped.

Force and collisions
A rubber ball and a clay ball are dropped on a gymnasium floor (Figure 3.18). The rubber ball has an elastic collision and bounces back up with the same speed it had when it hit the floor. The clay ball has an inelastic collision, hitting the floor with a thud and staying there. Both balls have the same mass and are dropped from the same height. They have the same speed as they hit the floor. Which ball exerts a greater force on the floor?

Force changes momentum
The total change in momentum is equal to the force multiplied by the time during which the force acts. Because force and time appear as a pair, we define the impulse to be the product of force and time.

Bounces have greater momentum change
Suppose each ball shown in Figure 3.18 has a mass of 1 kilogram and hits the floor at a velocity of -5 m/sec (negative is downward). The momentum of the clay ball changes from -5 kg·m/sec to zero. This is a change of 5 kg·m/sec. The rubber ball also starts with a momentum of -5 kg·m/sec. If the collision is perfectly elastic, it bounces up with the same momentum but in the opposite direction. Its momentum then goes from -5 kg·m/sec to +5 kg·m/sec, a change of +10 kg·m/sec. The rubber ball (elastic collision) has twice the change in momentum (Figure 3.19). The momentum change is always greater when objects bounce compared with when they do not bounce.

Bouncing vs. stopping
Because we don’t know the collision times, it is impossible to calculate the forces exactly. We can only say for certain that the impulse (force × time) is 10 N·sec for the rubber ball. This could be a force of 10 N for 1 second, or 100 N for 0.1 seconds, or any combination that results in 10 N·sec. However, we can be pretty sure the force from the rubber ball is greater because the momentum of the rubber ball changed twice as much as the momentum of the clay ball. Bouncing nearly always results in a greater force than just stopping because bouncing creates a larger change in momentum.

Figure 3.18: Bouncing results in a greater change in momentum and therefore almost always creates a greater force.

Figure 3.19: A number line can help you see clearly that a change from -5 to +5 is twice as great as a change from -5 to 0.
Solving impulse problems

Impulse can be used to solve many practical problems. For example, how much force does it take to stop a 1,000-kilogram car in 10 seconds if the car is moving at 30 m/sec (67 mph)? To solve this kind of problem, calculate the change in momentum, then use the impulse to calculate the force. For the car, the change in momentum is 30,000 kg·m/sec (1,000 kg × 30 m/sec). That means the impulse must be 30,000 N·sec. Since you know the time is 10 seconds, the force is 3,000 N because 3,000 N × 10 sec = 30,000 N·sec.

Collision force problems

If you know the time during which the colliding objects touch each other you can calculate the average force of the collision. The maximum force is larger than the average because forces in collisions tend to rise as the colliding objects come together, reach a maximum, and then drop off as the objects move apart. However, knowing the average force is useful.

Why does impulse equal the force multiplied by the time?

To find the relationship between momentum, force, and time, start with Newton’s second law:

\[ F = ma \]

Substituting for acceleration:

\[ F = m \frac{(v_2 - v_1)}{t} \]

Rearranging:

\[ Ft = m(v_2 - v_1) \]

\[ Ft = mv_2 - mv_1 \]

Therefore the change in momentum (impulse) equals the product of the force and time.

Impulse

A 1 kg clay ball hits the floor with a velocity of -5 m/sec and comes to a stop in 0.1 second. What force did the floor exert on it?

2. Given:

You are given the ball’s mass, initial speed, final speed, and stopping time.

3. Relationships:

\[ Ft = mv_2 - mv_1 \]

4. Solution:

\[ F(0.1 \text{ sec}) = (1 \text{ kg})(0 \text{ m/sec}) - (1 \text{ kg})(-5 \text{ m/sec}) \]

\[ F(0.1 \text{ sec}) = 5 \text{ kg·m/sec} \]

\[ F = 50 \text{ N} \]

Your turn...

a. What braking force is needed to stop a 1000 kg car moving at 30 m/sec in a time of 2 seconds? Answer: 15,000 N

b. You pedal your bicycle with a force of 40 N. If you start from rest and have a mass of 50 kg, what is your final speed after 10 seconds? Answer: 8 m/sec
Car crash safety

Stopping in an accident
The relationship between impulse, force, and time has been used by auto manufacturers to make vehicles safer in accidents. When a car crashes to a stop, its momentum drops to zero. The shorter the amount of stopping time, the greater the force on the car. Car bodies are designed to crumple in an accident to extend the stopping time. The ideal car crumples enough to stop gradually, but not so much that the passenger compartment is affected.

Seat belts
The stopping time of a car in a collision is very short even when crumpling occurs. A passenger without a seat belt will have a momentum that drops from a large value to zero when hitting the windshield, steering wheel, or dashboard. Seat belts are made of a very strong fabric that stretches slightly when a force is applied. Stretching extends the time over which the passenger comes to a stop and results in less force being exerted on the person’s body.

Air bags
Air bags work together with seat belts to make cars safer (Figure 3.20). An air bag inflates when the force applied to the front of a car reaches a dangerous level. The air bag deflates slowly as the person’s body applies a force to the bag upon impact. The force of impact pushes the air out of small holes in the air bag, bringing the person to a gradual stop. Many cars now contain both front and side air bags.

Crash test dummies
Automakers use crash test dummies to study the effects of collisions on passengers (Figure 3.21). Crash test dummies contain electronic sensors to measure the forces felt in various places on the body. Results of these tests have been used to make changes in automobile design, resulting in cars that are much safer than they were in the past.

3.3 Section Review
1. List three examples of elastic collisions and three examples of inelastic collisions not mentioned in this chapter.
2. Are momentum and kinetic energy conserved in all collisions?
3. What is the definition of impulse?
4. Why will an egg break if it is dropped on the ground but not if it is dropped on a pillow?
Rockets: Out of This World Travel

What if you wanted to travel to space? What type of vehicle would get you there? Your vehicle would need to reach incredible speeds to travel huge distances. Speed is also important in overcoming the gravitational pull of planets, moons, and the sun. Your vehicle would need to be able to travel in a vacuum because space has no air. It would also need a very powerful engine to get into space.

So what would be your vehicle of choice? A rocket, of course!

Rockets and Newton's 3r'd law

A rocket is a vehicle with a special type of engine. The basic principle behind how a rocket works is Newton’s third law, for every action, there is an equal and opposite reaction.

What happens when you blow up party balloon, then let it go, allowing the air to blow out the open end? The balloon darts around the room, travelling through the air. With the balloon, the action is the air being expelled. The reaction is the movement of the balloon in the opposite direction. Another example is the movement of squid. A squid takes water into its body chamber and rapidly expels it out of backward-directed tube. What are the action and reaction forces in this example?

Rocket science

The action/reaction forces demonstrated by the balloon and squid, are the main idea behind how a rocket engine works. A rocket engine forces material out the nozzle in one direction causing the rocket to move in the opposite direction.

The mass that is ejected in a rocket’s exhaust is the same as the mass of fuel that is burned. The speed of the fuel is very high, often more than 1,000 meters per second. Since the backward-moving fuel carries negative momentum, the rocket must increase its positive momentum to keep the total momentum constant.

To break free from Earth’s gravity and get into space, a rocket must reach a speed of over 40,250 kilometers per hour (called escape velocity). Attaining this speed requires a rocket engine to achieve the greatest possible action force, or thrust, in the shortest time. To do this, the engine must burn a large mass of fuel and push the gas out as fast as possible. The fuel required to achieve this thrust weighs over 30 times more than the rocket and its payload (what it carries). Rockets that travel into space are so huge because you need to carry lots of fuel!
Rocket scientists

Robert Goddard (1882 to 1945), an American scientist, concluded that it was possible to travel to space by applying the kind of thrust demonstrated by the balloon example. Goddard was able to take his ideas beyond theory and actually designed and built rockets. In fact he launched the first liquid-fueled rocket in 1926. Perhaps more importantly, Goddard proved rockets can propel objects in a vacuum. This touched off a revolution in thinking about space travel that continues to this day. His patents and technology innovations would solve the large problems of rockets in space. There are over 200 patents from Goddard's work.

A little help from gravity

In August 2004, NASA launched MESSENGER, a spacecraft headed for the planet Mercury. The entire trip will cover almost 7.9 billion kilometers (5.9 billion miles) rounding the sun 15 times. At 1,100 kilograms, MESSENGER is considered lightweight for a rocket. While more than half of the weight is fuel, it would not be enough to cover this great distance without some external help. Thankfully, not all of the trip is to be powered by the energy of the rocket. MESSENGER will get a slight boost from the sun and different planets it passes.

While rocket technology will continue to power the space exploration industry for years to come, we need to develop newer energy sources or whole new technologies to take us deeper into space. Scientists estimate that if we were to travel to distant regions of our own solar system using today's fuel technologies, 99% of the spacecraft launch weight would have to be fuel and only 1% would be payload. Can you think of ways to do this without having to carry so much fuel on board?

The future of rockets

Some new technologies being developed and tested for deep space travel minimize the fuel storage burden, by having their energy sources located behind them. One of these technologies uses the particles from the sun as a "wind" to accelerate the spacecraft like a sail boat. Another idea uses extremely light gases for fuels to reduce the mass required and increase the distances that can be covered. Still another idea is to find ways to accelerate atomic particles to extremely high speeds, creating thrust more efficiently. Even with these advanced technologies, all rockets rely on the ideas in Newton’s laws.

Questions:
1. Is a rocket’s thrust the action or reaction force?
2. Why are rockets for deep space travel so huge?
3. How is a rocket engine different than an automobile engine?
4. What are the major obstacles to bringing humans deeper into space?
Chapter 3 Review

Understanding Vocabulary

Select the correct term to complete the sentences.

<table>
<thead>
<tr>
<th>energy</th>
<th>momentum</th>
<th>elastic collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>work</td>
<td>inelastic collision</td>
<td>kinetic energy</td>
</tr>
<tr>
<td>Newton’s third law</td>
<td>joule</td>
<td>potential energy</td>
</tr>
<tr>
<td>law of conservation of energy</td>
<td>collision</td>
<td>impulse</td>
</tr>
</tbody>
</table>

Section 3.1

1. The ____ states that the total amount of momentum in a closed system cannot change.

2. ____ is calculated by multiplying a force and the time needed for the force to act.

3. According to ____ , for every action force, there is a reaction force equal in strength and opposite in direction.

4. The mass of an object multiplied by its velocity equals its ____.

Section 3.2

5. The ____ states that energy can never be created or destroyed, just changed from one form to another.

6. The unit of energy needed to push with a force of one newton over a distance of one meter is one ____.

7. Energy due to position is known as ____.

8. Energy of motion is called ____.

9. ____ is needed to cause change to an object, such as changing its speed or height.

10. ____ is force times distance moved in the direction of the force.

Section 3.3

11. When two or more objects hit each other, a ____ occurs.

12. When two objects collide and stick together or change shape, it is called a(n) ____.

13. Two billiard balls bouncing off each other is an example of a(n) ____.

Reviewing Concepts

Section 3.1

1. State Newton’s third law in your own words.

2. Action and reaction forces always have the _____ strength and act in _____ directions.

3. You and a friend are sitting across from each other on chairs with wheels. You push off each other and move in opposite directions. Explain the following:
   a. How does the force you feel compare to the force your friend feels?
   b. If your mass is greater than your friend’s mass, how do your accelerations compare?


5. Give three examples of Newton’s third law in everyday life. List the action and reaction forces in each example.

6. What two things does an object require to have momentum?

7. Consider an airplane at rest and a person walking through the airport.
   a. Which has greater mass?
   b. Which has greater velocity?
   c. Which has greater momentum? Explain.

8. Explain the two different ways to calculate impulse.

9. Is the unit used represent impulse the same as the unit for momentum? Explain.

10. State the law of conservation of momentum in your own words.

11. You and your little cousin are standing on inline skates. You push off of each other and both move backwards.
   a. Which of you moves back at a greater speed? Use the law of conservation of momentum to explain your answer.
   b. How does your impulse compare to your cousin’s impulse?

12. When you jump, you move upward with a certain amount of momentum. Earth moves downward with an equal amount of momentum. Why doesn’t anyone notice the Earth’s motion?
Section 3.2
13. What is anything with energy able to do?
14. The joule is an abbreviation for what combination of units?
15. When work is done, _____ is transferred.
16. How can you increase the gravitational potential energy of an object?
17. Explain why a bicycle at rest at the top of a hill has energy.
18. Which two quantities are needed to determine an object’s kinetic energy?
19. What happens to a car’s kinetic energy if its speed doubles? What if its speed triples?
20. A ball is thrown up into the air. Explain what happens to its potential and kinetic energies as it moves up and then back down.
21. Explain what it means to say energy is conserved as a ball falls toward the ground.
22. Will we ever run out of energy on Earth? Might we run out of certain forms of energy? Explain.

Section 3.3
23. Distinguish between elastic and inelastic collisions.
24. Classify each collision as elastic or inelastic.
   a. A dog catches a tennis ball in his mouth.
   b. A ping-pong ball bounces off a table.
   c. You jump on a trampoline.
   d. A light bulb is knocked onto the floor and breaks.

26. Why does bouncing nearly always cause a greater force than simply stopping during a collision?
27. Cars that crumple in a collision are safer than cars that bounce when they collide. Explain why this is so.
28. What is the secret to catching a water balloon without breaking it? Explain using physics.

Solving Problems

Section 3.1
1. You throw a basketball by exerting a force of 20 newtons. According to Newton’s third law, there is another 20-newton force created in the opposite direction. If there are two equal forces in opposite directions, how does the ball accelerate?
2. What is the momentum of a 2-kg ball traveling at 4 m/sec?
3. How fast does a 1000 kg car have to move to have a momentum of 50,000 kg-m/sec?
4. Idil’s momentum is 110 kg-m/sec when she walks at 2 m/sec. What’s her mass?
5. Which has more momentum: a 5000-kg truck moving at 10 m/sec or a sports car with a mass of 1200 kg moving at 50 m/sec?
6. Two hockey players on ice skates push off of each other. One has a mass of 60 kilograms. The other has a mass of 80 kilograms.
   a. If the 80-kilogram player moves back with a velocity of 3 m/sec, what is his momentum?
   b. What is the 60-kilogram player’s momentum?
   c. What is the 60-kilogram player’s velocity?
7. A 75 kg astronaut floating in space throws a 5 kg rock at 5 m/sec. How fast does the astronaut move backwards?
8. A 2-kilogram ball is accelerated from rest to a speed of 8 m/sec.
   a. What is the ball’s change in momentum?
   b. What is the impulse?
   c. A constant force of 32 newtons is used to change the momentum. For how much time does the force act?

9. A 1000-kg car uses a braking force of 10,000 N to stop in 2 seconds.
   a. What impulse acts on the car?
   b. What is the change in momentum of the car?
   c. What was the initial speed of the car?

Section 3.2

10. A 5-kg can of paint is sitting on top of a 2-meter high step ladder. How much work did you do to move the can of paint to the top of the ladder? What is the potential energy of the can of paint?

11. How much work is done to move a 10,000-N car 20 meters?

12. Which has more potential energy, a 5 kg rock lifted 2 meters off the ground on Earth, or the same rock lifted 2 meters on the moon? Why?

13. At the end of a bike ride up a mountain, Chris was at an elevation of 500 meters above where he started. If Chris’s mass is 60 kg, by how much did his potential energy increase?

14. Alexis is riding her skateboard. If Alexis has a mass of 50 kg:
   a. What is her kinetic energy if she travels at 5 m/sec?
   b. What is her kinetic energy if she travels at 10 m/sec?
   c. Alexis’s 50 kg dog Bruno gets on the skateboard with her. What is their total kinetic energy if they move at 5 m/sec?
   d. Based on your calculations, does doubling the mass or doubling the speed have more of an effect on kinetic energy?

15. A 1-kilogram coconut falls out of a tree from a height of 12 meters. Determine the coconut’s potential and kinetic energy at each point shown in the picture. Its speed is zero at point A.

16. A demolition derby is a car-crashing contest. Suppose an 800-kg car moving at 20 m/sec crashes into the back of and sticks to a 1200-kg car moving at 10 m/sec in the same direction.
   a. Is this collision elastic or inelastic? Why?
   b. Calculate the momentum of each car before the collision.
   c. What is the total momentum of the stuck together cars after the collision? Why?
   d. What is the speed of the stuck together cars after the collision?
17. A 5-kg ball moving at 6 m/sec collides with a 1-kg ball at rest. The balls bounce off each other and the second ball moves in the same direction as the first ball at 10 m/sec. What is the velocity of the first ball after the collision?

18. Yanick and Nancy drive two identical 1500-kilogram cars at 20 m/sec. Yanick slams on the brakes and his car comes to a stop in 1 second. Nancy lightly applies the brakes and stops her car in 5 seconds.
   a. How does the momentum change of Yanick’s car compare to the momentum change of Nancy’s car?
   b. How does the impulse on Yanick’s car compare to the impulse on Nancy’s car?
   c. How does the force of Yanick’s brakes compare to the force of Nancy’s brakes?
   d. Calculate the stopping force for each car.

19. Your neighbor’s car breaks down. You and a friend agree to push it two blocks to a repair shop while your neighbor steers. The two of you apply a net force of 800 newtons to the 1000-kilogram car for 10 seconds.
   a. What impulse is applied to the car?
   b. At what speed is the car moving after 10 seconds? The car starts from rest.

**Applying Your Knowledge**

**Section 3.1**

1. Think up some strange scenarios that might happen if the universe changed so that Newton’s third law were no longer true.

2. Identify at least three action-reaction force pairs in the picture of the firefighter below.

3. The greatest speed with which an athlete can jump vertically is around 5 m/sec. Determine the speed at which Earth would move down if you jumped up at 5 m/sec.

**Section 3.2**

4. A car going twice as fast requires four times as much stopping distance. What is it about the kinetic energy formula that accounts for this fact?

5. The energy is food is measured in Calories rather than joules. One Calorie is equal to 4187 joules. Look on the nutrition labels of three of your favorite foods. Determine the amount of energy in joules in one serving of each type of food.

**Section 3.3**

6. Major League Baseball requires players to use wooden bats, and does not allow the use of aluminum bats. Research to find out why this is. Relate what you find to what you learned in this chapter.

7. Use the internet to learn more about how cars are designed to be safer in collisions and how they are tested. Make a poster that summarizes what you learn.