ENERGY AND ENVIRONMENT



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Energy and Environment

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TABLE OF CONTENTS

Licensing

1: The Nature of Science

- 1.1: Prelude to Science and the Realm of Physics, Physical Quantities, and Units
- 1.2: An Introduction
- 1.3: Physical Quantities and Units
- 1.4: Accuracy, Precision, and Significant Figures
- 1.5: Approximation
- 1.E: The Nature of Science and Physics (Exercises)

2: Introduction to Environmental Sciences

- 2.1: The Chemical Foundations of Life
- 2.2: Biological Molecules
- 2.3: Biological Organization
- 2.4: Environment and environmental science
- 2.5: Sustainability and Sustainable Development
- 2.6: Appendix

3: Population Ecology

- 3.1: Introduction
- 3.2: Population Growth Models
- 3.3: Factors Limiting Population Growth
- 3.4: Life Tables and Survivorship
- 3.5: Population Ecology Practice Problems

4: Human Demography

- 4.1: The Human Population
- 4.2: Demography
- 4.3: Age structure diagrams
- 4.4: The Demographic Transition Model
- 4.5: Life Expectancy
- 4.6: Fertility
- 4.7: Appendix

5: Motion and Forces

- 5.1: Kinematics
  - 5.1.1: Introduction to One-Dimensional Kinematics
  - 5.1.2: Displacement
  - 5.1.3: Vectors, Scalars, and Coordinate Systems
  - 5.1.4: Time, Velocity, and Speed
  - 5.1.5: Acceleration
  - 5.1.6: Motion Equations for Constant Acceleration in One Dimension
  - 5.1.7: Falling Objects
  - 5.1.8: Projectile Motion

- 5.1.9: Centripetal Acceleration
- 5.1.E: Kinematics (Exercise)
- 5.2: Dynamics
  - 5.2.1: Introduction to Dynamics- Newton's Laws of Motion
  - 5.2.2: Development of Force Concept
  - 5.2.3: Newton's First Law of Motion- Inertia
  - 5.2.4: Newton's Second Law of Motion- Force and Acceleration
  - 5.2.5: Newton's Third Law of Motion- Symmetry in Forces
  - 5.2.6: Normal Force and Tension
  - 5.2.7: Spring Force- Hooke's Law
  - 5.2.8: Friction
  - 5.2.9: Newton's Universal Law of Gravitation
  - 5.2.10: Centripetal Force
  - 5.2.E: Dynamics (Exercise)

6: Energy

- 6.1: What is Energy?
- 6.2: Work and Kinetic Energy
- 6.3: Potential Energy
- 6.4: Chemical Energy
- 6.5: Thermal Energy

7: Non-Renewable Energy

- 7.1: Fossil Fuels
- 7.2: Coal
- 7.3: Oil
- 7.4: Natural Gas
- 7.5: Fossil Fuels and Greenhouse Gases
- 7.6: Nuclear Energy
- 7.7: Electric Power Generation
- 7.8: Appendix

8: Alternative Energy

- 8.1: Introduction
- 8.2: Solar Energy
- 8.3: Biomass Energy
- 8.4: Wind Power
- 8.5: Geothermal Power
- 8.6: Hydroelectric Power (Hydropower)
- 8.7: Other Alternative Renewable Energy Sources
- 8.8: Policy and Conservation
- 8.9: Appendix

9: Air Pollution

- 9.1: Composition and Structure of the Atmosphere
- 9.2: Ozone
- 9.3: Outdoor Air Pollution
- 9.4: Indoor Air Pollution

- 9.5: Effects of Air Pollution on Human Health
- 9.6: Acid Rain
- 9.7: Air Pollution Legislation
- 9.8: Appendix

10: Climate Change

- 10.1: The Carbon Cycle
- 10.2: Human Impacts on the Carbon Cycle
- 10.3: The Science of Climate Change
- 10.4: Greenhouse Gases
- 10.5: Tools Scientists Use to Study Climate Change
- 10.6: Consequences of Climate Change
- 10.7: Looking Forward- Climate Strategies

11: Water

- 11.1: Introduction
- 11.2: Properties of Water
- 11.3: Global Water Distribution Use
- 11.4: The Hydrologic Cycle
- 11.5: Water Scarcity and Storage
- 11.6: Water Quality (Pollution)
- 11.7: Water Management
- 11.8: Bibliography

Index

Glossary

Detailed Licensing

Detailed Licensing

Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

CHAPTER OVERVIEW

1: The Nature of Science

In this text, you will begin to explore the history of the formal study of physics, beginning with natural philosophy and the ancient Greeks, and leading up through a review of Sir Isaac Newton and the laws of physics that bear his name. You will also be introduced to the standards scientists use when they study physical quantities and the interrelated system of measurements most of the scientific community uses to communicate in a single mathematical language.

1.1: Prelude to Science and the Realm of Physics, Physical Quantities, and Units

1.2: An Introduction

1.3: Physical Quantities and Units

1.4: Accuracy, Precision, and Significant Figures

1.5: Approximation

1.E: The Nature of Science and Physics (Exercises)

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1.1: Prelude to Science and the Realm of Physics, Physical Quantities, and Units

What is your first reaction when you hear the word “physics”? Did you imagine working through difficult equations or memorizing formulas that seem to have no real use in life outside the physics classroom? Many people come to the subject of physics with a bit of fear. But as you begin your exploration of this broad-ranging subject, you may soon come to realize that physics plays a much larger role in your life than you first thought, no matter your life goals or career choice.



Figure 1.1.1: Galaxies are as immense as atoms are small. Yet the same laws of physics describe both, and all the rest of nature—an indication of the underlying unity in the universe. The laws of physics are surprisingly few in number, implying an underlying simplicity to nature’s apparent complexity. (credit: NASA, JPL-Caltech, P. Barmby, Harvard-Smithsonian Center for Astrophysics)

For example, take a look at the image above. This image is of the Andromeda Galaxy, which contains billions of individual stars, huge clouds of gas, and dust. Two smaller galaxies are also visible as bright blue spots in the background. At a staggering 2.5 million light years from the Earth, this galaxy is the nearest one to our own galaxy (which is called the Milky Way). The stars and planets that make up Andromeda might seem to be the furthest thing from most people’s regular, everyday lives. But Andromeda is a great starting point to think about the forces that hold together the universe. The forces that cause Andromeda to act as it does are the same forces we contend with here on Earth, whether we are planning to send a rocket into space or simply raise the walls for a new home. The same gravity that causes the stars of Andromeda to rotate and revolve also causes water to flow over hydroelectric dams here on Earth. Tonight, take a moment to look up at the stars. The forces out there are the same as the ones here on Earth. Through a study of physics, you may gain a greater understanding of the interconnectedness of everything we can see and know in this universe.

Think now about all of the technological devices that you use on a regular basis. Computers, smart phones, GPS systems, MP3 players, and satellite radio might come to mind. Next, think about the most exciting modern technologies that you have heard about in the news, such as trains that levitate above tracks, “invisibility cloaks” that bend light around them, and microscopic robots that fight cancer cells in our bodies. All of these groundbreaking advancements, commonplace or unbelievable, rely on the principles of physics. Aside from playing a significant role in technology, professionals such as engineers, pilots, physicians, physical therapists, electricians, and computer programmers apply physics concepts in their daily work. For example, a pilot must understand how wind forces affect a flight path and a physical therapist must understand how the muscles in the body experience forces as they move and bend. As you will learn in this text, physics principles are propelling new, exciting technologies, and these principles are applied in a wide range of careers.

In this text, you will begin to explore the history of the formal study of physics, beginning with natural philosophy and the ancient Greeks, and leading up through a review of Sir Isaac Newton and the laws of physics that bear his name. You will also be introduced to the standards scientists use when they study physical quantities and the interrelated system of measurements most of the scientific community uses to communicate in a single mathematical language. Finally, you will study the limits of our ability to be accurate and precise, and the reasons scientists go to painstaking lengths to be as clear as possible regarding their own limitations.

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1.2: An Introduction

Learning Objectives

By the end of this section, you will be able to:

- Explain the difference between a principle and a law.
- Explain the difference between a model and a theory.

The physical universe is enormously complex in its detail. Every day, each of us observes a great variety of objects and phenomena. Over the centuries, the curiosity of the human race has led us collectively to explore and catalog a tremendous wealth of information. From the flight of birds to the colors of flowers, from lightning to gravity, from quarks to clusters of galaxies, from the flow of time to the mystery of the creation of the universe, we have asked questions and assembled huge arrays of facts. In the face of all these details, we have discovered that a surprisingly small and unified set of physical laws can explain what we observe. As humans, we make generalizations and seek order. We have found that nature is remarkably cooperative—it exhibits the *underlying order and simplicity* we so value.



Figure 1.2.1: The flight formations of migratory birds such as Canada geese are governed by the laws of physics. (credit: David Merrett)

It is the underlying order of nature that makes science in general, and physics in particular, so enjoyable to study. For example, what do a bag of chips and a car battery have in common? Both contain energy that can be converted to other forms. The law of conservation of energy (which says that energy can change form but is never lost) ties together such topics as food calories, batteries, heat, light, and watch springs. Understanding this law makes it easier to learn about the various forms energy takes and how they relate to one another. Apparently unrelated topics are connected through broadly applicable physical laws, permitting an understanding beyond just the memorization of lists of facts.

The unifying aspect of physical laws and the basic simplicity of nature form the underlying themes of this text. In learning to apply these laws, you will, of course, study the most important topics in physics. More importantly, you will gain analytical abilities that will enable you to apply these laws far beyond the scope of what can be included in a single book. These analytical skills will help you to excel academically, and they will also help you to think critically in any professional career you choose to pursue. This module discusses the realm of physics (to define what physics is), some applications of physics (to illustrate its relevance to other disciplines), and more precisely what constitutes a physical law (to illuminate the importance of experimentation to theory).

1.2.1: Science and the Realm of Physics

Science consists of the theories and laws that are the general truths of nature as well as the body of knowledge they encompass. Scientists are continually trying to expand this body of knowledge and to perfect the expression of the laws that describe it. **Physics** is concerned with describing the interactions of energy, matter, space, and time, and it is especially interested in what fundamental mechanisms underlie every phenomenon. The concern for describing the basic phenomena in nature essentially defines the *realm of physics*.

Physics aims to describe the function of everything around us, from the movement of tiny charged particles to the motion of people, cars, and spaceships. In fact, almost everything around you can be described quite accurately by the laws of physics. Consider a smart phone (Figure 1.2.2). Physics describes how electricity interacts with the various circuits inside the device. This knowledge helps engineers select the appropriate materials and circuit layout when building the smart phone. Next, consider a GPS

system. Physics describes the relationship between the speed of an object, the distance over which it travels, and the time it takes to travel that distance. When you use a GPS device in a vehicle, it utilizes these physics equations to determine the travel time from one location to another.



Figure 1.2.2: The Apple “iPhone” is a common smart phone with a GPS function. Physics describes the way that electricity flows through the circuits of this device. Engineers use their knowledge of physics to construct an iPhone with features that consumers will enjoy. One specific feature of an iPhone is the GPS function. GPS uses physics equations to determine the driving time between two locations on a map. (credit: @gletham GIS, Social, Mobile Tech Images)

1.2.1.0.1: Applications of Physics

You need not be a scientist to use physics. On the contrary, knowledge of physics is useful in everyday situations as well as in nonscientific professions. It can help you understand how microwave ovens work, why metals should not be put into them, and why they might affect pacemakers (Figures 1.2.3 and 1.2.4). Physics allows you to understand the hazards of radiation and rationally evaluate these hazards more easily. Physics also explains the reason why a black car radiator helps remove heat in a car engine, and it explains why a white roof helps keep the inside of a house cool. Similarly, the operation of a car’s ignition system as well as the transmission of electrical signals through our body’s nervous system are much easier to understand when you think about them in terms of basic physics.



Figure 1.2.3: The laws of physics help us understand how common appliances work. For example, the laws of physics can help explain how microwave ovens heat up food, and they also help us understand why it is dangerous to place metal objects in a microwave oven. (credit: MoneyBlogNewz)



Figure 1.2.4: These two applications of physics have more in common than meets the eye. Microwave ovens use electromagnetic waves to heat food. Magnetic resonance imaging (MRI) also uses electromagnetic waves to yield an image of the brain, from which the exact location of tumors can be determined. (credit: Rashmi Chawla, Daniel Smith, and Paul E. Marik)

Physics is the foundation of many important disciplines and contributes directly to others. Chemistry, for example—since it deals with the interactions of atoms and molecules—is rooted in atomic and molecular physics. Most branches of engineering are applied physics. In architecture, physics is at the heart of structural stability, and is involved in the acoustics, heating, lighting, and cooling of buildings. Parts of geology rely heavily on physics, such as radioactive dating of rocks, earthquake analysis, and heat transfer in the Earth. Some disciplines, such as biophysics and geophysics, are hybrids of physics and other disciplines.

Physics has many applications in the biological sciences. On the microscopic level, it helps describe the properties of cell walls and cell membranes (Figures 1.2.5 and 1.2.6). On the macroscopic level, it can explain the heat, work, and power associated with the human body. Physics is involved in medical diagnostics, such as x-rays, magnetic resonance imaging (MRI), and ultrasonic blood flow measurements. Medical therapy sometimes directly involves physics; for example, cancer radiotherapy uses ionizing radiation. Physics can also explain sensory phenomena, such as how musical instruments make sound, how the eye detects color, and how lasers can transmit information.

It is not necessary to formally study all applications of physics. What is most useful is knowledge of the basic laws of physics and a skill in the analytical methods for applying them. The study of physics also can improve your problem-solving skills. Furthermore, physics has retained the most basic aspects of science, so it is used by all of the sciences, and the study of physics makes other sciences easier to understand.

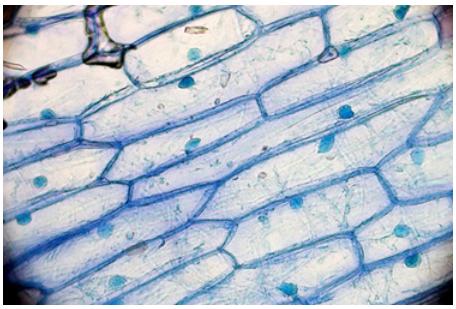


Figure 1.2.5: Physics, chemistry, and biology help describe the properties of cell walls in plant cells, such as the onion cells seen here. (credit: UmbertoSalvagnin)

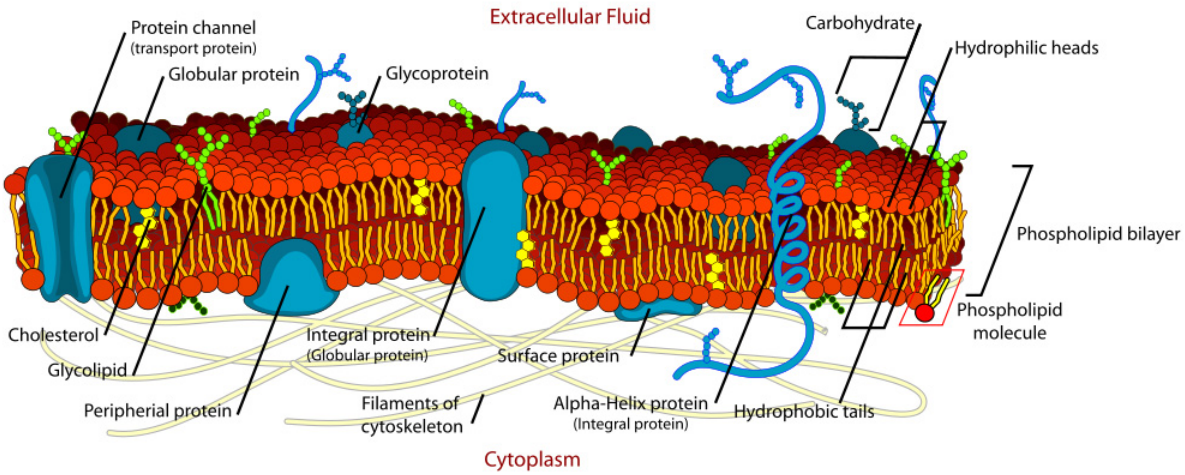


Figure 1.2.6: An artist's rendition of the the structure of a cell membrane. Membranes form the boundaries of animal cells and are complex in structure and function. Many of the most fundamental properties of life, such as the firing of nerve cells, are related to membranes. The disciplines of biology, chemistry, and physics all help us understand the membranes of animal cells. (credit: Mariana Ruiz)

1.2.2: Models, Theories, and Laws; The Role of Experimentation

The laws of nature are concise descriptions of the universe around us; they are human statements of the underlying laws or rules that all natural processes follow. Such laws are intrinsic to the universe; humans did not create them and so cannot change them. We can only discover and understand them. Their discovery is a very human endeavor, with all the elements of mystery, imagination, struggle, triumph, and disappointment inherent in any creative effort (Figures 1.2.7 and 1.2.8). The cornerstone of discovering natural laws is observation; science must describe the universe as it is, not as we may imagine it to be.

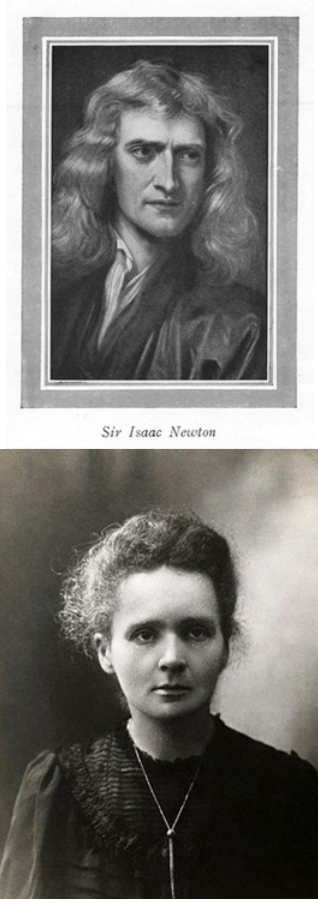


Figure 1.2.8: Marie Curie (1867–1934) sacrificed monetary assets to help finance her early research and damaged her physical well-being with radiation exposure. She is the only person to win Nobel prizes in both physics and chemistry. One of her daughters also won a Nobel Prize. (credit: Wikimedia Commons)

We all are curious to some extent. We look around, make generalizations, and try to understand what we see—for example, we look up and wonder whether one type of cloud signals an oncoming storm. As we become serious about exploring nature, we become more organized and formal in collecting and analyzing data. We attempt greater precision, perform controlled experiments (if we can), and write down ideas about how the data may be organized and unified. We then formulate models, theories, and laws based on the data we have collected and analyzed to generalize and communicate the results of these experiments.

A **model** is a representation of something that is often too difficult (or impossible) to display directly. While a model is justified with experimental proof, it is only accurate under limited situations. An example is the planetary model of the atom in which electrons are pictured as orbiting the nucleus, analogous to the way planets orbit the Sun. (See Figure 9.) We cannot observe electron orbits directly, but the mental image helps explain the observations we can make, such as the emission of light from hot gases (atomic spectra). Physicists use models for a variety of purposes. For example, models can help physicists analyze a scenario and perform a calculation, or they can be used to represent a situation in the form of a computer simulation. A theory is an explanation for patterns in nature that is supported by scientific evidence and verified multiple times by various groups of researchers. Some theories include models to help visualize phenomena, whereas others do not. Newton's theory of gravity, for example, does not require a model or mental image, because we can observe the objects directly with our own senses. The kinetic theory of gases, on the other hand, is a model in which a gas is viewed as being composed of atoms and molecules. Atoms and molecules are too small to be observed directly with our senses—thus, we picture them mentally to understand what our instruments tell us about the behavior of gases.

A **law** uses concise language to describe a generalized pattern in nature that is supported by scientific evidence and repeated experiments. Often, a law can be expressed in the form of a single mathematical equation. Laws and theories are similar in that they are both scientific statements that result from a tested hypothesis and are supported by scientific evidence. However, the designation*law* is reserved for a concise and very general statement that describes phenomena in nature, such as the law that energy

is conserved during any process, or Newton's second law of motion, which relates force, mass, and acceleration by the simple equation

$$F = ma. \tag{1.2.1}$$

A theory, in contrast, is a less concise statement of observed phenomena. For example, the Theory of Evolution and the Theory of Relativity cannot be expressed concisely enough to be considered a law. The biggest difference between a law and a theory is that a theory is much more complex and dynamic. A law describes a single action, whereas a theory explains an entire group of related phenomena. And, whereas a law is a postulate that forms the foundation of the scientific method, a theory is the end result of that process.

Less broadly applicable statements are usually called principles (such as Pascal's principle, which is applicable only in fluids), but the distinction between laws and principles often is not carefully made.

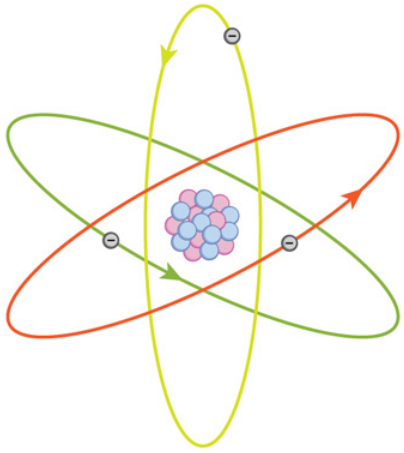


Figure 1.2.9: What is a model? This planetary model of the atom shows electrons orbiting the nucleus. It is a drawing that we use to form a mental image of the atom that we cannot see directly with our eyes because it is too small.

MODELS, THEORIES, AND LAWS

Models, theories, and laws are used to help scientists analyze the data they have already collected. However, often after a model, theory, or law has been developed, it points scientists toward new discoveries they would not otherwise have made.

The models, theories, and laws we devise sometimes *imply the existence of objects or phenomena as yet unobserved.* These predictions are remarkable triumphs and tributes to the power of science. It is the underlying order in the universe that enables scientists to make such spectacular predictions. However, if *experiment* does not verify our predictions, then the theory or law is wrong, no matter how elegant or convenient it is. Laws can never be known with absolute certainty because it is impossible to perform every imaginable experiment in order to confirm a law in every possible scenario. Physicists operate under the assumption that all scientific laws and theories are valid until a counterexample is observed. If a good-quality, verifiable experiment contradicts a well-established law, then the law must be modified or overthrown completely.

The study of science in general and physics in particular is an adventure much like the exploration of uncharted ocean. Discoveries are made; models, theories, and laws are formulated; and the beauty of the physical universe is made more sublime for the insights gained.

THE SCIENTIFIC METHOD

As scientists inquire and gather information about the world, they follow a process called the scientific method. This process typically begins with an observation and question that the scientist will research. Next, the scientist typically performs some research about the topic and then devises a hypothesis. Then, the scientist will test the hypothesis by performing an experiment. Finally, the scientist analyzes the results of the experiment and draws a conclusion. Note that the scientific method can be applied to many situations that are not limited to science, and this method can be modified to suit the situation.

Consider an example. Let us say that you try to turn on your car, but it will not start. You undoubtedly wonder: Why will the car not start? You can follow a scientific method to answer this question. First off, you may perform some research to determine a variety of reasons why the car will not start. Next, you will state a hypothesis. For example, you may believe that the car is not starting because it has no engine oil. To test this, you open the hood of the car and examine the oil level. You observe that the oil is at an acceptable level, and you thus conclude that the oil level is not contributing to your car issue. To troubleshoot the issue further, you may devise a new hypothesis to test and then repeat the process again.

1.2.3: The Evolution of Natural Philosophy into Modern Physics

Physics was not always a separate and distinct discipline. It remains connected to other sciences to this day. The word *physics*comes from Greek, meaning nature. The study of nature came to be called “natural philosophy.” From ancient times through the Renaissance, natural philosophy encompassed many fields, including astronomy, biology, chemistry, physics, mathematics, and medicine. Over the last few centuries, the growth of knowledge has resulted in ever-increasing specialization and branching of natural philosophy into separate fields, with physics retaining the most basic facets (Figures 1.2.10-Figure 1.2.12). Physics as it developed from the Renaissance to the end of the 19th century is called **classical physics**. It was transformed into modern physics by revolutionary discoveries made starting at the beginning of the 20th century.

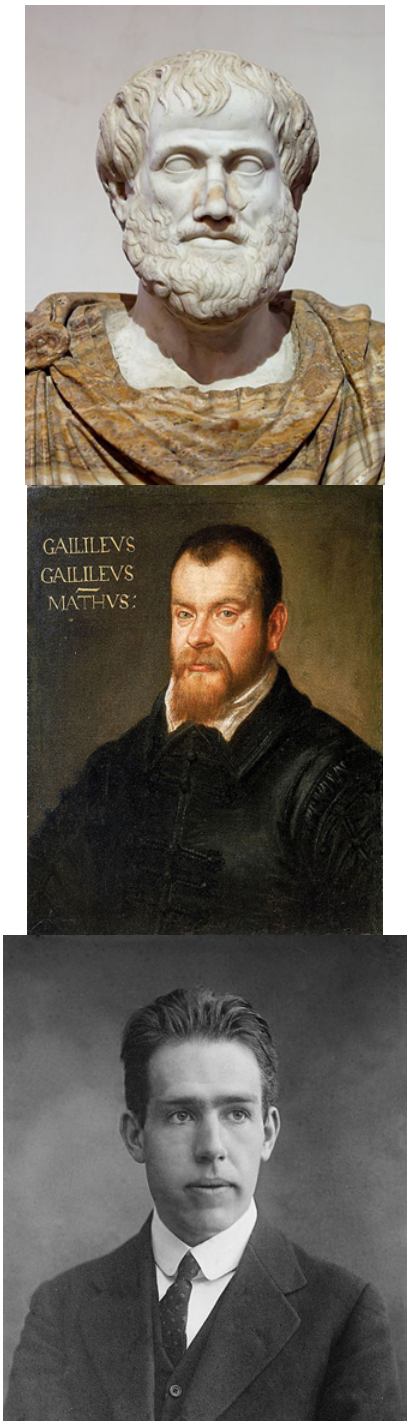


Figure 1.2.12: Niels Bohr (1885–1962) made fundamental contributions to the development of quantum mechanics, one part of modern physics. (credit: United States Library of Congress Prints and Photographs Division)

Classical physics is not an exact description of the universe, but it is an excellent approximation under the following conditions: Matter must be moving at speeds less than about 1% of the speed of light, the objects dealt with must be large enough to be seen with a microscope, and only weak gravitational fields, such as the field generated by the Earth, can be involved. Because humans live under such circumstances, classical physics seems intuitively reasonable, while many aspects of modern physics seem bizarre. This is why models are so useful in modern physics—they let us conceptualize phenomena we do not ordinarily experience. We can relate to models in human terms and visualize what happens when objects move at high speeds or imagine what objects too small to observe with our senses might be like. For example, we can understand an atom's properties because we can picture it in

our minds, although we have never seen an atom with our eyes. New tools, of course, allow us to better picture phenomena we cannot see. In fact, new instrumentation has allowed us in recent years to actually “picture” the atom.

LIMITS ON THE LAWS OF CLASSICAL PHYSICS

For the laws of classical physics to apply, the following criteria must be met: Matter must be moving at speeds less than about 1% of the speed of light, the objects dealt with must be large enough to be seen with a microscope, and only weak gravitational fields (such as the field generated by the Earth) can be involved.

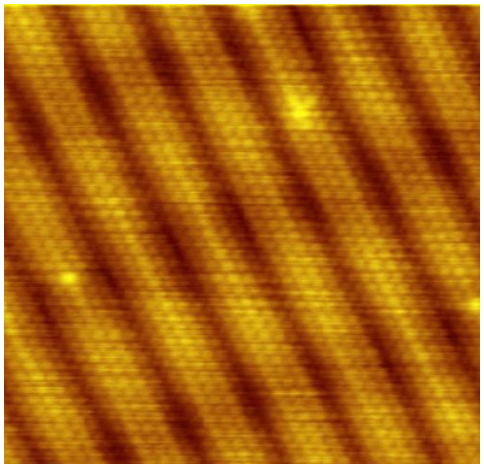


Figure 1.2.13: Using a scanning tunneling microscope (STM), scientists can see the individual atoms that compose this sheet of gold. (credit: Erwinrossen)

Some of the most spectacular advances in science have been made in modern physics. Many of the laws of classical physics have been modified or rejected, and revolutionary changes in technology, society, and our view of the universe have resulted. Like science fiction, modern physics is filled with fascinating objects beyond our normal experiences, but it has the advantage over science fiction of being very real. Why, then, is the majority of this text devoted to topics of classical physics? There are two main reasons: Classical physics gives an extremely accurate description of the universe under a wide range of everyday circumstances, and knowledge of classical physics is necessary to understand modern physics.

Modern physics itself consists of the two revolutionary theories, relativity and quantum mechanics. These theories deal with the very fast and the very small, respectively. **Relativity** must be used whenever an object is traveling at greater than about 1% of the speed of light or experiences a strong gravitational field such as that near the Sun. **Quantum mechanics** must be used for objects smaller than can be seen with a microscope. The combination of these two theories is *relativistic quantum mechanics*, and it describes the behavior of small objects traveling at high speeds or experiencing a strong gravitational field. Relativistic quantum mechanics is the best universally applicable theory we have. Because of its mathematical complexity, it is used only when necessary, and the other theories are used whenever they will produce sufficiently accurate results. We will find, however, that we can do a great deal of modern physics with the algebra and trigonometry used in this text.

? Exercise 1.2.1

A friend tells you he has learned about a new law of nature. What can you know about the information even before your friend describes the law? How would the information be different if your friend told you he had learned about a scientific theory rather than a law?

Answer

Without knowing the details of the law, you can still infer that the information your friend has learned conforms to the requirements of all laws of nature: it will be a concise description of the universe around us; a statement of the underlying rules that all natural processes follow. If the information had been a theory, you would be able to infer that the information will be a large-scale, broadly applicable generalization.

1.2.3.0.1: Summary

- Science seeks to discover and describe the underlying order and simplicity in nature.
- Physics is the most basic of the sciences, concerning itself with energy, matter, space and time, and their interactions.
- Scientific laws and theories express the general truths of nature and the body of knowledge they encompass. These laws of nature are rules that all natural processes appear to follow.

1.2.4: Glossary

classical physics
physics that was developed from the Renaissance to the end of the 19th century

physics
the science concerned with describing the interactions of energy, matter, space, and time; it is especially interested in what fundamental mechanisms underlie every phenomenon

model
representation of something that is often too difficult (or impossible) to display directly

theory
an explanation for patterns in nature that is supported by scientific evidence and verified multiple times by various groups of researchers

law
a description, using concise language or a mathematical formula, a generalized pattern in nature that is supported by scientific evidence and repeated experiments

scientific method
a method that typically begins with an observation and question that the scientist will research; next, the scientist typically performs some research about the topic and then devises a hypothesis; then, the scientist will test the hypothesis by performing an experiment; finally, the scientist analyzes the results of the experiment and draws a conclusion

modern physics
the study of relativity, quantum mechanics, or both

relativity
the study of objects moving at speeds greater than about 1% of the speed of light, or of objects being affected by a strong gravitational field

quantum mechanics
the study of objects smaller than can be seen with a microscope

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1.3: Physical Quantities and Units

Learning Objectives

By the end of this section, you will be able to:

- Perform unit conversions both in the SI and English units.
- Explain the most common prefixes in the SI units and be able to write them in scientific notation.

The range of objects and phenomena studied in physics is immense. From the incredibly short lifetime of a nucleus to the age of the Earth, from the tiny sizes of sub-nuclear particles to the vast distance to the edges of the known universe, from the force exerted by a jumping flea to the force between Earth and the Sun, there are enough factors of 10 to challenge the imagination of even the most experienced scientist. Giving numerical values for physical quantities and equations for physical principles allows us to understand nature much more deeply than does qualitative description alone. To comprehend these vast ranges, we must also have accepted units in which to express them. And we shall find that (even in the potentially mundane discussion of meters, kilograms, and seconds) a profound simplicity of nature appears—all physical quantities can be expressed as combinations of only four fundamental physical quantities: length, mass, time, and electric current.

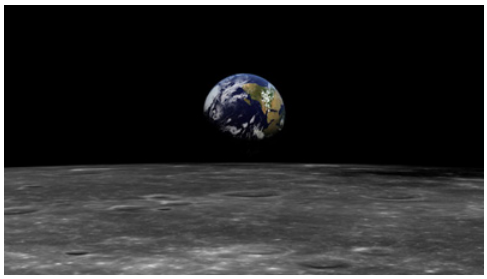


Figure 1.3.1: The distance from Earth to the Moon may seem immense, but it is just a tiny fraction of the distances from Earth to other celestial bodies. (credit: NASA)

We define a **physical quantity** either by *specifying how it is measured* or by *stating how it is calculated* from other measurements. For example, we define distance and time by specifying methods for measuring them, whereas we define *average speed* by stating that it is calculated as distance traveled divided by time of travel.

Measurements of physical quantities are expressed in terms of units, which are standardized values. For example, the length of a race, which is a physical quantity, can be expressed in units of meters (for sprinters) or kilometers (for distance runners). Without standardized units, it would be extremely difficult for scientists to express and compare measured values in a meaningful way (Figure 1.3.2).

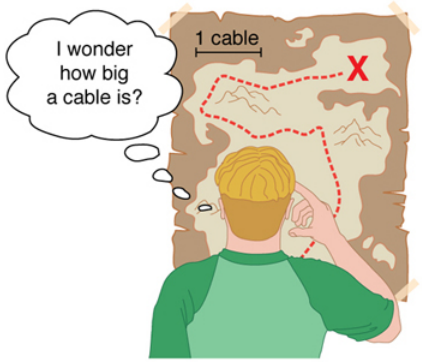


Figure 1.3.2: Distances given in unknown units are maddeningly useless.

There are two major systems of units used in the world: **SI units** (also known as the metric system) and **English units** (also known as the customary or imperial system). **English units** were historically used in nations once ruled by the British Empire and are still widely used in the United States. Virtually every other country in the world now uses SI units as the standard; the metric system is

also the standard system agreed upon by scientists and mathematicians. The acronym “SI” is derived from the French *Système International*.

1.3.1: SI Units: Fundamental and Derived Units

Table 1.3.1 gives the fundamental SI units that are used throughout this textbook. This text uses non-SI units in a few applications where they are in very common use, such as the measurement of blood pressure in millimeters of mercury (mm Hg). Whenever non-SI units are discussed, they will be tied to SI units through conversions.

Table 1.3.1: Fundamental SI Units

Length	Mass	Time	Electric Current
meter (m)	kilogram (kg)	second (s)	ampere (A)

It is an intriguing fact that some physical quantities are more fundamental than others and that the most fundamental physical quantities can be defined *only* in terms of the procedure used to measure them. The units in which they are measured are thus called **fundamental units**. In this textbook, the fundamental physical quantities are taken to be length, mass, time, and electric current. (Note that electric current will not be introduced until much later in this text.) All other physical quantities, such as force and electric charge, can be expressed as algebraic combinations of length, mass, time, and current (for example, speed is length divided by time); these units are called **derived units**.

1.3.1.1: Units of Time, Length, and Mass: The Second, Meter, and Kilogram

The Second

The SI unit for time, the **second** (abbreviated s), has a long history. For many years it was defined as 1/86,400 of a mean solar day. More recently, a new standard was adopted to gain greater accuracy and to define the second in terms of a non-varying, or constant, physical phenomenon (because the solar day is getting longer due to very gradual slowing of the Earth’s rotation). Cesium atoms can be made to vibrate in a very steady way, and these vibrations can be readily observed and counted. In 1967, the second was redefined as the time required for 9,192,631,770 of these vibrations (Figure 1.3.3). Accuracy in the fundamental units is essential, because all measurements are ultimately expressed in terms of fundamental units and can be no more accurate than are the fundamental units themselves.

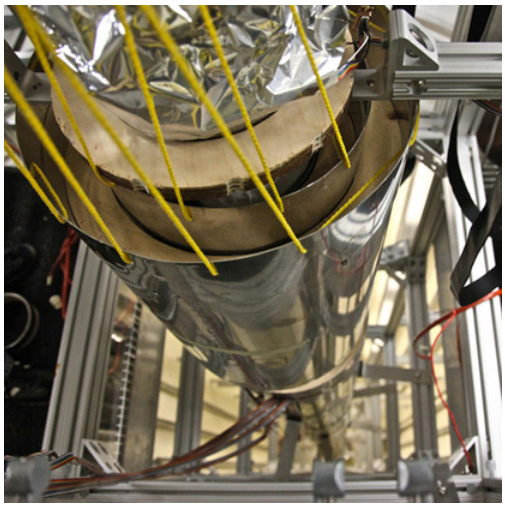


Figure 1.3.3: An atomic clock such as this one uses the vibrations of cesium atoms to keep time to a precision of better than a microsecond per year. The fundamental unit of time, the second, is based on such clocks. This image is looking down from the top of an atomic fountain nearly 30 feet tall! (credit: Steve Jurvetson/Flickr)

The Meter

The SI unit for length is the **meter** (abbreviated m); its definition has also changed over time to become more accurate and precise. The meter was first defined in 1791 as 1/10,000,000 of the distance from the equator to the North Pole. This measurement was improved in 1889 by redefining the meter to be the distance between two engraved lines on a platinum-iridium bar now kept near

Paris. By 1960, it had become possible to define the meter even more accurately in terms of the wavelength of light, so it was again redefined as 1,650,763.73 wavelengths of orange light emitted by krypton atoms. In 1983, the meter was given its present definition (partly for greater accuracy) as the distance light travels in a vacuum in 1/299,792,458 of a second (Figure 1.3.4). This change defines the speed of light to be exactly 299,792,458 meters per second. The length of the meter will change if the speed of light is someday measured with greater accuracy.

The Kilogram

The SI unit for mass is the **kilogram** (abbreviated kg); it is defined to be the mass of a platinum-iridium cylinder kept with the old meter standard at the International Bureau of Weights and Measures near Paris. Exact replicas of the standard kilogram are also kept at the United States' National Institute of Standards and Technology, or NIST, located in Gaithersburg, Maryland outside of Washington D.C., and at other locations around the world. The determination of all other masses can be ultimately traced to a comparison with the standard mass.

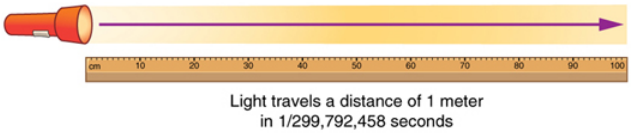


Figure 1.3.4:The meter is defined to be the distance light travels in 1/299,792,458 of a second in a vacuum. Distance traveled is speed multiplied by time.

Electric current and its accompanying unit, the ampere, will be introduced in Introduction to Electric Current, Resistance, and Ohm's Law when electricity and magnetism are covered. The initial modules in this textbook are concerned with mechanics, fluids, heat, and waves. In these subjects all pertinent physical quantities can be expressed in terms of the fundamental units of length, mass, and time.

1.3.1.2: Metric Prefixes

SI units are part of the **metric system**. The metric system is convenient for scientific and engineering calculations because the units are categorized by factors of 10. Table 2 gives metric prefixes and symbols used to denote various factors of 10.

Metric systems have the advantage that conversions of units involve only powers of 10. There are 100 centimeters in a meter, 1000 meters in a kilometer, and so on. In nonmetric systems, such as the system of U.S. customary units, the relationships are not as simple—there are 12 inches in a foot, 5280 feet in a mile, and so on. Another advantage of the metric system is that the same unit can be used over extremely large ranges of values simply by using an appropriate metric prefix. For example, distances in meters are suitable in construction, while distances in kilometers are appropriate for air travel, and the tiny measure of nanometers are convenient in optical design. With the metric system there is no need to invent new units for particular applications.

The term order of magnitude refers to the scale of a value expressed in the metric system. Each power of 1 0 in the metric system represents a different order of magnitude. For example, 10^1, 10^2, 10^3 , and so forth are all different orders of magnitude. All quantities that can be expressed as a product of a specific power of 10 are said to be of the same order of magnitude. For example, the number 800 can be written as 8×10^2 , and the number 450 can be written as 4.5×10^2. Thus, the numbers 800 and 450 are of the same order of magnitude: 10^2. Order of magnitude can be thought of as a ballpark estimate for the scale of a value. The diameter of an atom is on the order of 10^{-9} m, while the diameter of the Sun is on the order of 10^9 m.

THE QUEST FOR MICROSCOPIC STANDARDS FOR BASIC UNITS

The fundamental units described in this chapter are those that produce the greatest accuracy and precision in measurement. There is a sense among physicists that, because there is an underlying microscopic substructure to matter, it would be most satisfying to base our standards of measurement on microscopic objects and fundamental physical phenomena such as the speed of light. A microscopic standard has been accomplished for the standard of time, which is based on the oscillations of the cesium atom.

The standard for length was once based on the wavelength of light (a small-scale length) emitted by a certain type of atom, but it has been supplanted by the more precise measurement of the speed of light. If it becomes possible to measure the mass of atoms or a particular arrangement of atoms such as a silicon sphere to greater precision than the kilogram standard, it may become possible to base mass measurements on the small scale. There are also possibilities that electrical phenomena on the

small scale may someday allow us to base a unit of charge on the charge of electrons and protons, but at present current and charge are related to large-scale currents and forces between wires.

Table 1.3.2: Metric Prefixes for Powers of 10 and their Symbols

Prefix	Symbol	Value	Examples (some are Approximate)	
exa	E	10^18	exameter Em $10^{18}m$	distance light travels in a century
peta	P	10^15	petasecond Ps $10^{15}s$	30 million years
tera	T	10^12	terawatt TW $10^{12}W$	powerful laser output
giga	G	10^9	gigahertz GHz 10^9Hz	a microwave frequency
mega	M	10^6	megacurie MCi 10^6Ci	high radioactivity
kilo	k	10^3	kilometer km 10^3m	about 6/10 mile
hecto	h	10^2	hectoliter hL 10^2L	26 gallons
deka	da	10^1	dekagram dag 10^g	teaspoon of butter
—	—	$10^0(=1)$		
deci	d	10^{-1}	deciliter dL $10^{-1}L$	less than half a soda
centi	c	10^{-2}	centimeter cm $10^{-2}m$	fingertip thickness
milli	m	10^{-3}	millimeter mm $10^{-3}m$	flea at its shoulders
micro	μ	10^{-6}	micrometer μm $10^{-6}m$	detail in microscope
nano	n	10^{-9}	nanogram ng $10^{-9}g$	small speck of dust
pico	p	10^{-12}	picofarad pF $10^{-12}F$	small capacitor in radio
femto	f	10^{-15}	femtometer fm $10^{-15}m$	size of a proton
atto	a	10^{-18}	attosecond as $10^{-18}s$	time light crosses an atom

1.3.2: Known Ranges of Length, Mass, and Time

The vastness of the universe and the breadth over which physics applies are illustrated by the wide range of examples of known lengths, masses, and times in Table 1.3.2. Examination of this table will give you some feeling for the range of possible topics and numerical values (Figures 1.3.5 and 1.3.6).

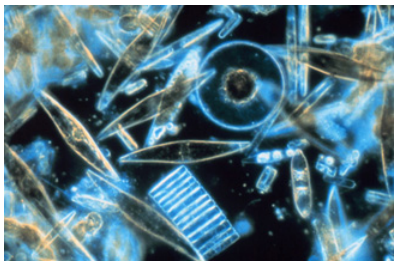


Figure 1.3.5: Tiny phytoplankton swims among crystals of ice in the Antarctic Sea. They range from a few micrometers to as much as 2 millimeters in length. (credit: Prof. Gordon T. Taylor, Stony Brook University; NOAA Corps Collections)

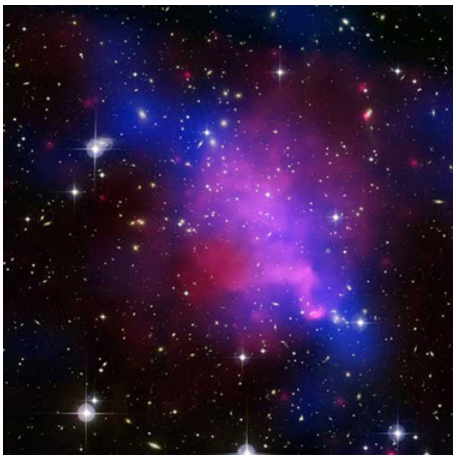


Figure 1.3.6: Galaxies collide 2.4 billion light years away from Earth. The tremendous range of observable phenomena in nature challenges the imagination. (credit: NASA/CXC/UVic./A. Mahdavi et al. Optical/lensing: CFHT/UVic./H. Hoekstra et al.)

1.3.3: Unit Conversion and Dimensional Analysis

It is often necessary to convert from one type of unit to another. For example, if you are reading a European cookbook, some quantities may be expressed in units of liters and you need to convert them to cups. Or, perhaps you are reading walking directions from one location to another and you are interested in how many miles you will be walking. In this case, you will need to convert units of feet to miles. Let us consider a simple example of how to convert units.

Let us say that we want to convert 80 meters (m) to kilometers (km).

1. The first thing to do is to list the units that you have and the units that you want to convert to. In this case, we have units in *meters* and we want to convert to *kilometers*.
2. Next, we need to determine a **conversion factor** relating meters to kilometers. A conversion factor is a ratio expressing how many of one unit are equal to another unit. For example, there are 12 inches in 1 foot, 100 centimeters in 1 meter, 60 seconds in 1 minute, and so on. In this case, we know that there are 1,000 meters in 1 kilometer.
3. Now we can set up our unit conversion. We will write the units that we have and then multiply them by the conversion factor so that the units cancel out, as shown:

$$80 \cancel{m} \times \frac{1\,km}{1000\,\cancel{m}} = 0.08\,km \tag{1.3.1}$$

   Note that the unwanted m unit cancels, leaving only the desired km unit. You can use this method to convert between any types of unit.

Click Appendix C for a more complete list of conversion factors.

Table 1.3.3: Approximate Values of Length, Mass, and Time

lengths in meters		Masses in kilograms (more precise values in parentheses)		Times in seconds (more precise values in parentheses)	
10^{-18}	Present experimental limit to smallest observable detail	10^{-30}	Mass of an electron (9.11×10^{-31} kg)	10^{-23}	Time for light to cross a proton
10^{-15}	Diameter of a proton	10^{-27}	Mass of a hydrogen atom (1.67×10^{-27} kg)	10^{-22}	Mean life of an extremely unstable nucleus
10^{-14}	Diameter of a uranium nucleus	10^{-15}	Mass of a bacterium	10^{-15}	Time for one oscillation of visible light
10^{-10}	Diameter of a hydrogen atom	10^{-5}	Mass of a mosquito	10^{-13}	Time for one vibration of an atom in a solid
10^{-8}	Thickness of membranes in cells of living organisms	10^{-2}	Mass of a hummingbird	10^{-8}	Time for one oscillation of an FM radio wave
10^{-6}	Wavelength of visible light	1	Mass of a liter of water (about a quart)	10^{-3}	Duration of a nerve impulse
10^{-3}	Size of a grain of sand	10^{2}	Mass of a person	1	Time for one heartbeat
1	Height of a 4-year-old child	10^{3}	Mass of a car	10^{5}	One day (8.64×10^{4}s)
10^{2}	Length of a football field	10^{8}	Mass of a large ship	10^{7}	One year (y) (3.16×10^{7}s)
10^{4}	Greatest ocean depth	10^{12}	Mass of a large iceberg	10^{9}	About half the life expectancy of a human
10^{7}	Diameter of the Earth	10^{15}	Mass of the nucleus of a comet	10^{11}	Recorded history
10^{11}	Distance from the Earth to the Sun	10^{23}	Mass of the Moon (7.35×10^{22} kg)	10^{17}	Age of the Earth
10^{16}	Distance traveled by light in 1 year (a light year)	10^{25}	Mass of the Earth (5.97×10^{24} kg)	10^{18}	Age of the universe
10^{21}	Diameter of the Milky Way galaxy	10^{30}	Mass of the Sun (1.99×10^{30} kg)		
10^{22}	Distance from the Earth to the nearest large galaxy (Andromeda)	10^{42}	Mass of the Milky Way galaxy (current upper limit)		
10^{26}	Distance from the	10^{53}	Mass of the known		

lengths in meters		Masses in kilograms (more precise values in parentheses)		Times in seconds (more precise values in parentheses)	
	Earth to the edges of the known universe		universe (current upper limit)		

Example 1.3.1: Unit Conversions: A Short Drive Home

Suppose that you drive the 10.0 km from your university to home in 20.0 min. Calculate your average speed (a) in kilometers per hour (km/h) and (b) in meters per second (m/s). (Note: Average speed is distance traveled divided by time of travel.)

Strategy

First we calculate the average speed using the given units. Then we can get the average speed into the desired units by picking the correct conversion factor and multiplying by it. The correct conversion factor is the one that cancels the unwanted unit and leaves the desired unit in its place.

Solution for (a)

(1) Calculate average speed. Average speed is distance traveled divided by time of travel. (Take this definition as a given for now—average speed and other motion concepts will be covered in a later module.) In equation form,

$$\text{average speed} = \frac{distance}{time}.$$

(2) Substitute the given values for distance and time.

$$\begin{aligned}\text{average speed} &= \frac{10.0\,km}{20.0\,min} \\ &= 0.500\frac{km}{min}.\end{aligned}$$

(3) Convert km/min to km/h: multiply by the conversion factor that will cancel minutes and leave hours. That conversion factor is *60 min/hr*. Thus,

$$\begin{aligned}\text{average speed} &= 0.500\frac{km}{min} \times \frac{60\,min}{1\,h} \\ &= 30.0\frac{km}{h}\end{aligned}$$

Discussion for (a)

To check your answer, consider the following:

(1) Be sure that you have properly cancelled the units in the unit conversion. If you have written the unit conversion factor upside down, the units will not cancel properly in the equation. If you accidentally get the ratio upside down, then the units will not cancel; rather, they will give you the wrong units as follows:

$$\frac{km}{min} \times \frac{1\,hr}{60\,min} = \frac{1}{60}\frac{km \cdot hr}{min^2},$$

which are obviously not the desired units of km/h.

(2) Check that the units of the final answer are the desired units. The problem asked us to solve for average speed in units of km/h and we have indeed obtained these units.

(3) Check the significant figures. Because each of the values given in the problem has three significant figures, the answer should also have three significant figures. The answer 30.0 km/hr does indeed have three significant figures, so this is appropriate. Note that the significant figures in the conversion factor are not relevant because an hour is defined to be 60 minutes, so the precision of the conversion factor is perfect.

(4) Next, check whether the answer is reasonable. Let us consider some information from the problem—if you travel 10 km in a third of an hour (20 min), you would travel three times that far in an hour. The answer does seem reasonable.

Solution for (b)

There are several ways to convert the average speed into meters per second.

(1) Start with the answer to (a) and convert km/h to m/s. Two conversion factors are needed—one to convert hours to seconds, and another to convert kilometers to meters.

(2) Multiplying by these yields

$$\text{Average speed} = 30.0\frac{\cancel{km}}{\cancel{h}} \times \frac{1\ \cancel{h}}{3,600\ s} \times \frac{1,000\,m}{1\ \cancel{km}}$$
$$= 8.33\,m/s$$

Discussion for (b)

If we had started with 0.500 km/min, we would have needed different conversion factors, but the answer would have been the same: 8.33 m/s.

You may have noted that the answers in the worked example just covered were given to three digits. Why? When do you need to be concerned about the number of digits in something you calculate? Why not write down all the digits your calculator produces? The module Accuracy, Precision, and Significant Figures will help you answer these questions.

NONSTANDARD UNITS

While there are numerous types of units that we are all familiar with, there are others that are much more obscure. For example, a firkin is a unit of volume that was once used to measure beer. One firkin equals about 34 liters. To learn more about nonstandard units, use a dictionary or encyclopedia to research different "weights and measures." Take note of any unusual units, such as a barleycorn, that are not listed in the text. Think about how the unit is defined and state its relationship to SI units.

Exercise 1.3.1

Some hummingbirds beat their wings more than 50 times per second. A scientist is measuring the time it takes for a hummingbird to beat its wings once. Which fundamental unit should the scientist use to describe the measurement? Which factor of 10 is the scientist likely to use to describe the motion precisely? Identify the metric prefix that corresponds to this factor of 10.

Answer

The scientist will measure the time between each movement using the fundamental unit of seconds. Because the wings beat so fast, the scientist will probably need to measure in milliseconds, or 10^{-3} seconds. (50 beats per second corresponds to 20 milliseconds per beat.)

Exercise 1.3.2

One cubic centimeter is equal to one milliliter. What does this tell you about the different units in the SI metric system?

Answer

The fundamental unit of length (meter) is probably used to create the derived unit of volume (liter). The measure of a milliliter is dependent on the measure of a centimeter.

1.3.3.0.1: Summary

- Physical quantities are a characteristic or property of an object that can be measured or calculated from other measurements.
- Units are standards for expressing and comparing the measurement of physical quantities. All units can be expressed as combinations of four fundamental units.
- The four fundamental units we will use in this text are the meter (for length), the kilogram (for mass), the second (for time), and the ampere (for electric current). These units are part of the metric system, which uses powers of 10 to relate quantities over the vast ranges encountered in nature.
- The four fundamental units are abbreviated as follows: meter, m; kilogram, kg; second, s; and ampere, A. The metric system also uses a standard set of prefixes to denote each order of magnitude greater than or lesser than the fundamental unit itself.
- Unit conversions involve changing a value expressed in one type of unit to another type of unit. This is done by using conversion factors, which are ratios relating equal quantities of different units.

1.3.4: Glossary

physical quantity
a characteristic or property of an object that can be measured or calculated from other measurements

units
a standard used for expressing and comparing measurements

SI units
the international system of units that scientists in most countries have agreed to use; includes units such as meters, liters, and grams

English units
system of measurement used in the United States; includes units of measurement such as feet, gallons, and pounds

fundamental units
units that can only be expressed relative to the procedure used to measure them

derived units
units that can be calculated using algebraic combinations of the fundamental units

second
the SI unit for time, abbreviated (s)

meter
the SI unit for length, abbreviated (m)

kilogram
the SI unit for mass, abbreviated (kg)

metric system
a system in which values can be calculated in factors of 10

order of magnitude
refers to the size of a quantity as it relates to a power of 10

conversion factor
a ratio expressing how many of one unit are equal to another unit

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1.4: Accuracy, Precision, and Significant Figures

Learning Objectives

By the end of this section, you will be able to:

- Determine the appropriate number of significant figures in both addition and subtraction, as well as multiplication and division calculations.
- Calculate the percent uncertainty of a measurement.

1.4.1: Accuracy and Precision of a Measurement

Science is based on observation and experiment—that is, on measurements. **Accuracy** is how close a measurement is to the correct value for that measurement. For example, let us say that you are measuring the length of standard computer paper. The packaging in which you purchased the paper states that it is 11.0 inches long. You measure the length of the paper three times and obtain the following measurements: 11.1 in., 11.2 in., and 10.9 in. These measurements are quite accurate because they are very close to the correct value of 11.0 inches. In contrast, if you had obtained a measurement of 12 inches, your measurement would not be very accurate.



Figure 1.4.1: A double-pan mechanical balance is used to compare different masses. Usually an object with unknown mass is placed in one pan and objects of known mass are placed in the other pan. When the bar that connects the two pans is horizontal, then the masses in both pans are equal. The “known masses” are typically metal cylinders of standard mass such as 1 gram, 10 grams, and 100 grams. (credit: Serge Melki)

The precision of a measurement system refers to how close the agreement is between repeated measurements (which are repeated under the same conditions). Consider the example of the paper measurements. The precision of the measurements refers to the spread of the measured values. One way to analyze the precision of the measurements would be to determine the range, or difference, between the lowest and the highest measured values. In that case, the lowest value was 10.9 in. and the highest value was 11.2 in. Thus, the measured values deviated from each other by at most 0.3 in. These measurements were relatively precise because they did not vary too much in value. However, if the measured values had been 10.9, 11.1, and 11.9, then the measurements would not be very precise because there would be significant variation from one measurement to another.

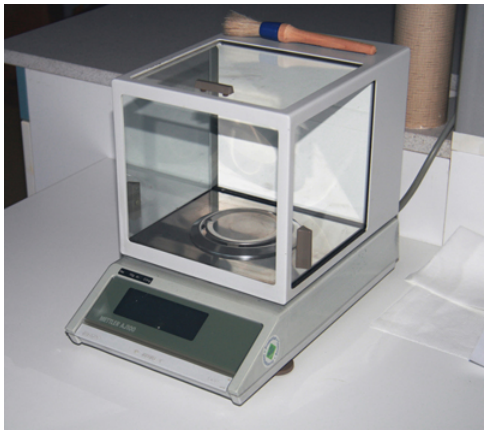


Figure 1.4.2: Many mechanical balances, such as double-pan balances, have been replaced by digital scales, which can typically measure the mass of an object more precisely. Whereas a mechanical balance may only read the mass of an object to the nearest tenth of a gram, many digital scales can measure the mass of an object up to the nearest thousandth of a gram. (credit: Karel Jakubec)

The measurements in the paper example are both accurate and precise, but in some cases, measurements are accurate but not precise, or they are precise but not accurate. Let us consider an example of a GPS system that is attempting to locate the position of a restaurant in a city. Think of the restaurant location as existing at the center of a bull's-eye target, and think of each GPS attempt to locate the restaurant as a black dot. In Figure 1.4.3, you can see that the GPS measurements are spread out far apart from each other, but they are all relatively close to the actual location of the restaurant at the center of the target. This indicates a low precision, high accuracy measuring system. However, in Figure 4, the GPS measurements are concentrated quite closely to one another, but they are far away from the target location. This indicates a high precision, low accuracy measuring system.



Figure 1.4.3: A GPS system attempts to locate a restaurant at the center of the bull's-eye. The black dots represent each attempt to pinpoint the location of the restaurant. The dots are spread out quite far apart from one another, indicating low precision, but they are each rather close to the actual location of the restaurant, indicating high accuracy. (credit: Dark Evil)



Figure 1.4.4: In this figure, the dots are concentrated rather closely to one another, indicating high precision, but they are rather far away from the actual location of the restaurant, indicating low accuracy. (credit: Dark Evil)

1.4.2: Accuracy, Precision, and Uncertainty

The degree of accuracy and precision of a measuring system are related to the uncertainty in the measurements. Uncertainty is a quantitative measure of how much your measured values deviate from a standard or expected value. If your measurements are not very accurate or precise, then the uncertainty of your values will be very high. In more general terms, uncertainty can be thought of as a disclaimer for your measured values. For example, if someone asked you to provide the mileage on your car, you might say that it is 45,000 miles, plus or minus 500 miles. The plus or minus amount is the uncertainty in your value. That is, you are indicating that the actual mileage of your car might be as low as 44,500 miles or as high as 45,500 miles, or anywhere in between. All measurements contain some amount of uncertainty. In our example of measuring the length of the paper, we might say that the length of the paper is 11 in., plus or minus 0.2 in. The uncertainty in a measurement, A, is often denoted as δA ("delta A"), so the measurement result would be recorded as $A \pm \delta A$. In our paper example, the length of the paper could be expressed as 11 in.$\pm$ 0.2.

The factors contributing to uncertainty in a measurement include:

1. Limitations of the measuring device,
2. The skill of the person making the measurement,
3. Irregularities in the object being measured,
4. Any other factors that affect the outcome (highly dependent on the situation).

In our example, such factors contributing to the uncertainty could be the following: the smallest division on the ruler is 0.1 in., the person using the ruler has bad eyesight, or one side of the paper is slightly longer than the other. At any rate, the uncertainty in a measurement must be based on a careful consideration of all the factors that might contribute and their possible effects.

MAKING CONNECTIONS: REAL-WORLD CONNECTIONS – FEVERS OR CHILLS?

Uncertainty is a critical piece of information, both in physics and in many other real-world applications. Imagine you are caring for a sick child. You suspect the child has a fever, so you check his or her temperature with a thermometer. What if the uncertainty of the thermometer were 3.0ºC? If the child's temperature reading was 37.0ºC (which is normal body temperature), the "true" temperature could be anywhere from a hypothermic 34.0ºC to a dangerously high 40.0ºC. A thermometer with an uncertainty of 3.0ºC would be useless.

1.4.2.0.1: Percent Uncertainty

One method of expressing uncertainty is as a percent of the measured value. If a measurement A is expressed with uncertainty, δA, the percent uncertainty (%uncertainty) is defined to be

$$\%\,\text{unc} = \frac{\delta A}{A} \times 100\% \tag{1.4.1}$$

Example 1.4.1: Calculating Percent Uncertainty: A Bag of Apples

A grocery store sells 5-lb bags of apples. You purchase four bags over the course of a month and weigh the apples each time. You obtain the following measurements:

Week 1 weight: **4.8 lb**
Week 2 weight: **5.3 lb**
Week 3 weight: **4.9 lb**
Week 4 weight: **5.4 lb**

You determine that the weight of the **5-lb** bag has an uncertainty of **±0.4lb.** What is the percent uncertainty of the bag's weight?

Strategy

First, observe that the expected value of the bag's weight, A, is 5 lb. The uncertainty in this value, δA, is 0.4 lb. We can use the following equation to determine the percent uncertainty of the weight:

$$= \frac{\delta A}{A} \times 100.$$

Solution

Plug the known values into the equation:

$$= \frac{0.4lb}{5lb} \times 100.$$

Discussion

We can conclude that the weight of the apple bag is $5lb \pm 8$. Consider how this percent uncertainty would change if the bag of apples were half as heavy, but the uncertainty in the weight remained the same. Hint for future calculations: when calculating percent uncertainty, always remember that you must multiply the fraction by 100%. If you do not do this, you will have a decimal quantity, not a percent value.

1.4.2.0.1: Uncertainties in Calculations

There is an uncertainty in anything calculated from measured quantities. For example, the area of a floor calculated from measurements of its length and width has an uncertainty because the length and width have uncertainties. How big is the uncertainty in something you calculate by multiplication or division? If the measurements going into the calculation have small uncertainties (a few percent or less), then the **method of adding percents** can be used for multiplication or division. This method says that *the percent uncertainty in a quantity calculated by multiplication or division is the sum of the percent uncertainties in the items used to make the calculation.* For example, if a floor has a length of 4.00m and a width of 3.00m, with uncertainties of 2% and 1%, respectively, then the area of the floor is $12.0m^2$ and has an uncertainty of 3%. (Expressed as an area this is $0.36m^2$, which we round to $0.4\,m^2$ since the area of the floor is given to a tenth of a square meter.)

? Exercise 1.4.1

A high school track coach has just purchased a new stopwatch. The stopwatch manual states that the stopwatch has an uncertainty of ±0.05s. Runners on the track coach's team regularly clock 100-m sprints of 11.49 s to 15.01 s. At the school's last track meet, the first-place sprinter came in at 12.04 s and the second-place sprinter came in at 12.07 s. Will the coach's new stopwatch be helpful in timing the sprint team? Why or why not?

Answer

No, the uncertainty in the stopwatch is too great to effectively differentiate between the sprint times.

1.4.3: Precision of Measuring Tools and Significant Figures

An important factor in the accuracy and precision of measurements involves the precision of the measuring tool. In general, a precise measuring tool is one that can measure values in very small increments. For example, a standard ruler can measure length to the nearest millimeter, while a caliper can measure length to the nearest 0.01 millimeter. The caliper is a more precise measuring tool because it can measure extremely small differences in length. The more precise the measuring tool, the more precise and accurate the measurements can be.

When we express measured values, we can only list as many digits as we initially measured with our measuring tool. For example, if you use a standard ruler to measure the length of a stick, you may measure it to be 36.7cm. You could not express this value as 36.71cm because your measuring tool was not precise enough to measure a hundredth of a centimeter. It should be noted that the last digit in a measured value has been estimated in some way by the person performing the measurement. For example, the person measuring the length of a stick with a ruler notices that the stick length seems to be somewhere in between 36.6cm and 36.7cm, and he or she must estimate the value of the last digit. Using the method of significant figures, the rule is that *the last digit written down in a measurement* is the first digit with some uncertainty. In order to determine the number of significant digits in a value, start with the first measured value at the left and count the number of digits through the last digit written on the right. For example, the measured value 36.7cm has three digits, or significant figures. Significant figures indicate the precision of a measuring tool that was used to measure a value.

1.4.3.1: Zeros

Special consideration is given to zeros when counting significant figures. The zeros in 0.053 are not significant, because they are only placekeepers that locate the decimal point. There are two significant figures in 0.053. The zeros in 10.053 are not placekeepers but are significant—this number has five significant figures. The zeros in 1300 may or may not be significant depending on the style of writing numbers. They could mean the number is known to the last digit, or they could be placekeepers. So 1300 could have two, three, or four significant figures. (To avoid this ambiguity, write 1300 in scientific notation.) *Zeros are significant except when they serve only as placekeepers*.

? Exercise 1.4.2

Determine the number of significant figures in the following measurements:

a. 0.0009
b. 15,450.0
c. ×103
d. 87.990
e. 30.42

Solutions

a. 1; the zeros in this number are placekeepers that indicate the decimal point
b. 6; here, the zeros indicate that a measurement was made to the 0.1 decimal point, so the zeros are significant
c. 1; the value 3 signifies the decimal place, not the number of measured values
d. 5; the final zero indicates that a measurement was made to the 0.001 decimal point, so it is significant
e. 4; any zeros located in between significant figures in a number are also significant

1.4.3.2: Significant Figures in Calculations

When combining measurements with different degrees of accuracy and precision, *the number of significant digits in the final answer can be no greater than the number of significant digits in the least precise measured value*. There are two different rules, one for multiplication and division and the other for addition and subtraction, as discussed below.

1. For multiplication and division: *The result should have the same number of significant figures as the quantity having the least significant figures entering into the calculation.* For example, the area of a circle can be calculated from its radius using $A = \pi r^2$. Let us see how many significant figures the area has if the radius has only two—say, $r = 1.2m$. Then,

$$A = \pi r^2 = (3.1415927...) \times (1.2m)^2 = 4.5238934\, m^2$$

is what you would get using a calculator that has an eight-digit output. But because the radius has only two significant figures, it limits the calculated quantity to two significant figures or

$$A = 4.5\, m^2,$$

even though π is good to at least eight digits.

2. For addition and subtraction: *The answer can contain no more decimal places than the least precise measurement.* Suppose that you buy 7.56-kg of potatoes in a grocery store as measured with a scale with precision 0.01 kg. Then you drop off 6.052-kg of potatoes at your laboratory as measured by a scale with precision 0.001 kg. Finally, you go home and add 13.7 kg of potatoes as measured by a bathroom scale with precision 0.1 kg. How many kilograms of potatoes do you now have, and how many significant figures are appropriate in the answer? The mass is found by simple addition and subtraction:

$$M = 7.56\, kg - 6.052\, kg + 13.7\, kg$$

$$M = 15.208\, kg$$

Next, we identify the least precise measurement: 13.7 kg. This measurement is expressed to the 0.1 decimal place, so our final answer must also be expressed to the 0.1 decimal place. Thus, the answer is rounded to the tenths place, giving us 15.2 kg.

$$M = 15.2\, kg$$

Significant Figures in this Text

In this text, most numbers are assumed to have three significant figures. Furthermore, consistent numbers of significant figures are used in all worked examples. You will note that an answer given to three digits is based on input good to at least three digits, for example. If the input has fewer significant figures, the answer will also have fewer significant figures. Care is also taken that the number of significant figures is reasonable for the situation posed. In some topics, particularly in optics, more accurate numbers are needed and more than three significant figures will be used. Finally, if a number is *exact*, such as the two in the formula for the circumference of a circle, $C = 2\pi r$ it does not affect the number of significant figures in a calculation.

? Exercise 1.4.3

Perform the following calculations and express your answer using the correct number of significant digits.

a. A woman has two bags weighing 13.5 pounds and one bag with a weight of 10.2 pounds. What is the total weight of the bags?
b. The force F on an object is equal to its mass m multiplied by its acceleration a. If a wagon with mass 55 kg accelerates at a rate of $0.0255 m/s^2$, what is the force on the wagon? (The unit of force is called the newton, and it is expressed with the symbol N.)

Answer

(a) 37.2 pounds; Because the number of bags is an exact value, it is not considered in the significant figures.

(b) 1.4 N; Because the value 55 kg has only two significant figures, the final value must also contain two significant figures.

1.4.4: Summary

- Accuracy of a measured value refers to how close a measurement is to the correct value. The uncertainty in a measurement is an estimate of the amount by which the measurement result may differ from this value.
- Precision of measured values refers to how close the agreement is between repeated measurements.
- The precision of a *measuring tool* is related to the size of its measurement increments. The smaller the measurement increment, the more precise the tool.
- Significant figures express the precision of a measuring tool.
- When multiplying or dividing measured values, the final answer can contain only as many significant figures as the least precise value.
- When adding or subtracting measured values, the final answer cannot contain more decimal places than the least precise value.

1.4.5: Glossary

accuracy
: the degree to which a measured value agrees with correct value for that measurement

method of adding percents
: the percent uncertainty in a quantity calculated by multiplication or division is the sum of the percent uncertainties in the items used to make the calculation

percent uncertainty
: the ratio of the uncertainty of a measurement to the measured value, expressed as a percentage

precision
: the degree to which repeated measurements agree with each other

significant figures
: express the precision of a measuring tool used to measure a value

uncertainty
: a quantitative measure of how much your measured values deviate from a standard or expected value

1.4.6: Contributors and Attributions

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1.5: Approximation

Learning Objectives

By the end of this section, you will be able to:

- Make reasonable approximations based on given data.

On many occasions, physicists, other scientists, and engineers need to make **approximations** or "guesstimates" for a particular quantity. What is the distance to a certain destination? What is the approximate density of a given item? About how large a current will there be in a circuit? Many approximate numbers are based on formulae in which the input quantities are known only to a limited accuracy. As you develop problem-solving skills (that can be applied to a variety of fields through a study of physics), you will also develop skills at approximating. You will develop these skills through thinking more quantitatively, and by being willing to take risks. As with any endeavor, experience helps, as well as familiarity with units. These approximations allow us to rule out certain scenarios or unrealistic numbers. Approximations also allow us to challenge others and guide us in our approaches to our scientific world. Let us do two examples to illustrate this concept.

Example 1.5.1: Approximate the Height of a Building

Can you approximate the height of one of the buildings on your campus, or in your neighborhood? Let us make an approximation based upon the height of a person. In this example, we will calculate the height of a 39-story building.

Strategy

Think about the average height of an adult male. We can approximate the height of the building by scaling up from the height of a person.

Solution

Based on information in the example, we know there are 39 stories in the building. If we use the fact that the height of one story is approximately equal to about the length of two adult humans (each human is about 2-m tall), then we can estimate the total height of the building to be

$$\frac{2\,m}{1\,person} \times \frac{2\,person}{1\,story} \times 39\,stories = 156\,m.$$

Discussion

You can use known quantities to determine an approximate measurement of unknown quantities. If your hand measures 10 cm across, how many hand lengths equal the width of your desk? What other measurements can you approximate besides length?

Example 1.5.2: Approximating Vast Numbers - a Trillion Dollar

The U.S. federal debt in the 2008 fiscal year was a little less than $10 trillion. Most of us do not have any concept of how much even one trillion actually is. Suppose that you were given a trillion dollars in $100 bills. If you made 100-bill stacks and used them to evenly cover a football field (between the end zones), make an approximation of how high the money pile would become. (We will use feet/inches rather than meters here because football fields are measured in yards.) One of your friends says 3 in., while another says 10 ft. What do you think?



Figure 1.5.1: A bank stack contains one-hundred $100 bills, and is worth $10,000. How many bank stacks make up a trillion dollars? (credit: Andrew Magill)

Strategy

When you imagine the situation, you probably envision thousands of small stacks of 100 wrapped $100 bills, such as you might see in movies or at a bank. Since this is an easy-to-approximate quantity, let us start there. We can find the volume of a stack of 100 bills, find out how many stacks make up one trillion dollars, and then set this volume equal to the area of the football field multiplied by the unknown height.

Solution

(1) Calculate the volume of a stack of 100 bills. The dimensions of a single bill are approximately 3 in. by 6 in. A stack of 100 of these is about 0.5 in. thick. So the total volume of a stack of 100 bills is:

$$\begin{aligned}\text{volume of stack} &= length \times width \times height\\ \text{volume of stack} &= 6\,in. \times 3\,in. \times 0.5\,in.,\\ \text{volume of stack} &= 9\,in.^3\end{aligned}$$

(2) Calculate the number of stacks. Note that a trillion dollars is equal to $\$1 \times 10^{12}$, and a stack of one-hundred $100 bills is equal to $10,000, or $\$1 \times 10^4$. The number of stacks you will have is:

$$\frac{\$1 \times 10^{12}\,(\text{a trillion dollars})}{\$1 \times 10^4\,\text{per stack}} = 1 \times 10^8\,\text{stacks.}$$

(3) Calculate the area of a football field in square inches. The area of a football field is $100\ yd \times 50\ yd$, which gives $5,000\ yd^2$. Because we are working in inches, we need to convert square yards to square inches:

$$\begin{aligned}Area &= 5,000\,yd^2 \times \frac{3\,ft}{1\,yd} \times \frac{3\,ft}{1\,yd} \times \frac{12\,in.}{1\,ft} \times \frac{12\,in}{1\,ft}\\ &= 6,480,000\,in.^2,\\ &\approx 6 \times 10^6\,in.^2.\end{aligned}$$

This conversion gives us $6 \times 10^6\ in^2$ for the area of the field. (Note that we are using only one significant figure in these calculations.)

(4) Calculate the total volume of the bills. The volume of all the $100 -bill stacks is

$$9\,in.^3/stack \times 10^8\,\text{stacks} = 9 \times 10^8\,in.^3.$$

(5) Calculate the height. To determine the height of the bills, use the equation:

$$\begin{aligned}\text{volume of bills} &= \text{area of field} \times \text{height of money}\\ \text{Height of money} &= \frac{\text{volume of bills}}{\text{area of field}}\\ \text{Height of money} &= \frac{9 \times 10^8 in.^3}{6 \times 10^6 in.^2} = 1.33 \times 10^2 in\\ \text{Height of money} &\approx 1 \times 10^2\,in. = 100\,in.\end{aligned}$$

The height of the money will be about 100 in. high. Converting this value to feet gives

$$100\,in. \times \frac{1\,ft}{12\,in.} = 8.33\,ft \approx 8\,ft.$$

Discussion

The final approximate value is much higher than the early estimate of 3 in., but the other early estimate of 10 ft (120 in.) was roughly correct. How did the approximation measure up to your first guess? What can this exercise tell you in terms of rough "guesstimates" versus carefully calculated approximations?

? Exercise 1.5.1

Using mental math and your understanding of fundamental units, approximate the area of a regulation basketball court. Describe the process you used to arrive at your final approximation

Answer

An average male is about two meters tall. It would take approximately 15 men laid out end to end to cover the length, and about 7 to cover the width. That gives an approximate area of $420m^2$.

1.5.1: Summary

- Scientists often approximate the values of quantities to perform calculations and analyze systems.

1.5.2: Glossary

approximation

an estimated value based on prior experience and reasoning

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1.E: The Nature of Science and Physics (Exercises)

Conceptual Questions

Physics: An Introduction

1. Models are particularly useful in relativity and quantum mechanics, where conditions are outside those normally encountered by humans. What is a model?
2. How does a model differ from a theory?
3. If two different theories describe experimental observations equally well, can one be said to be more valid than the other (assuming both use accepted rules of logic)?
4. What determines the validity of a theory?
5. Certain criteria must be satisfied if a measurement or observation is to be believed. Will the criteria necessarily be as strict for an expected result as for an unexpected result?
6. Can the validity of a model be limited, or must it be universally valid? How does this compare to the required validity of a theory or a law?
7. Classical physics is a good approximation to modern physics under certain circumstances. What are they?
8. When is it necessary to use relativistic quantum mechanic?
9. Can classical physics be used to accurately describe a satellite moving at a speed of 7500 m/s? Explain why or why not.

Physical Quantities and Units

1. Identify some advantages of metric units.

Accuracy, Precision, and Significant Figures

1. What is the relationship between the accuracy and uncertainty of a measurement?
2. Prescriptions for vision correction are given in units called *diopters* (D). Determine the meaning of that unit. Obtain information (perhaps by calling an optometrist or performing an internet search) on the minimum uncertainty with which corrections in diopters are determined and the accuracy with which corrective lenses can be produced. Discuss the sources of uncertainties in both the prescription and accuracy in the manufacture of lenses.

Problems & Exercises

Physical Quantities and Units

1. The speed limit on some interstate highways is roughly 100 km/h. (a) What is this in meters per second? (b) How many miles per hour is this? ANS: (a) 27.8 m/s, (b) 62.1 mi/hr
2. A car is traveling at a speed of 33m/s
   a. What is its speed in kilometers per hour?
   b. Is it exceeding the 90km/hr speed limit?
3. Show that 1.0 m/s=3.6 km/hr [Hint: Show the explicit steps involved in converting meters to kilometers and seconds to minutes to hours].
4. American football is played on a 100-yd-long field, excluding the end zones. How long is the field in meters? (Assume that 1 meter equals 3.281 feet.)
5. Soccer fields vary in size. A large soccer field is 115 m long and 85 m wide. What are its dimensions in feet and inches? (Assume that 1 meter equals 3.281 feet.) ANS: 377 ft and 4530 inches long; 280 ft and 3300 inches wide.
6. What is the height in meters of a person who is 6 ft 1.0 in. tall? (Assume that 1 meter equals 39.37 in.)
7. Mount Everest, at 29,028 feet, is the tallest mountain on the Earth. What is its height in kilometers? (Assume that 1 kilometer equals 3,281 feet.) ANS: 8.847 km
8. The speed of sound is measured to be 342 m/s on a certain day. What is this in km/h?
9. Tectonic plates are large segments of the Earth's crust that move slowly. Suppose that one such plate has an average speed of 4.0 cm/year.
   a. What distance does it move in 1 s at this speed? ANS: $1.3 \times 10^{-9}\, m$

b. What is its speed in kilometers per million years? ANS: 40 km/My

10. a. Refer to Table to determine the average distance between the Earth and the Sun. Then calculate the average speed of the Earth in its orbit in kilometers per second.
    b. What is this in meters per second?

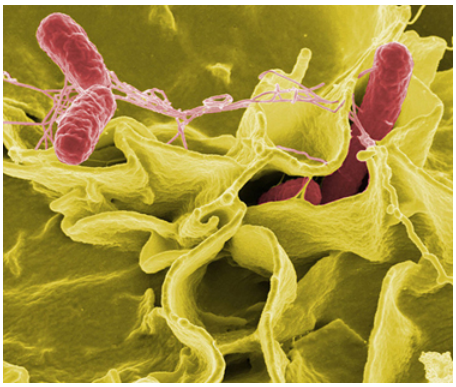
Accuracy, Precision, and Significant Figures

1. Suppose that your bathroom scale reads your mass as 65 kg with a 3% uncertainty. What is the uncertainty in your mass (in kilograms)? ANS: 2 kg
2. A good-quality measuring tape can be off by 0.50 cm over a distance of 20 m. What is its percent uncertainty?
3. a. A car speedometer has a 5.0 km/hr uncertainty. What is the range of possible speeds when it reads 90 km/hr? ANS: 85.5 to 94.5 km/hr
   b. Convert this range to miles per hour. (1 km=0.6214 mi) ANS: 53.1 to 58.7 mi/hr
4. An infant's pulse rate is measured to be 130±5130±5 beats/min. What is the percent uncertainty in this measurement?
5. a. Suppose that a person has an average heart rate of 72.0 beats/min. How many beats does he or she have in 2.0 y? ANS: $7.6 \times 10^7 beats$
   b. In 2.00 y? ANS: $7.57 \times 10^7 beats$
   c. In 2.000 y? ANS: $7.57 \times 10^7 beats$
6. A can contains 375 mL of soda. How much is left after 308 mL is removed?
7. State how many significant figures are proper in the results of the following calculations:
   a. $(106.7)(98.2)/(46.210)(1.01)$
   b. $(18.7)2$
   c. $(1.60 \times 10^{-19})(3712)$
8. a. How many significant figures are in the numbers 99 and 100?
   b. If the uncertainty in each number is 1, what is the percent uncertainty in each?
   c. Which is a more meaningful way to express the accuracy of these two numbers, significant figures or percent uncertainties?
9. a. If your speedometer has an uncertainty of 2.0km/hr at a speed of 90km/hr. what is the percent uncertainty? ANS: 2.2
   b. If it has the same percent uncertainty when it reads 60km/hr, what is the range of speeds you could be going? ANS: 59 to 61 km/hr
10. a. A person's blood pressure is measured to be 120±2 mm Hg. What is its percent uncertainty?
    b. Assuming the same percent uncertainty, what is the uncertainty in a blood pressure measurement of 80 mm Hg?
11. A person measures his or her heart rate by counting the number of beats in 30s. If 40±1 beats are counted in 30.0±0.5 s , what is the heart rate and its uncertainty in beats per minute? ANS: 80±3 beats/min
12. What is the area of a circle 3.102 cm in diameter?
13. If a marathon runner averages 9.5 mi/h, how long does it take him or her to run a 26.22-mi marathon? ANS: 2.8 hr
14. A marathon runner completes a 42.188−km course in 2h, 30 min, and 12s. There is an uncertainty of 25 m in the distance traveled and an uncertainty of 1 s in the elapsed time.
    a. (a) Calculate the percent uncertainty in the distance.
    b. Calculate the uncertainty in the elapsed time.
    c. What is the average speed in meters per second?
    d. What is the uncertainty in the average speed?
15. The sides of a small rectangular box are measured to be 1.80±0.01 cm, 2.05±0.02 cm, and 3.1±0.1 cm long. Calculate its volume and uncertainty in cubic centimeters. ANS: $11 \pm 1\, cm^3$
16. When non-metric units were used in the United Kingdom, a unit of mass called the pound-mass (lbm) was employed, where 1 lbm=0.4539 kg
    a. If there is an uncertainty of 0.0001 kg in the pound-mass unit, what is its percent uncertainty?
    b. Based on that percent uncertainty, what mass in pound-mass has an uncertainty of 1 kg when converted to kilograms?

17. The length and width of a rectangular room are measured to be 3.955±0.005 m and 3.050±0.005 m. Calculate the area of the room and its uncertainty in square meters. ANS: $12.06 \pm 0.04\, m^2$
18. A car engine moves a piston with a circular cross section of 7.500±0.002 cm diameter a distance of 3.250±0.001 cm to compress the gas in the cylinder.
    a. By what amount is the gas decreased in volume in cubic centimeters?
    b. Find the uncertainty in this volume.

Approximation

1. How many heartbeats are there in a lifetime? ANS: Sample answer: 2×10^9 heartbeats
2. A generation is about one-third of a lifetime. Approximately how many generations have passed since the year 0 AD?
3. How many times longer than the mean life of an extremely unstable atomic nucleus is the lifetime of a human? (Hint: The lifetime of an unstable atomic nucleus is on the order of $10^{-22}\, s$) ANS: Sample answer: 2×10^{31} if an average human lifetime is taken to be about 70 years.
4. Calculate the approximate number of atoms in a bacterium. Assume that the average mass of an atom in the bacterium is ten times the mass of a hydrogen atom. (Hint: The mass of a hydrogen atom is on the order of $10^{-27}\, kg$ and the mass of a bacterium is on the order of $10^{-15}\, kg$.)



This color-enhanced photo shows *Salmonella typhimurium* (red) attacking human cells. These bacteria are commonly known for causing foodborne illness. Can you estimate the number of atoms in each bacterium? (credit: Rocky Mountain Laboratories, NIAID, NIH)
5. Approximately how many atoms thick is a cell membrane, assuming all atoms there average about twice the size of a hydrogen atom? ANS: Sample answer: 50 atoms
6. a. What fraction of Earth's diameter is the greatest ocean depth?
   b. The greatest mountain height?
7. a. Calculate the number of cells in a hummingbird assuming the mass of an average cell is ten times the mass of a bacterium. ANS: Sample answer: 10^{12} cells/hummingbird
   b. Making the same assumption, how many cells are there in a human? ANS: Sample answer: 10^{16} cells/human
8. Assuming one nerve impulse must end before another can begin, what is the maximum firing rate of a nerve in impulses per second?

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CHAPTER OVERVIEW

2: Introduction to Environmental Sciences

2.1: The Chemical Foundations of Life

2.2: Biological Molecules

2.3: Biological Organization

2.4: Environment and environmental science

2.5: Sustainability and Sustainable Development

2.6: Appendix

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2.1: The Chemical Foundations of Life

Learning Objectives

At the end of this section, students will be able to:

- Describe, at an introductory level, the basic chemical and biological foundations of life on Earth
- Define environment, ecosystems, and environmental sciences
- Give examples of the interdisciplinary nature of environmental science
- Define sustainability and sustainable development
- Explain the complex relationship between natural and human systems, pertaining to environmental impact, the precautionary principle, and environmental justifications
- Understand scientific approach and begin to apply the scientific method

2.1.1: The Chemical and Biological Foundations of Life

Elements in various combinations comprise all matter on Earth, including living things. Some of the most abundant elements in living organisms include carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus. These form the nucleic acids, proteins, carbohydrates, and lipids that are the fundamental components of living matter. Biologists must understand these important building blocks and the unique structures of the atoms that make up molecules, allowing for the formation of cells, tissues, organ systems, and entire organisms.

At its most fundamental level, life is made up of **matter**. Matter is any substance that occupies space and has mass. **Elements** are unique forms of matter with specific chemical and physical properties that cannot be broken down into smaller substances by ordinary chemical reactions. There are 118 elements, but only 92 occur naturally. The remaining elements are synthesized in laboratories and are unstable. The five elements common to all living organisms are oxygen (O), carbon (C), hydrogen (H), and nitrogen (N) and phosphorous (P). In the non-living world, elements are found in different proportions, and some elements common to living organisms are relatively rare on the earth as a whole (Table 2.1.1). For example, the atmosphere is rich in nitrogen and oxygen but contains little carbon and hydrogen, while the earth's crust, although it contains oxygen and a small amount of hydrogen, has little nitrogen and carbon. In spite of their differences in abundance, all elements and the chemical reactions between them obey the same chemical and physical laws regardless of whether they are a part of the living or non-living world.

Table 2.1.1: Approximate percentage of elements in living organisms (from bacteria to humans) compared to the non-living world. Trace represents less than 1%.

	Biosphere	Atmosphere	Lithosphere
Oxygen (O)	65%	21%	46%
Carbon (C)	18%	trace	trace
Hydrogen (H)	10%	trace	trace
Nitrogen (N)	3%	78%	trace
Phosphorus (P)	trace	trace	>30%

2.1.2: The Structure of the Atom

An **atom** is the smallest unit of matter that retains all of the chemical properties of an element. For example, one gold atom has all of the properties of gold in that it is a solid metal at room temperature. A gold coin is simply a very large number of gold atoms molded into the shape of a coin and containing small amounts of other elements known as impurities. Gold atoms cannot be broken down into anything smaller while still retaining the properties of gold. An atom is composed of two regions: the **nucleus**, which is in the center of the atom and contains protons and neutrons, and the outermost region of the atom which holds its electrons in orbit

around the nucleus, as illustrated in Figure 2.1.1 Atoms contain protons, electrons, and neutrons, among other subatomic particles. The only exception is hydrogen (H), which is made of one proton and one electron with no neutrons.

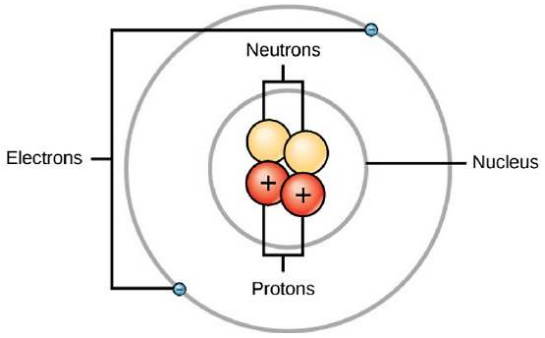


Figure 2.1.1: Elements, such as helium, depicted here, are made up of atoms. Atoms are made up of protons and neutrons located within the nucleus, with electrons in orbitals surrounding the nucleus.

Protons and neutrons have approximately the same mass, about 1.67×10^{-24} grams. Scientists arbitrarily define this amount of mass as one atomic mass unit (amu) (Table 2.1.2). Although similar in mass, protons and neutrons differ in their electric charge. A proton is positively charged whereas a **neutron** is uncharged. Therefore, the number of neutrons in an atom contributes significantly to its mass, but not to its charge.

Table 2.1.2: Protons, neutrons, and electrons

	Charge	Mass (amu)	Location in atom
Proton	+1	1	Nucleus
Neutron	0	1	Nucleus
Electron	-1	0	Orbitals

Electrons are much smaller in mass than protons, weighing only 9.11×10^{-28} grams, or about 1/1800 of an atomic mass unit. Hence, they do not contribute much to an element's overall atomic mass. Although not significant contributors to mass, electrons do contribute greatly to the atom's charge, as each electron has a negative charge equal to the positive charge of a proton. In uncharged, neutral atoms, the number of electrons orbiting the nucleus is equal to the number of protons inside the nucleus. In these atoms, the positive and negative charges cancel each other out, leading to an atom with no net charge. Accounting for the sizes of protons, neutrons, and electrons, most of the volume of an atom—greater than 99 percent—is, in fact, empty space. With all this empty space, one might ask why so-called solid objects do not just pass through one another. The reason they do not is that the electrons that surround all atoms are negatively charged and negative charges repel each other. When an atom gains or loses an electron, an **ion** is formed. Ions are charged forms of atoms. A positively charged ion, such as sodium (Na^+), has lost one or more electrons. A negatively charged ion, such as chloride (Cl^-), has gained one or more electrons.

2.1.3: Molecules

Molecules are formed when two or more atoms join together through chemical bonds to form a unit of matter. Throughout your study of environmental science, you will encounter many molecules including carbon dioxide gas. Its chemical formula is CO_2, indicating that this molecule is made up of one carbon atom and two oxygen atoms. Some molecules are charged due to the ions they contain. This is the case for the nitrate (NO_3^-), a common source of nitrogen to plants. It contains one nitrogen atom and three oxygen atoms, and has an overall charge of negative one.

2.1.4: Isotopes

Isotopes are different forms of an element that have the same number of protons but a different number of neutrons. Some elements—such as carbon, potassium, and uranium—have naturally occurring isotopes. Carbon-12 contains six protons, six neutrons, and six electrons; therefore, it has a mass number of 12 (six protons and six neutrons). Carbon-14 contains six protons, eight neutrons, and six electrons; its atomic mass is 14 (six protons and eight electrons). These two alternate forms of carbon are isotopes. Some isotopes may emit neutrons, protons, and electrons, and attain a more stable atomic configuration (lower level of

potential energy); these are radioactive isotopes, or radioisotopes. Radioactive decay describes the energy loss that occurs when an unstable atom's nucleus releases radiation, for example, carbon-14 losing neutrons to eventually become carbon-12.

2.1.5: Carbon

The basic functional unit of life is a cell and all organisms are made up of one or more cells. Cells are made of many complex molecules called macromolecules, such as proteins, nucleic acids (RNA and DNA), carbohydrates, and lipids. The macromolecules are a subset of **organic molecules** that are especially important for life. The fundamental component for all of these macromolecules is carbon. The carbon atom has unique properties that allow it to form covalent bonds with as many as four different atoms, making this versatile element ideal to serve as the basic structural component, or "backbone," of the macromolecules.

2.1.6: Hydrocarbons

Hydrocarbons are organic molecules consisting entirely of carbon and hydrogen, such as methane (CH_4). We often use hydrocarbons in our daily lives as fuels—like the propane in a gas grill or the butane in a lighter. The many covalent bonds between the atoms in hydrocarbons store a great amount of energy, which is released when these molecules are burned (oxidized). Methane, an excellent fuel, is the simplest hydrocarbon molecule, with a central carbon atom bonded to four different hydrogen atoms, as illustrated in Figure 2.1.2.

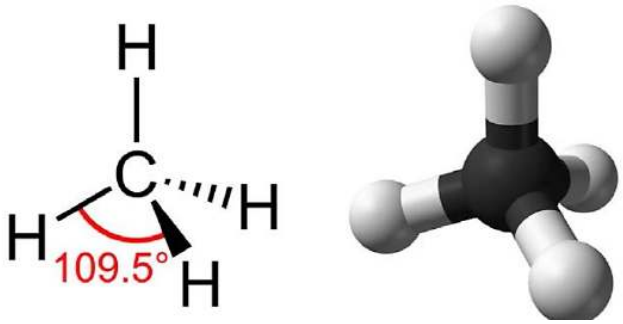


Figure 2.1.2: Methane (CH_4) has a tetrahedral geometry, with each of the four hydrogen atoms spaced 109.5° apart.

As the backbone of the large molecules of living things, hydrocarbons may exist as linear carbon chains, carbon rings, or combinations of both. This three-dimensional shape or conformation of the large molecules of life (macromolecules) is critical to how they function.

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2.2: Biological Molecules

Life on Earth is primarily made up of four major classes of biological molecules, or biomolecules. These include carbohydrates, lipids, proteins, and nucleic acids.

Most people are familiar with **carbohydrates**, one type of macromolecule, especially when it comes to what we eat. Carbohydrates are, in fact, an essential part of our diet; grains, fruits, and vegetables are all natural sources of carbohydrates. Carbohydrates provide energy to the body, particularly through **glucose**, a simple sugar that is a component of **starch** and an ingredient in many staple foods. Carbohydrates also have other important functions in humans, animals, and plants. Carbohydrates can be represented by the stoichiometric formula $(CH_2O)n$, where n is the number of carbons in the molecule. In other words, the ratio of carbon to hydrogen to oxygen is 1:2:1 in carbohydrate molecules. This formula also explains the origin of the term “carbohydrate”: the components are carbon (“carbo”) and the components of water (hence, “hydrate”). The chemical formula for glucose is $C_6H_{12}O_6$. In humans, glucose is an important source of energy.

During **cellular respiration,** energy is released from glucose, and that energy is used to help make **adenosine triphosphate** (ATP). Plants synthesize glucose using carbon dioxide and water, and glucose in turn is used for energy requirements for the plant. Excess glucose is often stored as starch that is catabolized (the breakdown of larger molecules by cells) by humans and other animals that feed on plants. Plants are able to synthesize glucose, and the excess glucose, beyond the plant’s immediate energy needs, is stored as starch in different plant parts, including roots and seeds. The starch in the seeds provides food for the embryo as it germinates and can also act as a source of food for humans and animals.

Lipids include a diverse group of compounds such as fats, oils, waxes, phospholipids, and steroids that are largely nonpolar in nature. Nonpolar molecules are hydrophobic (“water fearing”), or insoluble in water. These lipids have important roles in energy storage, as well as in the building of cell membranes throughout the body.

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. Proteins may be structural, regulatory, contractile, or protective; they may serve in transport, storage, or membranes; or they may be toxins or enzymes. Each cell in a living system may contain thousands of proteins, each with a unique function. Their structures, like their functions, vary greatly.

Enzymes, which are produced by living cells, speed up biochemical reactions (like digestion) and are usually complex proteins. Each enzyme has a specific shape or formation based on its use. The enzyme may help in breakdown, rearrangement, or synthesis reactions.

Proteins have different shapes and molecular weights. Protein shape is critical to its function, and many different types of chemical bonds maintain this shape. Changes in temperature, pH, and exposure to chemicals may cause a protein to **denature**. This is a permanent change in the shape of the protein, leading to loss of function. All proteins are made up of different arrangements of the same 20 types of **amino acids**. These amino acids are the units that make up proteins. Ten of these are considered essential amino acids in humans because the human body cannot produce them and they are obtained from the diet. The sequence and the number of amino acids ultimately determine the protein's shape, size, and function.

Nucleic acids are the most important macromolecules for the continuity of life. They carry the genetic blueprint of a cell and carry instructions for the functioning of the cell. The two main types of nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA is the genetic material found in all living organisms, ranging from single-celled bacteria to multicellular mammals. DNA controls all of the cellular activities by turning the genes “on” or “off.” The other type of nucleic acid, RNA, is mostly involved in protein synthesis. DNA has a double-helix structure (Figure 2.2.1)

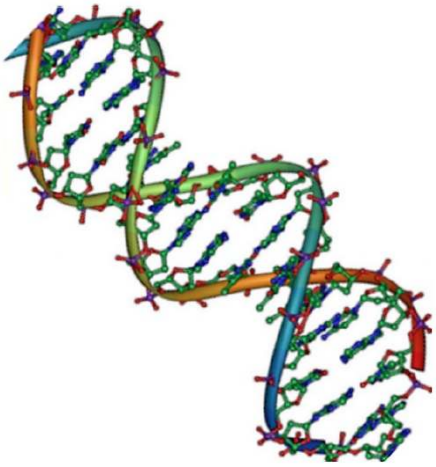


Figure 2.2.1: Native DNA is an antiparallel double helix. The phosphate backbone (indicated by the curvy lines) is on the outside, and the bases are on the inside. Each base from one strand interacts via hydrogen bonding with a base from the opposing strand. (credit: Jerome Walker/Dennis Myts)

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2.3: Biological Organization

All living things are made of cells; the **cell** itself is the smallest fundamental unit of structure and function in living organisms. In most organisms, these cells contain **organelles**, which provide specific functions for the cell. Living **organisms** have the following properties: all are highly organized, all require energy for maintenance and growth, and all grow over time and respond to their environment. All organisms adapt to the environment and all ultimately reproduce contributing genes to the next generation. Some organisms consist of a single cell and others are multicellular. Organisms are individual living entities. For example, each tree in a forest is an organism.

All the individuals of a species living within a specific area are collectively called a **population**. Populations fluctuate based on a number of factors: seasonal and yearly changes in the environment, natural disasters such as forest fires and volcanic eruptions, and competition for resources between and within species. A **community** is the sum of populations inhabiting a particular area. For instance, all of the trees, insects, and other populations in a forest form the forest's community. The forest itself is an ecosystem.

An **ecosystem** consists of all the living things in a particular area together with the abiotic, nonliving parts of that environment such as nitrogen in the soil or rain water. At the highest level of organization, the **biosphere** is the collection of all ecosystems, and it represents the zones of life on earth. It includes land, water, and even the atmosphere to a certain extent.

Life in an ecosystem is often about competition for limited resources, a characteristic of the process of natural selection. **Competition** in communities (all living things within specific habitats) is observed both within species and among different species. The resources for which organisms compete include organic material from living or previously living organisms, sunlight, and mineral nutrients, which provide the energy for living processes and the matter to make up organisms' physical structures. Other critical factors influencing community dynamics are the components of its physical and geographic environment: a habitat's latitude, amount of rainfall, topography (elevation), and available species. These are all important environmental variables that determine which organisms can exist within a particular area. Ecosystems can be small, such as the tidal pools found near the rocky shores of many oceans, or large, such as the Amazon Rainforest in Brazil (Figure 2.3.1).

There are three broad categories of ecosystems based on their general environment: freshwater, ocean water (marine), and terrestrial. Within these broad categories are individual ecosystem types based on the organisms present and the type of environmental habitat. Ocean ecosystems are the most common, comprising 75 percent of the Earth's surface. The shallow ocean ecosystems include extremely biodiverse coral reef ecosystems, and the deep ocean surface is known for its large numbers of plankton and krill (small crustaceans) that support it. These two environments are especially important to aerobic respirators worldwide as the phytoplankton perform 40 percent of all photosynthesis on Earth. Although not as diverse as the other two, deep ocean ecosystems contain a wide variety of marine organisms. Such ecosystems exist even at the bottom of the ocean where light is unable to penetrate through the water. Freshwater ecosystems are the rarest, occurring on only 1.8 percent of the Earth's surface. Lakes, rivers, streams, and springs comprise these systems; they are quite diverse, and they support a variety of fish, amphibians, reptiles, insects, phytoplankton, fungi, and bacteria.



Figure 2.3.1: (a) A tidal pool ecosystem in Matinicus Island, Maine, is a small ecosystem, while (b) the Amazon rainforest in Brazil is a large ecosystem. (credit a: modification of work by Jim Kuhn; credit b: modification of work by Ivan Mlinaric)

Terrestrial ecosystems, also known for their diversity, are grouped into large categories called **biomes**, such as tropical rainforests, savannas, deserts, coniferous forests, deciduous forests, and tundra. Grouping these ecosystems into just a few biome categories obscures the great diversity of the individual ecosystems within them. For example, there is great variation in desert vegetation: the saguaro cacti and other plant life in the Sonoran Desert, in the United States, are relatively abundant compared to the desolate rocky desert of Boa Vista, an island off the coast of Western Africa.

All living things require energy in one form or another. It is important to understand how organisms acquire energy and how that energy is passed from one organism to another through **food webs**. Food webs illustrate how energy flows directionally through ecosystems, including how efficiently organisms acquire it, use it, and how much remains for use by other organisms of the food web. The flow of energy and matter through the ecosystems influences the abundance and distribution of organisms within them.

Ecosystems are complex with many interacting parts. They are routinely exposed to various disturbances: changes in the environment that affect their compositions, such as yearly variations in rainfall and temperature. Many disturbances are a result of natural processes. For example, when lightning causes a forest fire and destroys part of a forest ecosystem, the ground is eventually populated with grasses, followed by bushes and shrubs, and later mature trees: thus, the forest is restored to its former state. This process is so universal that ecologists have given it a name—**succession**. The impact of environmental disturbances caused by human activities is now as significant as the changes wrought by natural processes. Human agricultural practices, air pollution, acid rain, global deforestation, overfishing, oil spills, and illegal dumping on land and into the ocean all have impacts on ecosystems.

We rely on **ecosystem services.** Earth's natural systems provide ecosystem services required for our survival such as: air and water purification, climate regulation, and plant pollination. We have degraded nature's ability to provide these services by depleting resources, destroying habitats, and generating pollution. The benefits people obtain from ecosystems include: nutrient cycling, soil formation, and **primary production**. Another important service of natural ecosystems is provisioning like food production, production of wood, fibers and fuel. Ecosystems are responsible for climate regulation, flood regulation together with disease regulation. Finally ecosystems provide cultural and esthetic services. As humans we benefit from observing natural habitats, recreation in waters and mountains. Nature is a source of inspiration for poets and writers. It is a source of aesthetic, religious and other nonmaterial benefits. Studying ecosystem structure in its original state is the only way we can make **anthropogenic** (man-made) systems like agricultural fields, reservoirs, fracking operations, and dammed rivers work for human benefit with minimal impact on our and other organisms' health.

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2.4: Environment and environmental science

Viewed from space, Earth **(Figure** 2.4.1) offers no clues about the diversity of lifeforms that reside there. The first forms of life on Earth are thought to have been microorganisms that existed for billions of years in the ocean before plants and animals appeared. The mammals, birds, and plants so familiar to us are all relatively recent, originating 130 to 200 million years ago. Humans have inhabited this planet for only the last 2.5 million years, and only in the last 200,000 years have humans started looking like we do today. There are around 8.1 billion people today (https://www.census.gov/popclock/).



Figure 2.4.1: This NASA image is a composite of several satellite-based views of Earth. To make the whole-Earth image, NASA scientists combine observations of different parts of the planet. (credit: NASA/GSFC/NOAA/USGS)

The word **environment** describes living and nonliving surroundings relevant to organisms. It incorporates physical, chemical and biological factors and processes that determine the growth and survival of organisms, populations, and communities. All these components fit within the ecosystem concept as a way to organize all of the factors and processes that make up the environment. The ecosystem includes organisms and their environment within a specific area. Review the previous section for in-depth information regarding the Earth's ecosystems. Today, human activities influence all of the Earth's ecosystems.

Environmental science studies all aspects of the environment in an **interdisciplinary** way. This means that it requires the knowledge of various other subjects including biology, chemistry, physics, statistics, microbiology, biochemistry, geology, economics, law, sociology, etc. It is a relatively new field of study that has evolved from integrated use of many disciplines. **Environmental engineering** is one of the fastest growing and most complex disciplines of engineering. Environmental engineers solve problems and design systems using knowledge of environmental concepts and ecology, thereby providing solutions to various environmental problems. **Environmentalism**, in contrast, is a social movement through which citizens are involved in activism to further the protection of environmental landmarks and natural resources. This is not a field of science, but incorporates some aspects of environmental knowledge to advance conservation and sustainability efforts.

2.4.1: The Process of Science

Environmental science is a science, but what exactly is science? **Science** (from the Latin scientia, meaning "knowledge") can be defined as all of the fields of study that attempt to comprehend the nature of the universe and all its parts. The **scientific method** is a method of research with defined steps that include experiments and careful observation. One of the most important aspects of this method is the testing of hypotheses by means of repeatable experiments. A **hypothesis** is a suggested explanation for an event, which can be tested. A **theory** is a tested and confirmed explanation for observations or phenomena that is supported by many repeated experiences and observations.

2.4.1.1: The scientific method

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed. Let's think about a simple problem that starts with an observation and apply the scientific method to solve the problem. One Monday morning, a student arrives in class and quickly discovers that the classroom is too warm. That is an observation that also describes a problem: the classroom is too warm. The student then asks a question: "Why is the classroom so warm?"

2.4.1.1.1: Proposing a Hypothesis

Recall that a hypothesis is a suggested explanation that can be tested. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, “The classroom is warm because no one turned on the air conditioning.” But there could be other responses to the question, and therefore other hypotheses may be proposed. A second hypothesis might be, “The classroom is warm because there is a power failure, and so the air conditioning doesn’t work.” Once a hypothesis has been selected, the student can make a prediction. A prediction is similar to a hypothesis but it typically has the format “If . . . then . . . .” For example, the prediction for the first hypothesis might be, “If the student turns on the air conditioning, then the classroom will no longer be too warm.”

2.4.1.1.2: Testing a Hypothesis

A valid hypothesis must be testable. It should also be falsifiable, meaning that it can be disproven by experimental results. Importantly, science does not claim to “prove” anything because scientific understandings are always subject to modification with further information. This step — openness to disproving ideas — is what distinguishes sciences from non-sciences. The presence of the supernatural, for instance, is neither testable nor falsifiable.

To test a hypothesis, a researcher will conduct one or more **experiments** designed to eliminate, or disprove, the hypotheses. Each experiment will have one or more variables and one or more controls. A **variable** is any part of the experiment that can vary or change during the experiment. The **independent variable** is the variable that is manipulated throughout the course of the experiment. The **dependent variable**, or response variable is the variable by which we measure change in response to the independent variable. Ideally, all changes that we measure in the dependent variable are because of the manipulations we made to the independent variable. In most experiments, we will maintain one group that has had no experimental change made to it. This is the **control group**. It contains every feature of the **experimental group** except it is not given any manipulation. Therefore, if the results of the experimental group differ from the control group, the difference must be due to the hypothesized manipulation, rather than some outside factor. Look for the variables and controls in the examples that follow.

To test the hypothesis *“The classroom is warm because no one turned on the air conditioning,”* the student would find out if the air conditioning is on. If the air conditioning is turned on but does not work, there should be another reason, and this hypothesis should be rejected. To test the second hypothesis, the student could check if the lights in the classroom are functional. If so, there is no power failure and this hypothesis should be rejected. Each hypothesis should be tested by carrying out appropriate experiments. Be aware that rejecting one hypothesis does not determine whether or not the other hypotheses can be accepted; it simply eliminates one hypothesis that is not valid (Figure 2.4.2). Using the scientific method, the hypotheses that are inconsistent with experimental data are rejected.

The scientific method may seem too rigid and structured. It is important to keep in mind that, although scientists often follow this sequence, there is flexibility. Sometimes an experiment leads to conclusions that favor a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Many times, science does not operate in a linear fashion; instead, scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests. Notice, too, that the scientific method can be applied to solving problems that aren’t necessarily scientific in nature.

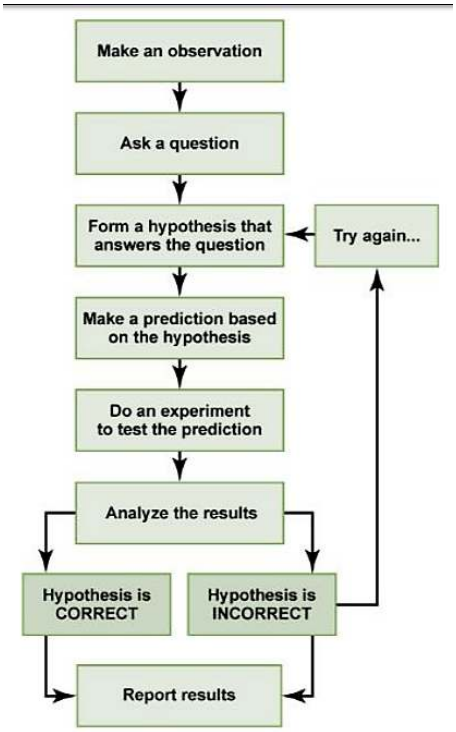


Figure 12.4.2: The scientific method consists of a series of well-defined steps. If a hypothesis is not supported by experimental data, a new hypothesis can be proposed.

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2.5: Sustainability and Sustainable Development

In 1983 the United Nations General Assembly passed a resolution that established the Special Commission on the Environmental Perspective to the Year 2000 and Beyond (www.un.org/documents/ga/res/38/a38r161.htm).

Their charge was:

a. To propose long-term environmental strategies for achieving sustainable development to the year 2000 and beyond;

b. To recommend ways in which concern for the environment may be translated into greater co-operation among developing countries and between countries at different stages of economic and social development and lead to the achievement of common and mutually supportive objectives which take account of the interrelationships between people, resources, environment and development;

c. To consider ways and means by which the international community can deal more effectively with environmental concerns, in light of the other recommendations in its report;

d. To help define shared perceptions of long-term environmental issues and of the appropriate efforts needed to deal successfully with the problems of protecting and enhancing the environment, a long-term agenda for action during the coming decades, and aspirational goals for the world community, taking into account the relevant resolutions of the session of a special character of the Governing Council in 1982.

Although the report did not technically invent the term **sustainability**, it was the first credible and widely disseminated study that used this term in the context of the global impacts of humans on the environment. Its main and often quoted definition refers to **sustainable development** as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. The report uses the terms 'sustainable development', 'sustainable', and 'sustainability' interchangeably, emphasizing the connections among social equity, economic productivity, and environmental quality (Figure 2.5.1). This three-pronged approach to sustainability is now commonly referred to as the **triple bottom-line**. Preserving the environment for humans today and in the future is a responsibility of every generation and a long-term global goal. Sustainability and the triple bottom-line (meeting environmental, economic, and social goals simultaneously) require that we limit our environmental impact, while promoting economic well-being and social equity.

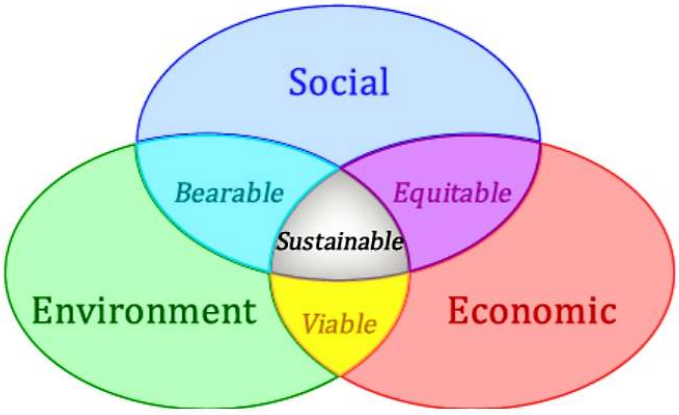


Figure 2.5.1: A depiction of the sustainability paradigm in terms of its three main components, showing various intersections among them. Source: International Union for the Conservation of Nature.

Examples of sustainable development include sustainable agriculture, which is agriculture that does not deplete soils faster than they form and does not destroy the biodiversity of the area. Sustainable farming and ranching do not reduce the amount of healthy soil, clean water, genetic diversity of crop plants and animals. Maintaining as much ecological **biodiversity** as possible in the agro-ecosystem is essential to long-term crop and livestock production.

2.5.1: The IPAT Equation

As attractive as the concept of sustainability may be as a means of framing our thoughts and goals, its definition is rather broad and difficult to work with when confronted with choices among specific courses of action. One way of measuring progress toward

achieving sustainable goals can be with the application of the **IPAT equation.** This equation was designed in an attempt to define the different ways that a variety of factors contribute to the environmental degradation, or impact, of a particular setting. Importantly, IPAT tells us that there are more ways we impact our environment than just through pollution:

$$I = P \times A \times T \tag{2.5.1}$$

I represents the impacts on an environment

P is the size of the relevant human population

A is the affluence of the population

T is the technology available to the population

Affluence, or wealth, tells us the level of consumption per person. Wealthy societies consume more goods and services per person. Because of this, their environmental impact is multiplied. Technology, or impact per unit of consumption, interpreted in its broadest sense. This includes any human-created tool, system, or organization designed to enhance efficiency. As societies gain greater access to technology, they are able to do more work with fewer individuals. This equates to a greater impact per person. While this equation is not meant to be mathematically rigorous, it provides a way of organizing information for analysis.

The proportion of people living in cities has greatly increased over the past 50 years. We can use the IPAT equation to estimate the impact of these urban populations. When the impact of technology, which is much easier to access in urban settings, is combined with the impact of population, the impact on the environment is multiplied. In an increasingly urban world, we must focus much of our attention on the environments of cities and on the effects of cities on the rest of the environment. This equation also has large-scale applications in the environmental sciences and was included in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (2001) to project future greenhouse gas emissions across the globe.

2.5.2: The precautionary principle

The precautionary principle or the precautionary approach is one perspective of environmental risk management. The precautionary principle stakes that “When the health of humans and the environment is at stake, it may not be necessary to wait for scientific certainty to take protective action”. In other words, better to be safe than sorry. Proponents of the precautionary principle also believe that the burden of proof should be on the individual, company or government who is proposing the action, not on the people who will be affected by it. For example, if environmental regulations concerning pesticides were based on the precautionary principle (in the United States, they are not), then any pesticide that could potentially harm the environment or human health would not be used. Overuse of the precautionary principle can have negative consequences as well. If federal regulations concerning medicines for human use were based on the precautionary principle (again, in the United States, they are not), then any medicine that could potentially harm any person would not be used. This would effectively ban nearly all medical trials leading to new medications.

2.5.3: What is the environment worth to you?

The environment, and its benefits to individuals or groups, can be viewed and justified from multiple perspectives. A **utilitarian justification** for environmental conservation means that we should protect the environment because doing so provides a direct economic benefit to people. For example, someone might propose not developing Georgia’s coastal salt marshes because the young of many commercial fishes live in salt marshes and the fishers will collapse without this habitat. An **ecological justification** for environmental conservation means that we should protect the environment because doing so will protect both species that are beneficial to other as well as other species and an ecological justification for conservation acknowledges the many ecosystem services that we derive from healthy ecosystems. For example, we should protect Georgia’s coastal salt marshes because salt marshes purify water, salt marshes are vital to the survival of many marine fishes and salt marshes protect our coasts from storm surges. An **aesthetic justification** for conservation acknowledges that many people enjoy the outdoors and do not want to live in a world without wilderness. One could also think of this as recreational, inspirational, or spiritual justification for conservation. For example, salt marshes are beautiful places and I always feel relaxed and calm when I am visiting one, therefore we should protect salt marshes. And finally, a **moral justification** represents the belief that various aspects of the environment have a right to exist and that it is our moral obligation to allow them to continue or help them persist. Someone who was arguing for conservation using a moral justification would say that it is wrong to destroy the coastal salt marshes.

2.5.4: Global perspective

The solution to most environmental problems requires a global perspective. Human population size has now reached a scale where the environmental impacts are global in scale and will require multilateral solutions. You will notice this theme continue as you move through the next seven chapters of this text. As you do so, keep in mind that the set of environmental, regulatory, and economic circumstances common in the United States are not constant throughout the world. Be ready to investigate environmental situations and problems from a diverse set of viewpoints throughout this semester.

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2.6: Appendix

Parts of this chapter have been modified from the OpenStax textbooks.

2.6.1: Study questions

1. Why there was a need to study the impact of human population growth on the environment?

2. What does sustainability mean to you?

3. What are the consequences of unsustainable vs. sustainable living? What impacts do these have on quality of life do we want for us and future generations?

4. Think of an environmental problem that requires a global perspective for a solution. How might this problem be examined from a variety of environmental justification perspectives?

2.6.2: Websites for more information and further discussion

Information about the field of environmental science: www.environmentalscience.org/

"Process" of science undsci.berkeley.edu/

2.6.3: Terms List

Adenosine triphosphate

Aesthetic justification

Amino acid

Anthropogenic

Atom

ATP

Biome

Biosphere

Carbohydrate

Cellular respiration

Community

Competition

Control group

Denature

Deoxyribonucleic acid

Dependent variable

DNA

Ecological justification

Ecosystem

Ecosystem service

Electron

Element

Environment

Environmental engineering

Environmental science

Environmentalism

Experiment

Experimental group

Food web

Glucose

Hydrocarbon

Hypothesis

Independent variable

Interdisciplinary

Ion

IPAT equation

Isotope

Lipid

Matter

Molecule

Moral justification

Neutron

Nucleic acid

Nucleus

Organelle

Organic molecule

Organism

Population

Precautionary principle

Primary production

Protein

Proton

Radioisotope

Ribonucleic acid

RNA

Science

Scientific method

Starch

Succession

Sustainability

Sustainable development

Theory

Triple-bottom-line

Utilitarian justification

Variable

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CHAPTER OVERVIEW

3: Population Ecology

3.1: Introduction

3.2: Population Growth Models

3.3: Factors Limiting Population Growth

3.4: Life Tables and Survivorship

3.5: Population Ecology Practice Problems

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3.1: Introduction

Learning Objectives

At the end of this, chapter students will be able to:

- Define the variables in the exponential and logistic growth equations.
- Use the exponential and logistic equations to predict population growth rate.
- Compare the environmental conditions represented by the exponential growth model vs. the logistic growth model.
- Define carrying capacity and be able to label the carrying capacity on a graph.
- Compare density-dependent and density-independent factors that limit population growth and give examples of each.
- Interpret survivorship curves and give examples of organisms that would fit each type of curve.

Ecology is a sub-discipline of biology that studies the interactions between organisms and their environments. A group of interbreeding individuals (individuals of the same species) living and interacting in a given area at a given time is defined as a **population**. These individuals rely on the same resources and are influenced by the same environmental factors. **Population ecology,** therefore, is the study of how individuals of a particular species interact with their environment and change over time. The study of any population usually begins by determining how many individuals of a particular species exist, and how closely associated they are with each other. Within a particular habitat, a population can be characterized by its **population size (N)**, defined by the total number of individuals, and its **population density,** the number of individuals of a particular species within a specific area or volume (units are number of individuals/unit area or unit volume). Population size and density are the two main characteristics used to describe a population. For example, larger populations may be more stable and able to persist better than smaller populations because of the greater amount of genetic variability, and their potential to adapt to the environment or to changes in the environment. On the other hand, a member of a population with low population density (more spread out in the habitat), might have more difficulty finding a mate to reproduce compared to a population of higher density. Other characteristics of a population include **dispersion** – the way individuals are spaced within the area; **age structure** – number of individuals in different age groups and; **sex ratio** – proportion of males to females; and growth – change in population size (increase or decrease) over time.



A population of elephants at Pinnewala Elephant Orphanage, Sri Lanka. Photo by Paginazero, Wikimedia commons.



A shoal of anchovies in Liguria, Italy. Photo by Alessandro Duci. Wikimedia commons.

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3.2: Population Growth Models

Populations change over time and space as individuals are born or immigrate (arrive from outside the population) into an area and others die or emigrate (depart from the population to another location). Populations grow and shrink and the age and gender composition also change through time and in response to changing environmental conditions. Some populations, for example trees in a mature forest, are relatively constant over time while others change rapidly. Using idealized models, population ecologists can predict how the size of a particular population will change over time under different conditions.

3.2.1: Exponential Growth

Charles Darwin, in his theory of natural selection, was greatly influenced by the English clergyman Thomas Malthus. Malthus published a book (An Essay on the Principle of Population) in 1798 stating that populations with unlimited natural resources grow very rapidly. According to the Malthus' model, once population size exceeds available resources, population growth decreases dramatically. This accelerating pattern of increasing population size is called **exponential growth**, meaning that the population is increasing by a fixed percentage each year. When plotted (visualized) on a graph showing how the population size increases over time, the result is a J-shaped curve (Figure 3.2.1). Each individual in the population reproduces by a certain amount (r) and as the population gets larger, there are more individuals reproducing by that same amount (the fixed percentage). In nature, exponential growth only occurs if there are no external limits.

One example of exponential growth is seen in bacteria. Bacteria are prokaryotes (organisms whose cells lack a nucleus and membrane-bound organelles) that reproduce by fission (each individual cell splits into two new cells). This process takes about an hour for many bacterial species. If 100 bacteria are placed in a large flask with an unlimited supply of nutrients (so the nutrients will not become depleted), after an hour, there is one round of division and each organism divides, resulting in 200 organisms - an increase of 100. In another hour, each of the 200 organisms divides, producing 400 - an increase of 200 organisms. After the third hour, there should be 800 bacteria in the flask - an increase of 400 organisms. After ½ a day and 12 of these cycles, the population would have increased from 100 cells to more than 24,000 cells. When the population size, N, is plotted over time, a J-shaped growth curve is produced (Figure 3.2.1). This shows that the number of individuals added during each reproduction generation is accelerating – increasing at a faster rate.

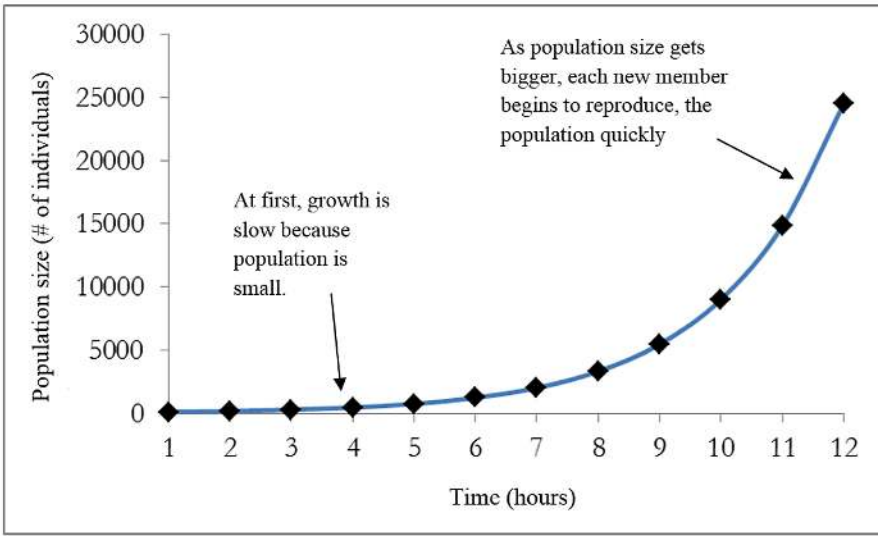


Figure 3.2.1: The "J" shaped curve of exponential growth for a hypothetical population of bacteria. The population starts out with 100 individuals and after 11 hours there are over 24,000 individuals. As time goes on and the population size increases, the rate of increase also increases (each step up becomes bigger). In this figure "r" is positive.

This type of growth can be represented using a mathematical function known as the exponential growth model:

$$G = r \times N$$

also expressed as

$$\frac{dN}{dt} = r \times N$$

In these equation

- G (or $\frac{dN}{dt}$) is the population growth rate, it is a measure of the number of individuals added per time interval time.
- r is the per capita rate of increase (the average contribution of each member in a population to population growth; per capita means “per person”).
- N is the population size, the number of individuals in the population at a particular time.

3.2.1.1: Per capita rate of increase (r)

In exponential growth, the *population growth rate* (***G***) depends on population size (***N***) and the per capita rate of increase (***r***). In this model *r* does not change (fixed percentage) and change in population growth rate, ***G***, is due to change in population size, ***N***. As new individuals are added to the population, each of the new additions contribute to population growth at the same rate (*r*) as the individuals already in the population.

$$r = (\text{birth rate} + \text{immigration rate})–(\text{death rate and emigration rate}).$$

- If r is positive (> zero), the population is increasing in size; this means that the birth and immigration rates are greater than death and emigration.
- If r is negative (< zero), the population is decreasing in size; this means that the birth and immigration rates are less than death and emigration rates.
- If r is zero, then the population growth rate (G) is zero and population size is unchanging, a condition known as zero population growth. “r” varies depending on the type of organism, for example a population of bacteria would have a much higher “r” than an elephant population. In the exponential growth model r is multiplied by the population size, N, so population growth rate is largely influenced by N. This means that if two populations have the same per capita rate of increase (r), the population with a larger N will have a larger population growth rate than the one with a smaller N.

3.2.2: Logistic Growth

Exponential growth cannot continue forever because resources (food, water, shelter) will become limited. Exponential growth may occur in environments where there are few individuals and plentiful resources, but soon or later, the population gets large enough that individuals run out of vital resources such as food or living space, slowing the growth rate. When resources are limited, populations exhibit **logistic growth**. In logistic growth a population grows nearly exponentially at first when the population is small and resources are plentiful but growth rate slows down as the population size nears limit of the environment and resources begin to be in short supply and finally stabilizes (zero population growth rate) at the maximum population size that can be supported by the environment (**carrying capacity**). This results in a characteristic S-shaped growth curve (Figure 3.2.2). The mathematical function or logistic growth model is represented by the following equation:

$$G = r \times N \times \left(1 - \frac{N}{K}\right)$$

where K is the **carrying capacity** – the maximum population size that a particular environment can sustain (“carry”). Notice that this model is similar to the exponential growth model except for the addition of the carrying capacity. In the exponential growth model, population growth rate was mainly dependent on *N* so that each new individual added to the population contributed equally to its growth as those individuals previously in the population because per capita rate of increase is fixed. In the logistic growth model, individuals’ contribution to population growth rate depends on the amount of resources available (K). As the number of individuals (N) in a population increases, fewer resources are available to each individual. As resources diminish, each individual on average, produces fewer offspring than when resources are plentiful, causing the birth rate of the population to decrease.

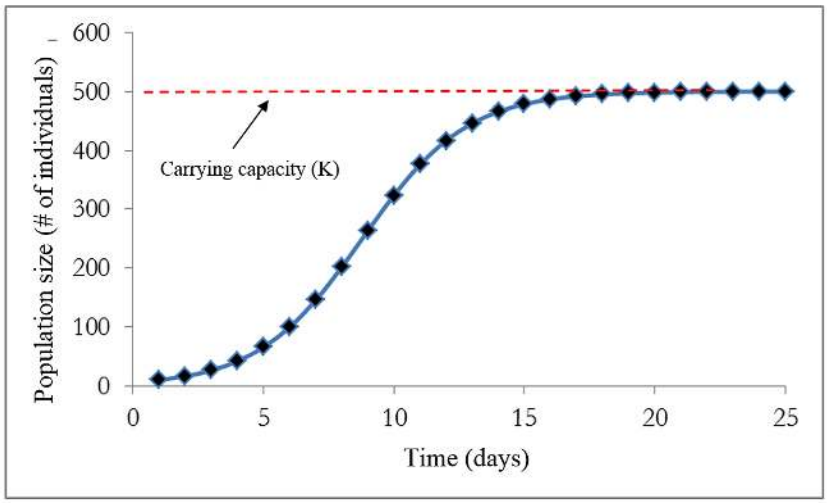


Figure 3.2.2: Shows logistic growth of a hypothetical bacteria population. The population starts out with 10 individuals and then reaches the carrying capacity of the habitat which is 500 individuals.

3.2.2.1: Influence of K on population growth rate

In the logistic growth model, the exponential growth $(r \times N)$ is multiplied by fraction or expression that describes the effect that limiting factors $(1 - \frac{N}{K})$ have on an increasing population. Initially when the population is very small compared to the capacity of the environment (K), $1 - \frac{N}{K}$ is a large fraction that nearly equals 1 so population growth rate is close to the exponential growth $(r \times N)$. For example, supposing an environment can support a maximum of 100 individuals and N = 2, N is so small that $1 - \frac{N}{K}$ $1 - \frac{2}{100} = 0.98$ will be large, close to 1. As the population increases and population size gets closer to carrying capacity (N nearly equals K), then $1 - \frac{N}{K}$is a small fraction that nearly equals zero and when this fraction is multiplied by $r \times N$, population growth rate is slowed down. In the earlier example, if the population grows to 98 individuals, which is close to (but not equal) K, then $1 - \frac{N}{K}$ $(1 - \frac{98}{100} = 0.02)$ will be so small, close to zero. If population size equals the carrying capacity, $\frac{N}{K} = 1$, so $1 - \frac{N}{K} = 0$, population growth rate will be zero (in the above example, $1 - \frac{100}{100} = 0$. This model, therefore, predicts that a population's growth rate will be small when the population size is either small or large, and highest when the population is at an intermediate level relative to K. At small populations, growth rate is limited by the small amount of individuals (N) available to reproduce and contribute to population growth rate whereas at large populations, growth rate is limited by the limited amount of resources available to each of the large number of individuals to enable them reproduce successfully. In fact, maximum population growth rate (G) occurs when N is half of K.

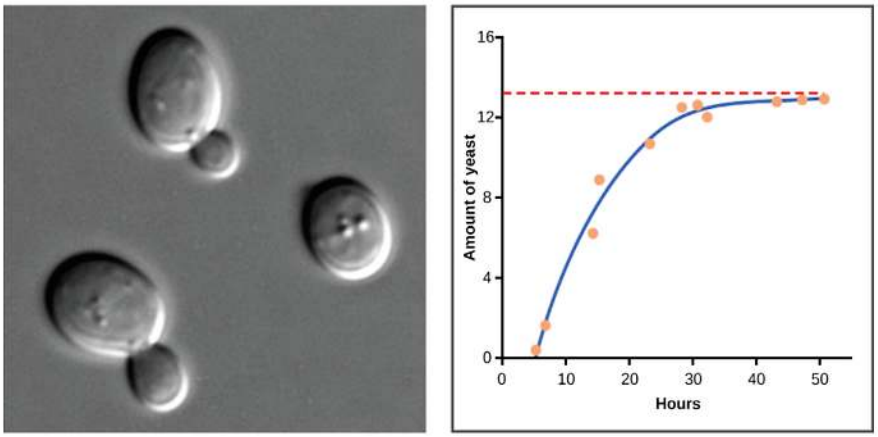


Figure 3.2.3: Graph showing amount of yeast versus time of growth in hours. The curve rises steeply, and then plateaus at the carrying capacity. Data points tightly follow the curve. The image is a micrograph (microscope image) of yeast cells

Yeast is a microscopic fungus, used to make bread and alcoholic beverages, that exhibits the classical S-shaped logistic growth curve when grown in a test tube (Figure 3.2.3). Its growth levels off as the population depletes the nutrients that are necessary for its growth. In the real world, however, there are variations to this idealized curve. For example, a population of harbor seals may

exceed the carrying capacity for a short time and then fall below the carrying capacity for a brief time period and as more resources become available, the population grows again (Figure 3.2.4). This fluctuation in population size continues to occur as the population oscillates around its carrying capacity. Still, even with this oscillation, the logistic model is exhibited.

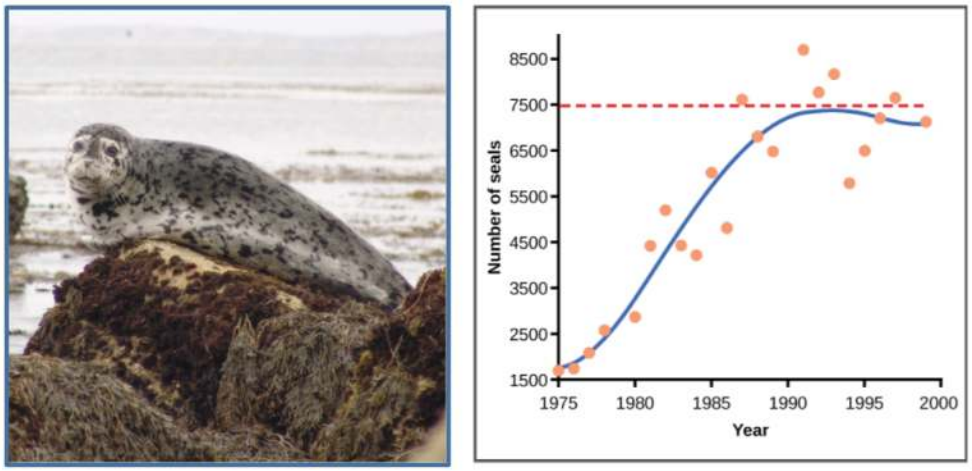


Figure 3.2.4 Graph showing the number of harbor seals versus time in years. The curve rises steeply then plateaus at the carrying capacity, but this time there is much more scatter in the data. A photo of a harbor seal is shown.

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3.3: Factors Limiting Population Growth

Recall previously that we defined density as the number of individuals per unit area. In nature, a population that is introduced to a new environment or is rebounding from a catastrophic decline in numbers may grow exponentially for a while because density is low and resources are not limiting. Eventually, one or more environmental factors will limit its population growth rate as the population size approaches the carrying capacity and density increases. Example: imagine that in an effort to preserve elk, a population of 20 individuals is introduced to a previously unoccupied island that's 200 km^2 in size. The population density of elk on this island is 0.1 elk/km^2 (or 10 km^2 for each individual elk). As this population grows (depending on its per capita rate of increase), the number of individuals increases but the amount of space does not so density increases. Suppose that 10 years later, the elk population has grown to 800 individuals, density = 4 elk/ km^2 (or 0.25 km^2 for each individual). The population growth rate will be limited by various factors in the environment. For example, birth rates may decrease due to limited food or death rate increase due to rapid spread of disease as individuals encounter one another more often. This impact on birth and death rate in turn influences the per capita rate of increase and how the population size changes with changes in the environment. When birth and death rates of a population change as the density of the population changes, the rates are said to be density-dependent and the environmental factors that affect birth and death rates are known as **density-dependent factors**. In other cases, populations are held in check by factors that are not related to the density of the population and are called **density-independent** factors and influence population size regardless of population density. Conservation biologists want to understand both types because this helps them manage populations and prevent extinction or overpopulation.

The density of a population can enhance or diminish the impact of *density-dependent* factors. Most density-dependent factors are *biological in nature* (biotic), and include such things as predation, inter- and intraspecific competition for food and mates, accumulation of waste, and diseases such as those caused by parasites. Usually, higher population density results in higher death rates and lower birth rates. For example, as a population increases in size food becomes scarcer and some individuals will die from starvation meaning that the death rate from starvation increases as population size increases. Also as food becomes scarcer, birth rates decrease due to fewer available resources for the mother meaning that the birth rate decreases as population size increases. For density-dependent factors, there is a feedback loop between population density and the density-dependent factor.

Two examples of density-dependent regulation are shown in Figure 3.3.1. First one is showing results from a study focusing on the giant intestinal roundworm (*Ascaris lumbricoides*), a parasite that infects humans and other mammals. Denser populations of the parasite exhibited lower fecundity (number of eggs per female). One possible explanation for this is that females would be smaller in more dense populations because of limited resources and smaller females produce fewer eggs.

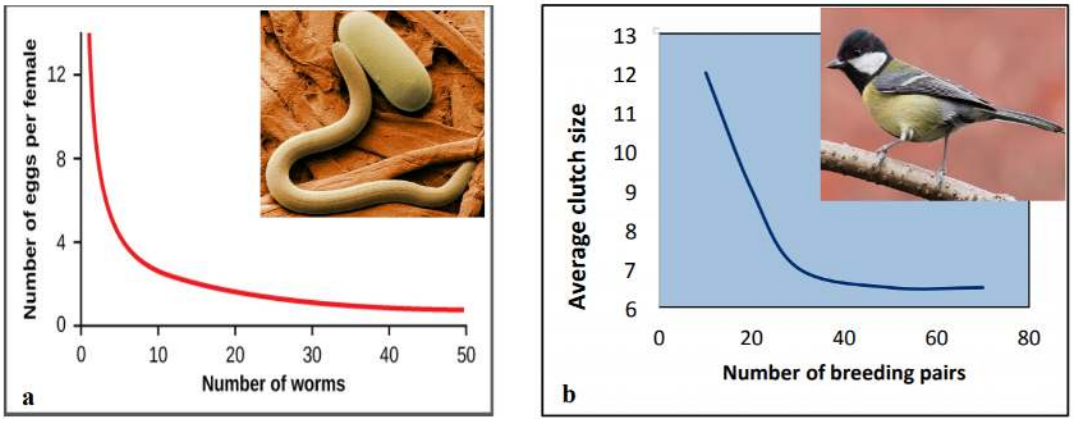


Figure 3.3.1: (a) Graph of number of eggs per female (fecundity), as a function of population size. In this population of roundworms, fecundity (number of eggs) decreases with population density. (b) Graph of clutch size (number of eggs per "litter") of the great tits bird as a function of population size (breeding pairs). Again, clutch size decreases as population density increases. (Photo credits: Worm image from Wikimedia commons, public domain image; bird image from Wikimedia commons, photo by Francis C. Franklin / CC-BY-SA-3.0)

Density-independent birth rates and death rates do NOT depend on population size; these factors are independent of, or not influenced by, population density. Many factors influence population size regardless of the population density, including weather extremes, natural disasters (earthquakes, hurricanes, tornadoes, tsunamis, etc.), pollution and other physical/abiotic factors. For

example, an individual deer may be killed in a forest fire regardless of how many deer happen to be in the forest. The forest fire is not responding to deer population size. As the weather grows cooler in the winter, many insects die from the cold. The change in weather does not depend on whether there is a population size of 100 mosquitoes or 100,000 mosquitoes, most mosquitoes will die from the cold regardless of the population size and the weather will change irrespective of mosquito population density. Looking at the growth curve of such a population would show something like an exponential growth followed by a rapid decline rather than levelling off (Figure 3.3.2).

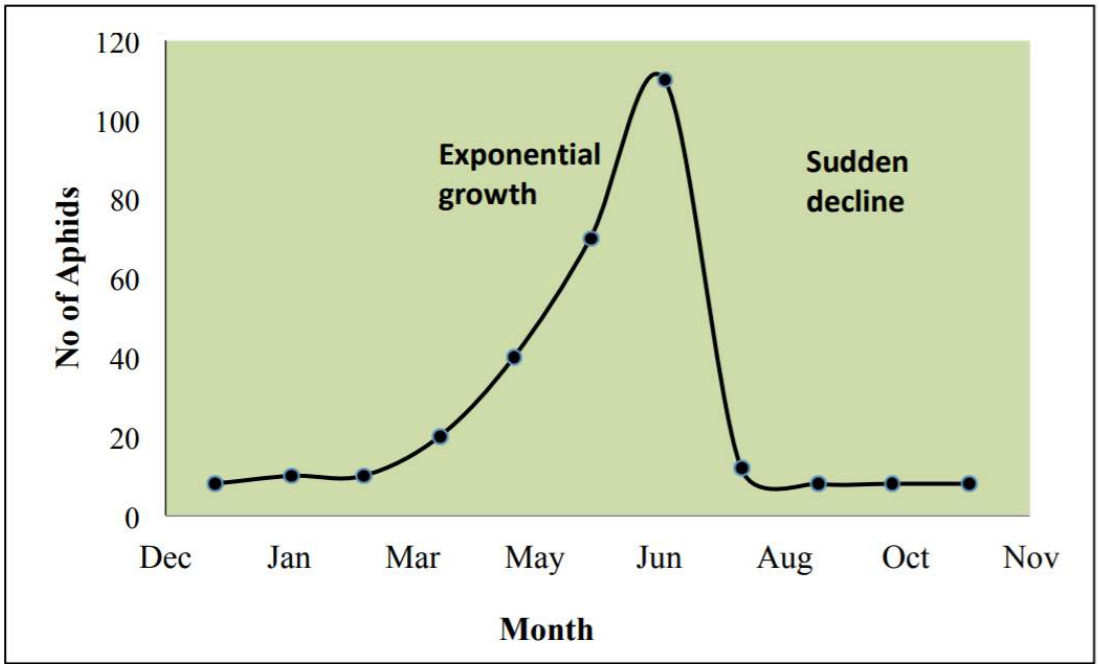


Figure 3.3.2: Weather change acting as a density-independent factor limiting aphid population growth. This insect undergoes exponential growth in the early spring and then rapidly die off when the weather turns hot and dry in the summer

In real-life situations, density-dependent and independent factors interact. For example, a devastating earthquake occurred in Haiti in 2010. This earthquake was a natural geologic event that caused a high human death toll from this *density-independent* event. Then there were high densities of people in refugee camps and the high density caused disease to spread quickly, representing a *density-dependent* death rate.

Q: Can you think of other density-dependent (biological) and density-independent (abiotic) population limiting factors?

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3.4: Life Tables and Survivorship

Population ecologists use life tables to study species and identify the most vulnerable stages of organisms' lives to develop effective measures for maintaining viable populations. Life tables, like Table 3.4.1, track **survivorship**, the chance of an individual in a given population surviving to various ages. Life tables were invented by the insurance industry to predict how long, on average, a person will live. Biologists use a life table as a quick window into the lives of the individuals of a population, showing how long they are likely to live, when they'll reproduce, and how many offspring they'll produce. Life tables are used to construct **survivorship curves**, which are graphs showing the proportion of individuals of a particular age that are now alive in a population. Survivorship (chance of surviving to a particular age) is plotted on the y-axis as a function of age or time on the x-axis. However, if the percent of maximum lifespan is used on the x-axis instead of actual ages, it is possible to compare survivorship curves for different types of organisms (Figure 3.4.1). All survivorship curves start along the y-axis intercept with all of the individuals in the population (or 100% of the individuals surviving). As the population ages, individuals die and the curves goes down. A survivorship curve never goes up.

Table 3.4.1: Life Table for the U.S. population in 2011 showing the number who are expected to be alive at the beginning of each age interval based on the death rates in 2011. For example, 95,816 people out of 100,000 are expected to live to age 50 (0.983 chance of survival). The chance

of surviving to age 60 is 0.964 but the chance of surviving to age 90 is only 0.570.

Age (years)	Number Living at Start of Age Interval	Number Dying During Interval	Chance of Surviving Interval	Chance of Dying During Interval
0-1	100000	606	0.993942	0.006058
1-5	99394	105	0.998946	0.001054
5-10	99289	60	0.999397	0.000603
10-15	99230	70	0.999291	0.000709
15-20	99159	242	0.997562	0.002438
20-25	98917	425	0.995704	0.004296
25-30	98493	475	0.995176	0.004824
30-35	98017	553	0.994362	0.005638
35-40	97465	681	0.993015	0.006985
40-45	96784	968	0.989994	0.010006
45-50	95816	1535	0.983982	0.016018
50-55	94281	2306	0.975541	0.024459
55-60	91975	3229	0.964895	0.035105
60-65	88746	4378	0.950668	0.049332
65-70	84368	6184	0.926698	0.073302
70-75	87184	8670	0.889101	0.110899
75-80	69513	12021	0.827073	0.172927
80-85	57493	15760	0.725879	0.274121
85-90	41733	17935	0.570241	0.429759
90-95	23798	14701	0.382258	0.617742
95-100	9097	7169	0.211924	0.788076
100 and over	1928	1928	0	1.000000

SOURCE: CDC/NCHS, National Vital Statistics System.

Survivorship curves reveal a huge amount of information about a population, such as whether most offspring die shortly after birth or whether most survive to adulthood and likely to live long lives. They generally fall into one of three typical shapes, Types I, II and III (Figure 3.4.1a). Organisms that exhibit **Type I** survivorship curves have the highest probability of surviving every age interval until old age, then the risk of dying increases dramatically. Humans are an example of a species with a Type I survivorship curve. Others include the giant tortoise and most large mammals such as elephants. These organisms have few natural predators and are, therefore, likely to live long lives. They tend to produce only a few offspring at a time and invest significant time and effort in each offspring, which increases survival.

In the **Type III** survivorship curve most of the deaths occur in the youngest age groups. Juvenile survivorship is very low and many individuals die young but individuals lucky enough to survive the first few age intervals are likely to live a much longer time. Most plants species, insect species, frogs as well as marine species such as oysters and fishes have a Type III survivorship curve. A female frog may lay hundreds of eggs in a pond and these eggs produce hundreds of tadpoles. However, predators eat many of the

young tadpoles and competition for food also means that many tadpoles don't survive. But the few tadpoles that do survive and metamorphose into adults then live for a relatively long time (for a frog). The mackerel fish, a female is capable of producing a million eggs and on average only about 2 survive to adulthood. Organisms with this type of survivorship curve tend to produce very large numbers of offspring because most will not survive. They also tend not to provide much parental care, if any.

Type II survivorship is intermediate between the others and suggests that such species have an even chance of dying at any age. Many birds, small mammals such as squirrels, and small reptiles, like lizards, have a Type II survivorship curve. The straight line indicates that the proportion alive in each age interval drops at a steady, regular pace. The likelihood of dying in any age interval is the same.

In reality, most species don't have survivorship curves that are definitively type I, II, or III. They may be anywhere in between. These three, though, represent the extremes and help us make predictions about reproductive rates and parental investment without extensive observations of individual behavior. For example, humans in less industrialized countries tend to have higher mortality rates in all age intervals, particularly in the earliest intervals when compared to individuals in industrialized countries. Looking at the population of the United States in 1900 (Figure 3.4.1b), you can see that mortality was much higher in the earliest intervals and throughout, the population seemed to exhibit a type II survivorship curve, similar to what might be seen in less industrialized countries or amongst the poorest populations.

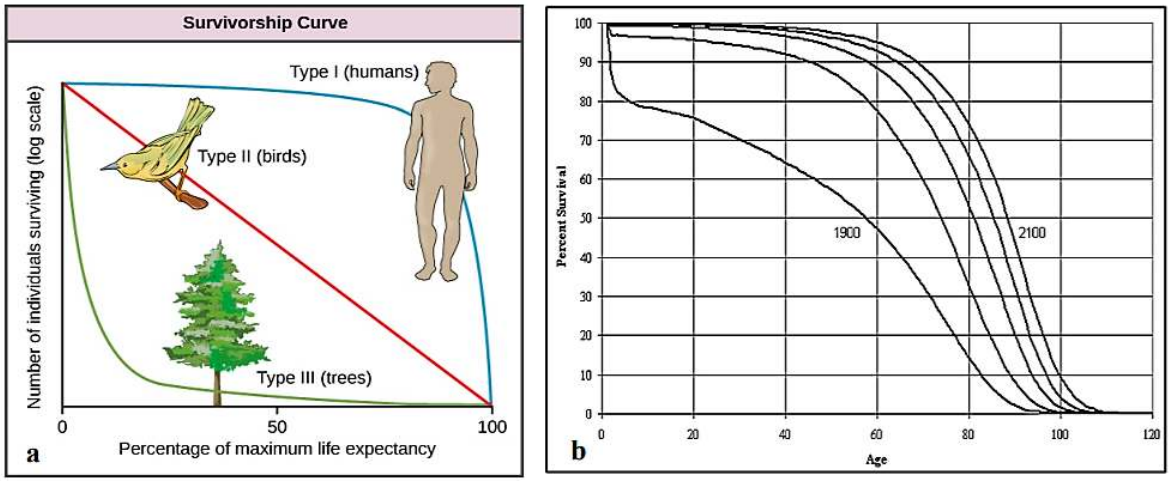


Figure 3.4.1: (a) Survivorship curves show the distribution of individuals in a population according to age. Humans and most large mammals have a Type I survivorship curve because most death occurs in the older years. Birds have a Type II survivorship curve, as death at any age is equally probable. Trees have a Type III survivorship curve because very few survive the younger years, but after a certain age, individuals are much more likely to survive. (b) Survivoship curves for the US population for 1900, 1950, 2000, 2050, 2100

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3.5: Population Ecology Practice Problems

1. If a population is experiencing exponential growth, what happens to N, r and G over time (increase, decrease or stay the same)?

2. At the beginning of the year, there are 7650 individuals in a population of beavers whose per capita rate of increase for the year is 0.18. What is its population growth rate at the end of the year?

3. A zebrafish population of 1000 individuals lives in an ecosystem that can support a maximum of 2000 zebrafish. The per capita rate of increase for the population is 0.01 for the year. What is the population growth rate?

4. In a scenario where: r = 0.25; K = 18,000;

a. What is G when i) N = 4,500; ii) N = 9,000; and iii) N = 13,500?

b. Which N level results in the highest population growth rate and why?

5. A chipmunk population is experiencing exponential growth with a population growth rate of 265 individuals/year, and a per capita rate of increase of 0.15. How many chipmunks are currently in this population?

6. Scientists discovered a new species of frog and were able to estimate its population at 755 individuals. At the end of the year, 105 frogs were added to this population. Assuming the population is undergoing exponential growth, what is the per capita rate of increase? Test your skills (extra challenge)

7. At the beginning of the year, a wildlife area that is 1,000,000 ha in size has a population of 90 Brown bears with a per capita growth rate of 0.02. It's estimated that brown bears need a territory of about 10 km2 per individual (note: 1 km2 = 100 ha). Use this information to answer the following questions.

a. What is the density of brown bears in this wildlife preserve currently?

b. What is the carrying capacity of the preserve?

c. What is the population growth rate for this year?

8. A wildlife ranch currently has a population of polar bears whose death rate is 0.05 and birth rate is 0.12 per year. This particular ranch is isolated from other suitable habitats so there's no immigration into or emigration from this population. This population is experiencing logistic growth and currently has 550 bears. If the population growth rate for the year was 36 bears, what is the carrying capacity of the preserve?

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CHAPTER OVERVIEW

4: Human Demography

4.1: The Human Population

4.2: Demography

4.3: Age structure diagrams

4.4: The Demographic Transition Model

4.5: Life Expectancy

4.6: Fertility

4.7: Appendix

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4.1: The Human Population

Learning Objectives

By the end of this chapter, you will be able to:

- State the current size of the human population.
- Interpret age-structure diagrams.
- Explain what the demographic transition model represents and describe the societal changes that cause the demographic transition.
- Describe what happens to birth rates, death rates, population growth rate, and population size as a country moves through the stages of the demographic transition model.
- Give examples of countries in the different stages of the demographic transition models and match age-structure diagrams with the stages of the demographic transition model.
- Define life expectancy and explain how it changes as a country moves through the demographic transition model.
- Define fertility and explain how it changes as a country moves through the demographic transition model.

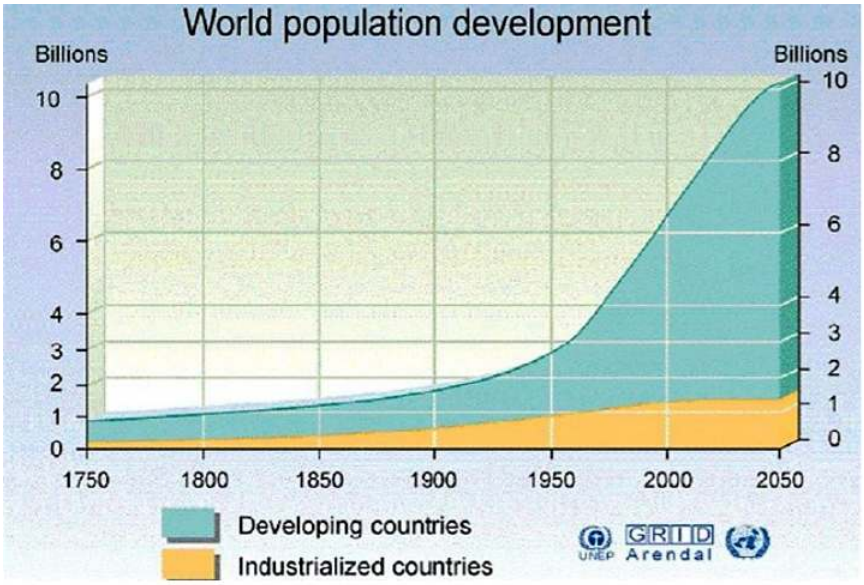


Figure 4.1.1**:** *Shows the increase in human population size starting in 1750 and predicted out to 2050. The orange area represents the human population in industrialized countries and the blue/green area represents the human population in less-industrialized (developing) countries. The greatest amount of human population growth will be in less-industrialized countries.*

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4.2: Demography

Demography applies the principles of population ecology (chapter 2) to the human population. Demographers study how human populations grow, shrink, and change in terms of age and gender compositions. Demographers also compare populations in different countries or regions.

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4.3: Age structure diagrams

One of the tools that demographers use to understand populations is the **age structure diagram**. This diagram shows the distribution by ages of females and males within a certain population in graphic form. Figure 4.3.1 shows a diagram for the United States population. In this diagram, the ages are arranged so that age ranges are grouped together, for example: 0 – 4 years, 5 – 9 years, and so on. The population of each group is represented as a bar extending from a central vertical line, with the length of each bar dependent upon the total population for that particular group. The centerline separates the females from the males. The female and male populations for each group are represented by the distance from the centerline, with females on the right and males on the left.

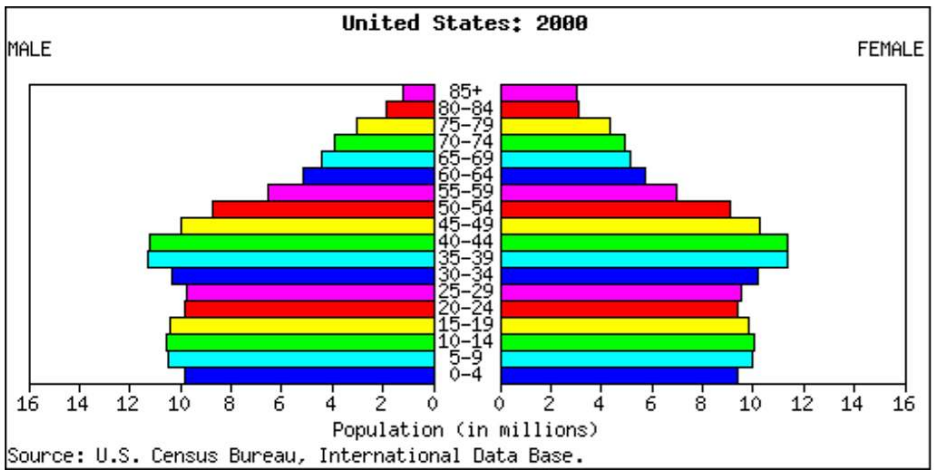


Figure 4.3.1: Age Structure diagram for the U.S. in 2000

By looking closely at the age structure diagram, one will notice slightly more boys in the younger age groups than girls; however, the ratio tends to reverse in the upper age groups, when females tend to outnumber males. Many countries have a female majority as a result of the longer life expectancy for females.

The following age structure diagrams (Figure 4.3.2) show the United States in 2005 and 2010. Please note the slightly different x-axes scale on these diagrams compared to the 2000 diagram above (Figure 4.3.1). You can see the ageing group of baby boomers move upward when you compare these 3 age structure diagrams. There are also more elderly (80+) individuals, especially women, in 2005 and 2010.

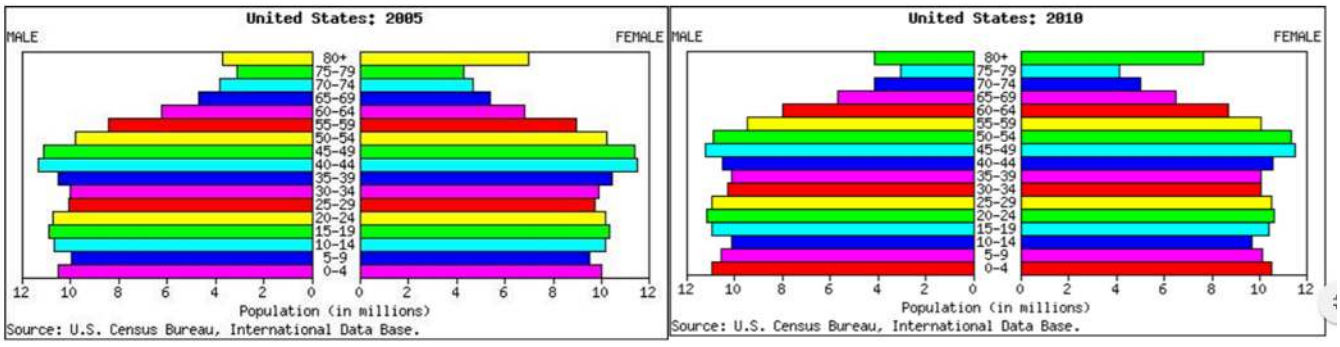


Figure 4.3.2: Age Structure diagram for the U.S. in 2005 and 2010.

An age-structure diagram provides a snapshot of the current population and can represent information about the past and give potential clues about future problems. When you are interpreting age-structure diagrams, it is important to compare the width of the base to the rest of the population. If the base is very wide compared to the upper parts of the diagram, then this indicates a lot of young people (pre-reproductive) in the population compared to older generations i.e. a high birth rate and a rapidly growing population. If the base is smaller than the upper parts of the diagram, then this indicates few young people in the population compared to older generations (post-reproductive). This population has low birth rates and is shrinking.

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4.4: The Demographic Transition Model

The demographic transition model shows the changes in the patterns of birth rates and death rates that typically occur as a country moves through the process of industrialization or development. The demographic transition model was built based on patterns observed in European counties as they were going through industrialization. This model can be applied to other countries, but not all countries or regions fit the model exactly. And the pace or rate at which a country moves through the demographic transition varies among countries.

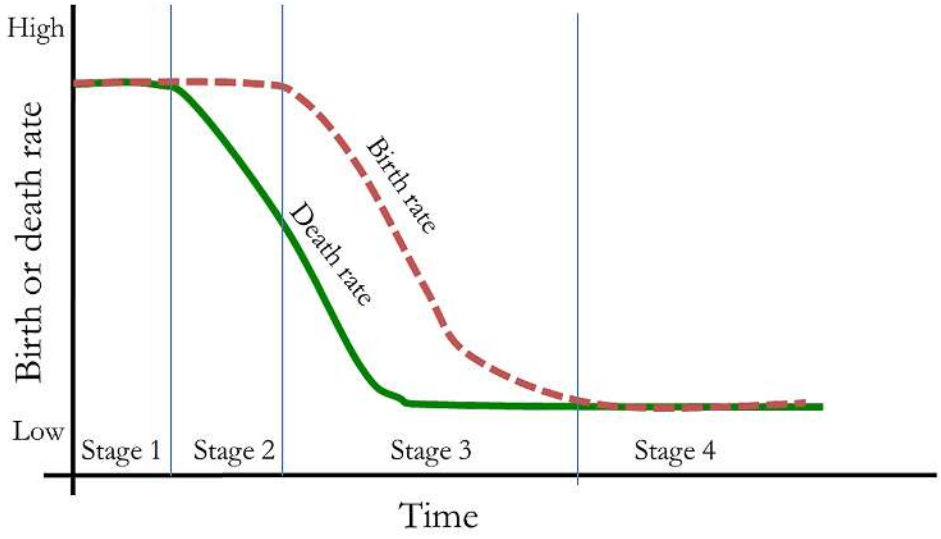


Figure 4.4.1: The demographic transition model shows how birth rates and death rates change over time as a country becomes more developed. The demographic transition model is typically divided into four stages. The green line represents death rates and the dashed red line represents birth rates .

In the demographic transition model, a country begins in Stage 1, the preindustrial stage. In Stage 1 (Figure 4.4.1), both birth rates and death rates are high. The high death rates are because of disease and potential food scarcity. A country in Stage 1 of the demographic transition model does not have good health care; there may not be any hospitals or doctors. Children are not vaccinated against common diseases and therefore many children die at a young age. Infant and childhood **mortality rates** (death rates) are very high. A society in Stage 1 is likely based upon agriculture and most people grow their own food. Therefore, droughts or flood can lead to widespread food shortages and death from famine. All of these factors contribute to the high death rate in Stage 1. Partly to compensate for the high death rates, birth rates are also high. High birth rates mean that families are large and each couple, on average, has many children. When death rates are high, having many children means that at least one or two will live to adulthood. In Stage 1, children are an important part of the family workforce and are expected to work growing food and taking care of the family.

As you are examining the stages of the demographic transition model, remember that:

$$\text{Population Growth Rate} = \text{Birth Rate–Death Rate}$$

In Stage 1, birth rates are high, but death rates are high as well. Therefore, population growth rate is low or close to zero (Figure 4.4.2).

As a country develops, medical advances are made such as access to antibiotics and vaccines. Sanitation improvements, such as proper waste and sewage disposal, and water treatment for clean drinking water also progress. Food production also increases. Together these changes lead to falling death rates which marks the beginning of Stage 2 (Figure 4.4.1). Death rates continue to fall throughout Stage 2 as conditions improve. This means that people are living longer and childhood morality drops. However, birth rates are still high in Stage 2. There is a time lag between the improving conditions and any subsequent changes in family size, so women are still having many children and now more of these children are living into adulthood. In Stage 2, the birth rate is higher than the death rate, so population growth rate is high. This means that population size increases greatly during Stage 2 of the demographic transition model (Figure 4.4.2).

A falling birth rate marks the beginning of Stage 3 in the demographic transition model. As a country continues to industrialize, many women join the workforce. Additionally, raising children becomes more expensive and children no longer work on the family farm or make large economic contributions to the family. Individuals may have access to birth control and choose to have fewer children. This leads to a drop in birth rates and smaller family sizes. Death rates also continue to drop during Stage 3 as medicine, sanitation and food security continue to improve. Even though both birth rates and death rates are falling throughout Stage 3, birth rates are higher than death rates. This means that population growth rate is high and that population size continues to increase in Stage 3 of the demographic transition model (Figure 4.4.2).

Birth rate and death rates drop to low, stable, approximately equal levels in Stage 4. Death rates are low because of medical advances, good sanitation, clean drinking water and food security. Birth rates are low because of access to birth control and many women delay having their first child until they have worked. Childhood mortality is low, life expectancy is high, and family size is approximately two children per couple. With low birth rates and low death rates, population growth rate is approximately zero in Stage 4 (Figure 4.4.2).

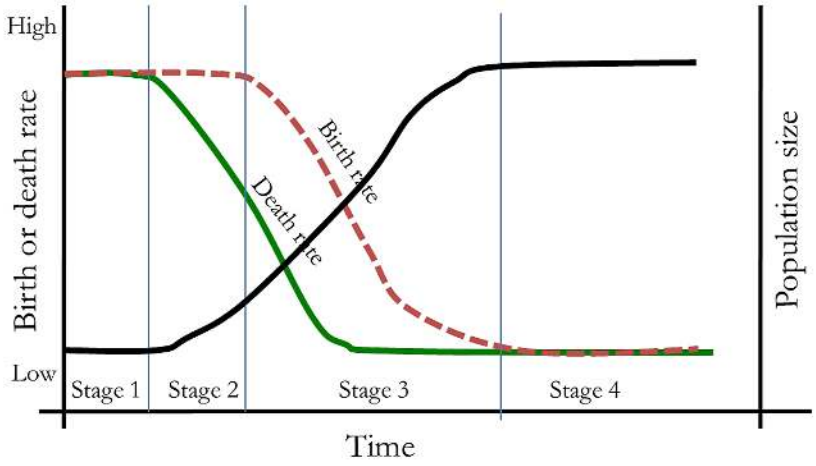


Figure 3.4, with the changes in population size (y-axes on the far right) shown by the black line. Population size is low and stable in Stage 1, increases rapidly in Stage 2 and 3 because birth rates are higher than death rates, and then is high and stable again in Stage 4.

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4.5: Life Expectancy

Life expectancy is the average number of years that a person in a particular population is expected to live. Life expectancy at birth is the number of years a newborn infant would live if mortality rates at the time of its birth did not change. For example, the life expectancy at birth for someone born in 2014 in Japan is 84.46 years while the life expectancy at birth for someone born in the United States in 2014 is 79.56 years (source: https://www.cia.gov). As a country moves through the demographic transition model, life expectancy increases. Overall, life expectancy has increased for most countries and regions over the past 100 years. However, there is still a significant amount of variation in life expectancy in different regions of the world.

Use Our World in Data's interactive map to compare life expectancy among different countries: https://ourworldindata.org/grapher/life-expectancy-at-different-ages?time=2007..latest&country=~USA

What other countries have a life expectancy at birth similar to the United States? List two countries that have a higher life expectancy and two countries that have a lower life expectancy than the United States.

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4.6: Fertility

Fertility is the actual level of reproduction of a population per individual, based on the number of live births that occur. Total fertility is the average number of children born to each woman, over the woman's lifespan, in a population. Birth rate and fertility are closely linked terms. As a country moves through the demographic transition model, fertility rates decrease. Overall, fertility rates have decreased for most countries and regions over the past 50 years (Figure 4.6.1). However, there is still a significant amount of variation among different regions of the world.

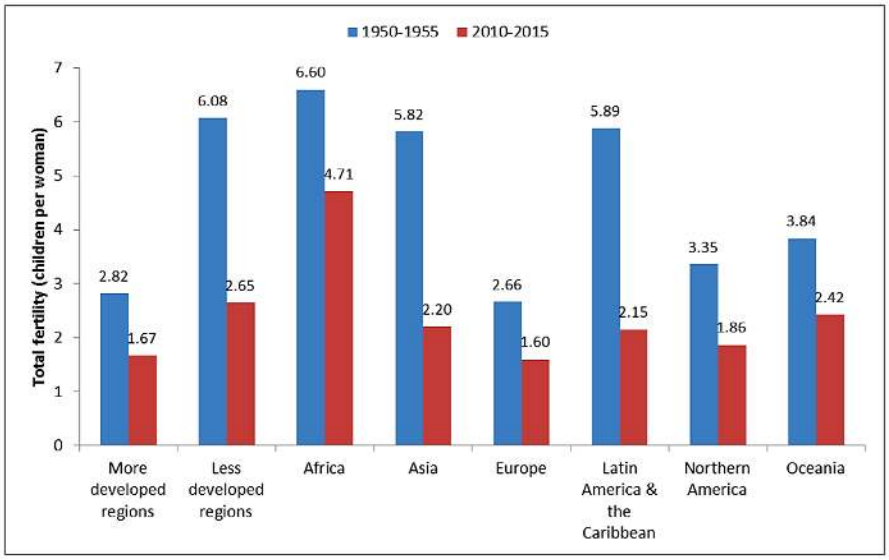


Figure 4.6.1: Shows the total fertility of different regions of the world. The blue bars are the total fertility estimates from 1950-1955. The red bars are the total fertility estimates from 2010-2015. More developed regions include Europe, Northern America (US and Canada), Australia, New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia. Oceania includes Australia, New Zealand, Melanesia, Micronesia and Polynesia. Data are from the United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects, 2015 Revision. UN http://esa.un.org/unpd/wpp/DVD/

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4.7: Appendix

Additional resources

United Nations Development Programme, Human Development Reports http://hdr.undp.org/en/content/demog...an-development

Carrying capacity of ecosystems and human demography http://institutmichelserres.ens-lyon....php?article38

Terms list

- Age structure diagram
- Mortality rate
- Demography
- Population growth rate
- Demographic transition model
- Pre-reproductive/post-reproductive age
- Fertility
- Life expectancy

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CHAPTER OVERVIEW

5: Motion and Forces

5.1: Kinematics

5.1.1: Introduction to One-Dimensional Kinematics

5.1.2: Displacement

5.1.3: Vectors, Scalars, and Coordinate Systems

5.1.4: Time, Velocity, and Speed

5.1.5: Acceleration

5.1.6: Motion Equations for Constant Acceleration in One Dimension

5.1.7: Falling Objects

5.1.8: Projectile Motion

5.1.9: Centripetal Acceleration

5.1.E: Kinematics (Exercise)

5.2: Dynamics

5.2.1: Introduction to Dynamics- Newton’s Laws of Motion

5.2.2: Development of Force Concept

5.2.3: Newton’s First Law of Motion- Inertia

5.2.4: Newton's Second Law of Motion- Force and Acceleration

5.2.5: Newton’s Third Law of Motion- Symmetry in Forces

5.2.6: Normal Force and Tension

5.2.7: Spring Force- Hooke’s Law

5.2.8: Friction

5.2.9: Newton’s Universal Law of Gravitation

5.2.10: Centripetal Force

5.2.E: Dynamics (Exercise)

Thumbnail: A Newton's cradle, named after physicist Isaac Newton. (CC BY-SA 3.0; Dominique Toussaint via Wikipedia)

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SECTION OVERVIEW

5.1: Kinematics

5.1.1: Introduction to One-Dimensional Kinematics

5.1.2: Displacement

5.1.3: Vectors, Scalars, and Coordinate Systems

5.1.4: Time, Velocity, and Speed

5.1.5: Acceleration

5.1.6: Motion Equations for Constant Acceleration in One Dimension

5.1.7: Falling Objects

5.1.8: Projectile Motion

5.1.9: Centripetal Acceleration

5.1.E: Kinematics (Exercise)

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5.1.1: Introduction to One-Dimensional Kinematics



Figure 5.1.1.1: The motion of an American kestrel through the air can be described by the bird's displacement, speed, velocity, and acceleration. When it flies in a straight line without any change in direction, its motion is said to be one dimensional. (credit: Vince Maidens, Wikimedia Commons)

Objects are in motion everywhere we look. Everything from a tennis game to a space-probe flyby of the planet Neptune involves motion. When you are resting, your heart moves blood through your veins. And even in inanimate objects, there is continuous motion in the vibrations of atoms and molecules. Questions about motion are interesting in and of themselves: *How long will it take for a space probe to get to Mars?* But an understanding of motion is also key to understanding other concepts in physics. An understanding of acceleration, for example, is crucial to the study of force.

Our formal study of physics begins with **kinematics** which is defined as the *study of motion without considering its causes*. The word "kinematics" comes from a Greek term meaning motion and is related to other English words such as "cinema" (movies) and "kinesiology" (the study of human motion). In one-dimensional kinematics we will study only the *motion* of a football, for example, without worrying about what forces cause or change its motion. Such considerations come in other chapters. In this chapter, we examine the simplest type of motion—namely, motion along a straight line, or one-dimensional motion.

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5.1.2: Displacement

Learning Objectives

- Define position, displacement, distance, and distance traveled.
- Explain the relationship between position and displacement.
- Distinguish between displacement and distance traveled.
- Calculate displacement and distance given initial position, final position, and the path between the two.



Figure 5.1.2.1: These cyclists in Vietnam can be described by their position relative to buildings and a canal. Their motion can be described by their change in position, or displacement, in the frame of reference. (credit: Suzan Black, Fotopedia)

Position

In order to describe the motion of an object, you must first be able to describe its **position**—where it is at any particular time. More precisely, you need to specify its position relative to a convenient reference frame. Earth is often used as a reference frame, and we often describe the position of an object as it relates to stationary objects in that reference frame. For example, a rocket launch would be described in terms of the position of the rocket with respect to the Earth as a whole, while a professor's position could be described in terms of where she is in relation to the nearby white board. (See Figure 5.1.2.2.) In other cases, we use reference frames that are not stationary but are in motion relative to the Earth. To describe the position of a person in an airplane, for example, we use the airplane, not the Earth, as the reference frame. (See Figure 5.1.2.3.)

Displacement

If an object moves relative to a reference frame (for example, if a professor moves to the right relative to a white board or a passenger moves toward the rear of an airplane), then the object's position changes. This change in position is known as **displacement**. The word "displacement" implies that an object has moved, or has been displaced.

Definition: DISPLACEMENT

Displacement is the *change in position* of an object:

$$\Delta x = x_{\mathrm{f}} - x_0,$$

where Δx is displacement, x_{f} is the final position, and x_0 is the initial position.

In this text the upper case Greek letter Δ always means "change in" whatever quantity follows it; thus, Δx means *change in position*. Always solve for displacement by subtracting initial position x_0 from final position x_f.

Note that the SI unit for displacement is the meter (m), but sometimes kilometers, miles, feet, and other units of length are used. Keep in mind that when units other than the meter are used in a problem, you may need to convert them into meters to complete the calculation.

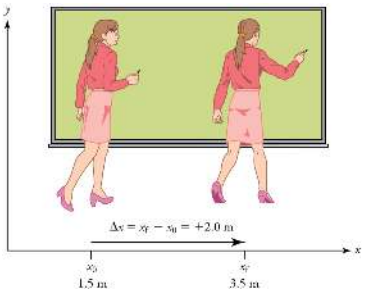


Figure 5.1.2.2: A professor paces left and right while lecturing. Her position relative to Earth is given by x. The **+2.0 m** displacement of the professor relative to Earth is represented by an arrow pointing to the right.

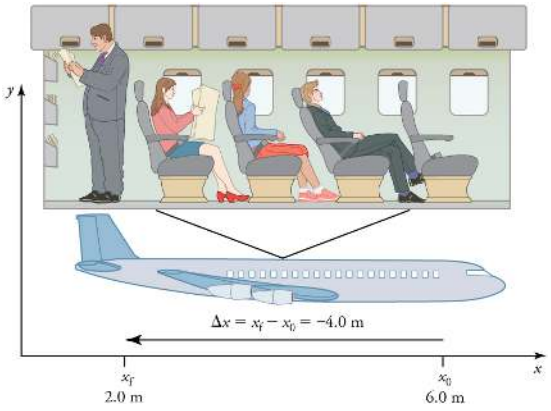


Figure 5.1.2.3: A passenger moves from his seat to the back of the plane. His location relative to the airplane is given by x. The **−4.0-m** displacement of the passenger relative to the plane is represented by an arrow toward the rear of the plane. Notice that the arrow representing his displacement is twice as long as the arrow representing the displacement of the professor (he moves twice as far) in Figure 5.1.2.2.

Note that displacement has a direction as well as a magnitude. The professor's displacement is 2.0 m to the right, and the airline passenger's displacement is 4.0 m toward the rear. In one-dimensional motion, direction can be specified with a plus or minus sign. When you begin a problem, you should select which direction is positive (usually that will be to the right or up, but you are free to select positive as being any direction). The professor's initial position is $x_0 = 1.5$ m and her final position is $x_f = 3.5$ m. Thus her displacement is

$$\Delta x = x_f - x_0 = 3.5 \text{ m} - 1.5 \text{ m} = +2.0 \text{ m}.$$

In this coordinate system, motion to the right is positive, whereas motion to the left is negative. Similarly, the airplane passenger's initial position is $x_0 = 6.0$ m and his final position is $x_f = 2.0$ m, so his displacement is

$$\Delta x = x_f - x_0 = 2.0 \text{ m} - 6.0 \text{ m} = -4.0 \text{ m}.$$

His displacement is negative because his motion is toward the rear of the plane, or in the negative x direction in our coordinate system.

Distance

Although displacement is described in terms of direction, distance is not. **Distance** is defined to be *the magnitude or size of displacement between two positions*. Note that the distance between two positions is not the same as the distance traveled between them. **Distance traveled** is *the total length of the path traveled between two positions*. Distance has no direction and, thus, no sign. For example, the distance the professor walks is 2.0 m. The distance the airplane passenger walks is 4.0 m.

MISCONCEPTION ALERT: DISTANCE TRAVELED VS. MAGNITUDE OF DISPLACEMENT

It is important to note that the *distance traveled*, however, can be greater than the magnitude of the displacement (by magnitude, we mean just the size of the displacement without regard to its direction; that is, just a number with a unit). For example, the professor could pace back and forth many times, perhaps walking a distance of 150 m during a lecture, yet still end up only 2.0 m to the right of her starting point. In this case her displacement would be +2.0 m, the magnitude of her displacement would be 2.0 m, but the distance she traveled would be 150 m. In kinematics we nearly always deal with displacement and magnitude of displacement, and almost never with distance traveled. One way to think about this is to

assume you marked the start of the motion and the end of the motion. The displacement is simply the difference in the position of the two marks and is independent of the path taken in traveling between the two marks. The distance traveled, however, is the total length of the path taken between the two marks.

Exercise 5.1.2.1

A cyclist rides 3 km west and then turns around and rides 2 km east. (a) What is her displacement? (b) What distance does she ride? (c) What is the magnitude of her displacement?

Answer



Figure 5.1.2.4

(a) The rider's displacement is $\Delta x = x_{\mathrm{f}} - x_0 = -1\ \mathrm{km}$. (The displacement is negative because we take east to be positive and west to be negative.)

(b) The distance traveled is **3 km + 2 km = 5 km**.

(c) The magnitude of the displacement is **1 km**.

Section Summary

- Kinematics is the study of motion without considering its causes. In this chapter, it is limited to motion along a straight line, called one-dimensional motion.
- Displacement is the change in position of an object.
- In symbols, displacement Δx is defined to be

$$\Delta x = x_{\mathrm{f}} - x_0,$$

  where x_0 is the initial position and x_f is the final position. In this text, the Greek letter Δ (delta) always means "change in" whatever quantity follows it. The SI unit for displacement is the meter (m). Displacement has a direction as well as a magnitude.
- When you start a problem, assign which direction will be positive.
- Distance is the magnitude of displacement between two positions.
- Distance traveled is the total length of the path traveled between two positions.

Glossary

kinematics
the study of motion without considering its causes

position
the location of an object at a particular time

displacement
the change in position of an object

distance
the magnitude of displacement between two positions

distance traveled
the total length of the path traveled between two positions

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5.1.3: Vectors, Scalars, and Coordinate Systems

Learning Objectives

- Define and distinguish between scalar and vector quantities.
- Assign a coordinate system for a scenario involving one-dimensional motion.



Figure 5.1.3.1: The motion of this Eclipse Concept jet can be described in terms of the distance it has traveled (a scalar quantity) or its displacement in a specific direction (a vector quantity). In order to specify the direction of motion, its displacement must be described based on a coordinate system. In this case, it may be convenient to choose motion toward the left as positive motion (it is the forward direction for the plane), although in many cases, the x-coordinate runs from left to right, with motion to the right as positive and motion to the left as negative. (credit: Armchair Aviator, Flickr)

What is the difference between distance and displacement? Whereas displacement is defined by both direction and magnitude, distance is defined only by magnitude. Displacement is an example of a vector quantity. Distance is an example of a scalar quantity. A **vector** is any quantity with both *magnitude and direction*. Other examples of vectors include a velocity of 90 km/h east and a force of 500 newtons straight down.

The direction of a vector in one-dimensional motion is given simply by a plus (+) or minus (−) sign. Vectors are represented graphically by arrows. An arrow used to represent a vector has a length proportional to the vector's magnitude (e.g., the larger the magnitude, the longer the length of the vector) and points in the same direction as the vector.

Some physical quantities, like distance, either have no direction or none is specified. A **scalar** is any quantity that has a magnitude, but no direction. For example, a 20ºC temperature, the 250 kilocalories (250 Calories) of energy in a candy bar, a 90 km/h speed limit, a person's 1.8 m height, and a distance of 2.0 m are all scalars—quantities with no specified direction. Note, however, that a scalar can be negative, such as a −20ºC temperature. In this case, the minus sign indicates a point on a scale rather than a direction. Scalars are never represented by arrows.

Coordinate Systems for One-Dimensional Motion

In order to describe the direction of a vector quantity, you must designate a coordinate system within the reference frame. For one-dimensional motion, this is a simple coordinate system consisting of a one-dimensional coordinate line. In general, when describing horizontal motion, motion to the right is usually considered positive, and motion to the left is considered negative. With vertical motion, motion up is usually positive and motion down is negative. In some cases, however, as with the jet in Figure 5.1.3.1, it can be more convenient to switch the positive and negative directions. For example, if you are analyzing the motion of falling objects, it can be useful to define downwards as the positive direction. If people in a race are running to the left, it is useful to define left as the positive direction. It does not matter as long as the system is clear and consistent. Once you assign a positive direction and start solving a problem, you cannot change it.

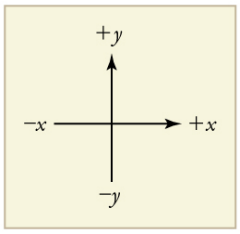


Figure 5.1.3.2: It is usually convenient to consider motion upward or to the right as positive (+) and motion downward or to the left as negative (−).

Exercise 5.1.3.1

A person's speed can stay the same as he or she rounds a corner and changes direction. Given this information, is speed a scalar or a vector quantity? Explain.

Answer

Speed is a scalar quantity. It does not change at all with direction changes; therefore, it has magnitude only. If it were a vector quantity, it would change as direction changes (even if its magnitude remained constant).

Section Summary

- A vector is any quantity that has magnitude and direction.
- A scalar is any quantity that has magnitude but no direction.
- Displacement and velocity are vectors, whereas distance and speed are scalars.
- In one-dimensional motion, direction is specified by a plus or minus sign to signify left or right, up or down, and the like.

Glossary

scalar

a quantity that is described by magnitude, but not direction

vector

a quantity that is described by both magnitude and direction

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5.1.4: Time, Velocity, and Speed

Learning Objectives

- Explain the relationships between instantaneous velocity, average velocity, instantaneous speed, average speed, displacement, and time.
- Calculate velocity and speed given initial position, initial time, final position, and final time.
- Interpret graphs of position vs. time and velocity vs. time.



Figure 5.1.4.1: The motion of these racing snails can be described by their speeds and their velocities. (credit: tobitasflickr, Flickr)

There is more to motion than distance and displacement. Questions such as, “How long does a foot race take?” and “What was the runner’s speed?” cannot be answered without an understanding of other concepts. In this section we add definitions of time, velocity, and speed to expand our description of motion.

Time

The most fundamental physical quantities are defined by how they are measured. This is the case with time. Every measurement of time involves measuring a change in some physical quantity. It may be a number on a digital clock, a heartbeat, or the position of the Sun in the sky. In physics, the definition of time is simple—**time** is *change*, or the interval over which change occurs. It is impossible to know that time has passed unless something changes.

The amount of time or change is calibrated by comparison with a standard. The SI unit for time is the second, abbreviated s. We might, for example, observe that a certain pendulum makes one full swing every 0.75 s. We could then use the pendulum to measure time by counting its swings or, of course, by connecting the pendulum to a clock mechanism that registers time on a dial. This allows us to not only measure the amount of time, but also to determine a sequence of events.

How does time relate to motion? We are usually interested in elapsed time for a particular motion, such as how long it takes an airplane passenger to get from his seat to the back of the plane. To find elapsed time, we note the time at the beginning and end of the motion and subtract the two. For example, a lecture may start at 11:00 A.M. and end at 11:50 A.M., so that the elapsed time would be 50 min. **Elapsed time Δt** is the difference between the ending time and beginning time,

$$\Delta t = t_{\mathrm{f}} - t_0,$$

where Δt is the change in time or elapsed time, t_{f} is the time at the end of the motion, and t_0 is the time at the beginning of the motion. (As usual, the delta symbol, Δ, means the change in the quantity that follows it.)

Velocity

Your notion of velocity is probably the same as its scientific definition. You know that if you have a large displacement in a small amount of time you have a large velocity, and that velocity has units of distance divided by time, such as miles per hour or kilometers per hour.

Definition: AVERAGE VELOCITY

Average velocity is *displacement (change in position) divided by the time of travel*,

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_{\mathrm{f}} - x_0}{t_{\mathrm{f}} - t_0},$$

where $\bar{v}$ is the *average* (indicated by the bar over the v) velocity,Δx is the change in position (or displacement), and x_f and x_0 are the final and beginning positions at times t_f and t_0, respectively.

Notice that this definition indicates that *velocity is a vector because displacement is a vector*. It has both magnitude and direction. The SI unit for velocity is meters per second or m/s, but many other units, such as km/h, mi/h (also written as mph), and cm/s, are in common use. Suppose, for example, an airplane passenger took 5 seconds to move −4 m (the negative sign indicates that displacement is toward the back of the plane). His average velocity would be

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{-4 \text{ m}}{5 \text{ s}} = -0.8 \text{ m/s}.$$

The minus sign indicates the average velocity is also toward the rear of the plane.

The average velocity of an object does not tell us anything about what happens to it between the starting point and ending point, however. For example, we cannot tell from average velocity whether the airplane passenger stops momentarily or backs up before he goes to the back of the plane. To get more details, we must consider smaller segments of the trip over smaller time intervals.

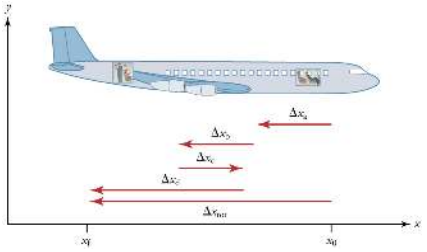


Figure 5.1.4.2: A more detailed record of an airplane passenger heading toward the back of the plane, showing smaller segments of his trip.

The smaller the time intervals considered in a motion, the more detailed the information. When we carry this process to its logical conclusion, we are left with an infinitesimally small interval. Over such an interval, the average velocity becomes the *instantaneous velocity* or the *velocity at a specific instant*. A car's speedometer, for example, shows the magnitude (but not the direction) of the instantaneous velocity of the car. (Police give tickets based on instantaneous velocity, but when calculating how long it will take to get from one place to another on a road trip, you need to use average velocity.) **Instantaneous velocity** v is the average velocity at a specific instant in time (or over an infinitesimally small time interval).

Mathematically, finding instantaneous velocity, v, at a precise instant t can involve taking a limit, a calculus operation beyond the scope of this text. However, under many circumstances, we can find precise values for instantaneous velocity without calculus.

Speed

In everyday language, most people use the terms "speed" and "velocity" interchangeably. In physics, however, they do not have the same meaning and they are distinct concepts. One major difference is that speed has no direction. Thus *speed is a scalar*. Just as we need to distinguish between instantaneous velocity and average velocity, we also need to distinguish between instantaneous speed and average speed.

Instantaneous speed is the magnitude of instantaneous velocity. For example, suppose the airplane passenger at one instant had an instantaneous velocity of −3.0 m/s (the minus meaning toward the rear of the plane). At that same time his instantaneous speed was 3.0 m/s. Or suppose that at one time during a shopping trip your instantaneous velocity is 40 km/h due north. Your instantaneous speed at that instant would be 40 km/h—the same magnitude but without a direction. Average speed, however, is very different from average velocity. **Average speed** is the distance traveled divided by elapsed time.

We have noted that distance traveled can be greater than displacement. So average speed can be greater than average velocity, which is displacement divided by time. For example, if you drive to a store and return home in half an hour, and your car's odometer shows the total distance traveled was 6 km, then your average speed was 12 km/h. Your average velocity, however, was zero, because your displacement for the round trip is zero. (Displacement is change in position and, thus, is zero for a round trip.) Thus average speed is *not* simply the magnitude of average velocity.

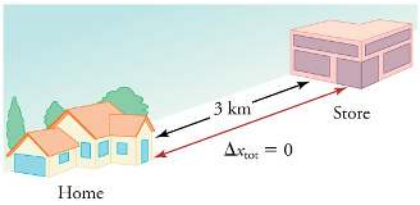


Figure 5.1.4.3: During a 30-minute round trip to the store, the total distance traveled is 6 km. The average speed is 12 km/h. The displacement for the round trip is zero, since there was no net change in position. Thus the average velocity is zero.

Another way of visualizing the motion of an object is to use a graph. A plot of position or of velocity as a function of time can be very useful. For example, for this trip to the store, the position, velocity, and speed-vs.-time graphs are displayed in Figure 5.1.4.4. (Note that these graphs depict a very simplified **model** of the trip. We are assuming that speed is constant during the trip, which is unrealistic given that we'll probably stop at the store. But for simplicity's sake, we will model it with no stops or changes in speed. We are also assuming that the route between the store and the house is a perfectly straight line.)

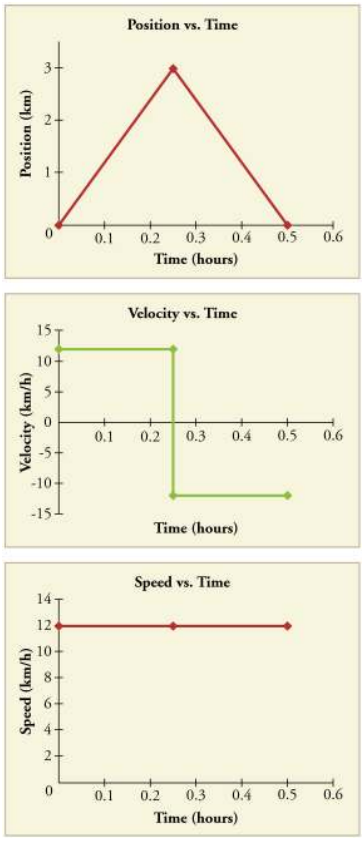


Figure 5.1.4.4: Position vs. time, velocity vs. time, and speed vs. time on a trip. Note that the velocity for the return trip is negative.

MAKING CONNECTIONS: TAKE-HOME INVESTIGATION—GETTING A SENSE OF SPEED

If you have spent much time driving, you probably have a good sense of speeds between about 10 and 70 miles per hour. But what are these in meters per second? What do we mean when we say that something is moving at 10 m/s? To get a better sense of what these values really mean, do some observations and calculations on your own:

- calculate typical car speeds in meters per second
- estimate jogging and walking speed by timing yourself; convert the measurements into both m/s and mi/h
- determine the speed of an ant, snail, or falling leaf

Exercise 5.1.4.1

A commuter train travels from Baltimore to Washington, DC, and back in 1 hour and 45 minutes. The distance between the two stations is approximately 40 miles. What is (a) the average velocity of the train, and (b) the average speed of the train in m/s?

Answer

(a) The average velocity of the train is zero because $x_f = x_0$; the train ends up at the same place it starts.

(b) The average speed of the train is calculated below. Note that the train travels 40 miles one way and 40 miles back, for a total distance of 80 miles.

$$\frac{\text{distance}}{\text{time}} = \frac{80 \text{ miles}}{105 \text{ minutes}} \tag{5.1.4.1}$$

$$\frac{80 \text{ miles}}{105 \text{ minutes}} \times \frac{5280 \text{ feet}}{1\text{mile}} \times \frac{1 \text{ meter}}{3.28 \text{ feet}} \times \frac{1 \text{ minute}}{60 \text{ seconds}} = 20 \text{ m/s} \tag{5.1.4.2}$$

Section Summary

- Time is measured in terms of change, and its SI unit is the second (s). Elapsed time for an event is

$$\Delta t = t_f - t_0,$$

  where t_f is the final time and t_0 is the initial time.
- Average velocity $\bar{v}$ is defined as displacement divided by the travel time. In symbols, average velocity is

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_0}{t_f - t_0}.$$

- The SI unit for velocity is m/s.
- Velocity is a vector and thus has a direction.
- Instantaneous velocity v is the velocity at a specific instant or the average velocity for an infinitesimal interval.
- Instantaneous speed is the magnitude of the instantaneous velocity.
- Instantaneous speed is a scalar quantity, as it has no direction specified.
- Average speed is the total distance traveled divided by the elapsed time. (Average speed is *not* the magnitude of the average velocity.) Speed is a scalar quantity; it has no direction associated with it.

Glossary

average speed
distance traveled divided by time during which motion occurs

average velocity
displacement divided by time over which displacement occurs

instantaneous velocity
velocity at a specific instant, or the average velocity over an infinitesimal time interval

instantaneous speed
magnitude of the instantaneous velocity

time
change, or the interval over which change occurs

model
simplified description that contains only those elements necessary to describe the physics of a physical situation

elapsed time

the difference between the ending time and beginning time

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5.1.5: Acceleration

Learning Objectives

- Define and distinguish between velocity and acceleration, and between instantaneous and average acceleration.
- Calculate acceleration given initial time, initial velocity, final time, and final velocity.



Figure 5.1.5.1: A plane slows down as it comes in for landing in St. Maarten. It is accelerating in a direction opposite to its velocity. (credit: Steve Conry, Flickr)

In everyday conversation, to accelerate means to speed up. The accelerator in a car can in fact cause it to speed up. The greater the **acceleration**, the greater the change in velocity over a given time. The formal definition of acceleration is consistent with these notions, but more inclusive.

Definition: AVERAGE ACCELERATION

Average Acceleration is *the rate at which velocity changes*,

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_{\mathrm{f}} - v_0}{t_{\mathrm{f}} - t_0},$$

where $\bar{a}$ is average acceleration, v is velocity, and t is time. (The bar over the a means *average* acceleration.)

Because acceleration is velocity in m/s divided by time in s, the SI units for acceleration are $\mathrm{m/s^2}$, meters per second squared or meters per second per second, which literally means by how many meters per second the velocity changes every second.

Recall that velocity is a vector—it has both magnitude and direction. This means that a change in velocity can be a change in magnitude (or speed), but it can also be a change in *direction*. For example, if a car turns a corner at constant speed, it is accelerating because its direction is changing. The quicker you turn, the greater the acceleration. So there is an acceleration when velocity changes either in magnitude (an increase or decrease in speed) or in direction, or both.

ACCELERATION AS A VECTOR

Acceleration is a vector in the same direction as the *change* in velocity, Δv. Since velocity is a vector, it can change either in magnitude or in direction. Acceleration is therefore a change in either speed or direction, or both.

Keep in mind that although acceleration is in the direction of the *change* in velocity, it is not always in the direction of *motion*. If acceleration is in a direction opposite to the direction of motion, the object slows down.



Figure 5.1.5.2: A subway train in Sao Paulo, Brazil, slows down as it comes into a station. It is accelerating in a direction opposite to its direction of motion. (credit: Yusuke Kawasaki, Flickr)

Example 5.1.5.1: Calculating Acceleration: A Racehorse Leaves the Gate

A racehorse coming out of the gate accelerates from rest to a velocity of 15.0 m/s due west in 1.80 s. What is its average acceleration?



Figure 5.1.5.3

Strategy

First we draw a sketch and assign a coordinate system to the problem. This is a simple problem, but it always helps to visualize it. Notice that we assign east as positive and west as negative. Thus, in this case, we have negative velocity.

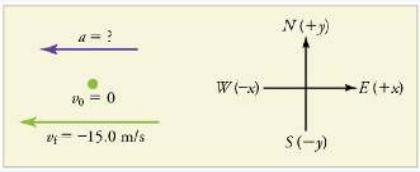


Figure 5.1.5.4

We can solve this problem by identifying Δv and Δt from the given information and then calculating the average acceleration directly from the equation $\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_0}{t_f - t_0}$.

Solution

1. Identify the knowns. $v_0 = 0$, $v_f = -15.0$ m/s (the negative sign indicates direction toward the west), $\Delta t = 1.80$ s.

2. Find the change in velocity. Since the horse is going from zero to **−15.0 m/s**, its change in velocity equals its final velocity: $\Delta v = v_f = -15.0$ m/s.

3. Plug in the known values (Δv and Δt) and solve for the unknown $\bar{a}$.

$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{-15.0 \text{ m/s}}{1.80 \text{ s}} = -8.33 \text{ m/s}^2$.

Discussion

The negative sign for acceleration indicates that acceleration is toward the west. An acceleration of 8.33 m/s^2 due west means that the horse increases its velocity by 8.33 m/s due west each second, that is, 8.33 meters per second per second, which we write as 8.33 m/s^2. This is truly an average acceleration, because the ride is not smooth. We shall see later that an acceleration of this magnitude would require the rider to hang on with a force nearly equal to his weight.

Instantaneous Acceleration

Instantaneous acceleration a, or the *acceleration at a specific instant in time*, is obtained by the same process as discussed for instantaneous velocity—that is, by considering an infinitesimally small interval of time. How do we find instantaneous acceleration using only algebra? The answer is that we choose an average acceleration that is representative of the motion. Figure 5.1.5.5 shows graphs of instantaneous acceleration versus time for two very different motions. In Figure 5.1.5.5 (a), the acceleration varies slightly and the average over the entire interval is nearly the same as the instantaneous acceleration at any time. In this case, we should treat this motion as if it had a constant acceleration equal to the average (in this case about 1.8 m/s^2). In Figure 5.1.5.5 (b), the acceleration varies drastically over time. In such situations it is best to consider smaller time intervals and choose an average acceleration for each. For example, we could consider motion over the time intervals from 0 to 1.0 s and from 1.0 to 3.0 s as separate motions with accelerations of $+3.0 \text{ m/s}^2$ and -2.0 m/s^2, respectively.

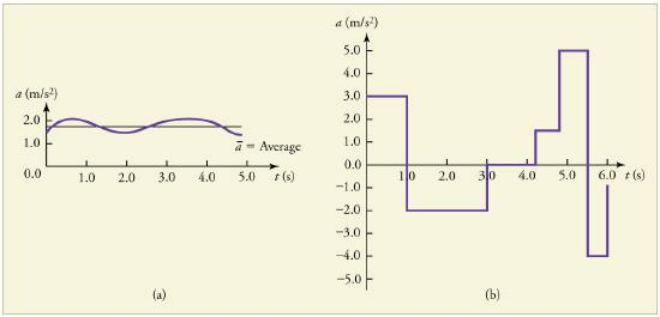


Figure 5.1.5.5: Graphs of instantaneous acceleration versus time for two different one-dimensional motions. (a) Here acceleration varies only slightly and is always in the same direction, since it is positive. The average over the interval is nearly the same as the acceleration at any given time. (b) Here the acceleration varies greatly, perhaps representing a package on a post office conveyor belt that is accelerated forward and backward as it bumps along. It is necessary to consider small time intervals (such as from 0 to 1.0 s) with constant or nearly constant acceleration in such a situation.

The next several examples consider the motion of the subway train shown in Figure 5.1.5.6. In (a) the shuttle moves to the right, and in (b) it moves to the left. The examples are designed to further illustrate aspects of motion and to illustrate some of the reasoning that goes into solving problems.

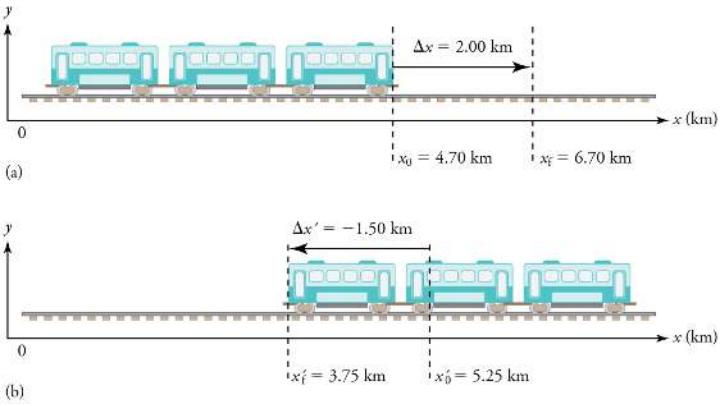


Figure 5.1.5.6: One-dimensional motion of a subway train considered in Example 5.1.5.2, Example 5.1.5.3, Example 5.1.5.4, Example 5.1.5.5, Example 5.1.5.6, and Example 5.1.5.7. Here we have chosen the x-axis so that + means to the right and − means to the left for displacements, velocities, and accelerations. (a) The subway train moves to the right from x_0 to x_f. Its displacement Δx is +2.0 km. (b) The train moves to the left from x'_0 to x'_f. Its displacement $\Delta x'$ is −1.5 km. (Note that the prime symbol (′) is used simply to distinguish between displacement in the two different situations. The distances of travel and the size of the cars are on different scales to fit everything into the diagram.)

Example 5.1.5.2: Calculating Displacement: A Subway Train

What are the magnitude and sign of displacements for the motions of the subway train shown in parts (a) and (b) of Figure 5.1.5.6?

Strategy

A drawing with a coordinate system is already provided, so we don't need to make a sketch, but we should analyze it to make sure we understand what it is showing. Pay particular attention to the coordinate system. To find displacement, we use the equation $\Delta x = x_f - x_0$. This is straightforward since the initial and final positions are given.

Solution

1. Identify the knowns. In the figure we see that $x_f = 6.70$ km and $x_0 = 4.70$ km for part (a), and $x'_f = 3.75$ km and $x'_0 = 5.25$ km for part (b).

2. Solve for displacement in part (a).

$$\Delta x = x_f - x_0 = 6.70 \text{ km} - 4.70 \text{ km} = +2.00 \text{ km}$$

3. Solve for displacement in part (b).

$$\Delta x' = x'_f - x'_0 = 3.75 \text{ km} - 5.25 \text{ km} = -1.50 \text{ km}$$

Discussion

The direction of the motion in (a) is to the right and therefore its displacement has a positive sign, whereas motion in (b) is to the left and thus has a negative sign.

Example 5.1.5.3: Comparing Distance Traveled with Displacement: A Subway Train

What are the distances traveled for the motions shown in parts (a) and (b) of the subway train in Figure 5.1.5.6?

Strategy

To answer this question, think about the definitions of distance and distance traveled, and how they are related to displacement. Distance between two positions is defined to be the magnitude of displacement, which was found in Example 5.1.5.2. Distance traveled is the total length of the path traveled between the two positions. In the case of the subway train shown in Figure 5.1.5.6, the distance traveled is the same as the distance between the initial and final positions of the train.

Solution

1. The displacement for part (a) was +2.00 km. Therefore, the distance between the initial and final positions was 2.00 km, and the distance traveled was 2.00 km.

2. The displacement for part (b) was **−1.5 km**. Therefore, the distance between the initial and final positions was 1.50 km, and the distance traveled was 1.50 km.

Discussion

Distance is a scalar. It has magnitude but no sign to indicate direction.

Example 5.1.5.4: Calculating Acceleration: A Subway Train Speeding Up

Suppose the train in Figure 5.1.5.6 (a) accelerates from rest to 30.0 km/h in the first 20.0 s of its motion. What is its average acceleration during that time interval?

Strategy

It is worth it at this point to make a simple sketch:

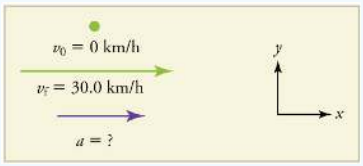


Figure 5.1.5.7

This problem involves three steps. First we must determine the change in velocity, then we must determine the change in time, and finally we use these values to calculate the acceleration.

Solution

1. Identify the knowns. $v_0 = 0$ (the trains starts at rest), $v_f = 30.0$ km/h, and $\Delta t = 20.0$ s.

2. Calculate Δv. Since the train starts from rest, its change in velocity is $\Delta v = +30.0$ km/h, where the plus sign means velocity to the right.

3. Plug in known values and solve for the unknown, $\bar{a}$.

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{+30.0 \text{ km/h}}{20.0 \text{ s}}$$

4. Since the units are mixed (we have both hours and seconds for time), we need to convert everything into SI units of meters and seconds.

$$\bar{a} = \left(\frac{+30 \text{ km/h}}{20.0 \text{ s}}\right)\left(\frac{10^3 \text{ m}}{1 \text{ km}}\right)\left(\frac{1 \text{ h}}{3600 \text{ s}}\right) = 0.417 \text{ m/s}^2$$

Discussion

The plus sign means that acceleration is to the right. This is reasonable because the train starts from rest and ends up with a velocity to the right (also positive). So acceleration is in the same direction as the *change* in velocity, as is always the case.

Example 5.1.5.5: Calculate Acceleration: A Subway Train Slowing Down

Now suppose that at the end of its trip, the train in Figure 5.1.5.6 (a) slows to a stop from a speed of 30.0 km/h in 8.00 s. What is its average acceleration while stopping?

Strategy

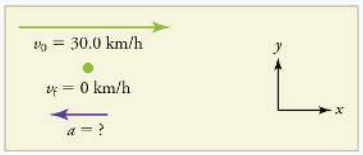


Figure 5.1.5.8

In this case, the train is slowing down and its acceleration is negative because it is toward the left. As in the previous example, we must find the change in velocity and the change in time and then solve for acceleration.

Solution

1. Identify the knowns. $v_0 = 30.0$ km/h, $v_f = 0$ km/h (the train is stopped, so its velocity is 0), and $\Delta t = 8.00$ s.

2. Solve for the change in velocity, Δv.

$$\Delta v = v_f - v_0 = 0 - 30.0 \text{ km/h} = -30.0 \text{ km/h}$$

3. Plug in the knowns, Δv and Δt, and solve for $\bar{a}$.

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{-30.0 \text{ km/h}}{8.00 \text{ s}}$$

4. Convert the units to meters and seconds.

$$\bar{a} = \frac{\Delta v}{\Delta t} = \left(\frac{-30.0 \text{ km/h}}{8.00 \text{ s}}\right)\left(\frac{10^3 \text{ m}}{1 \text{ km}}\right)\left(\frac{1 \text{ h}}{3600 \text{ s}}\right) = -1.04 \text{ m/s}^2.$$

Discussion

The minus sign indicates that acceleration is to the left. This sign is reasonable because the train initially has a positive velocity in this problem, and a negative acceleration would oppose the motion.

The graphs of position, velocity, and acceleration vs. time for the trains in Example 5.1.5.4 and Example 5.1.5.5 are displayed in Figure 5.1.5.9. (We have taken the velocity to remain constant from 20 to 40 s, after which the train slows down.)

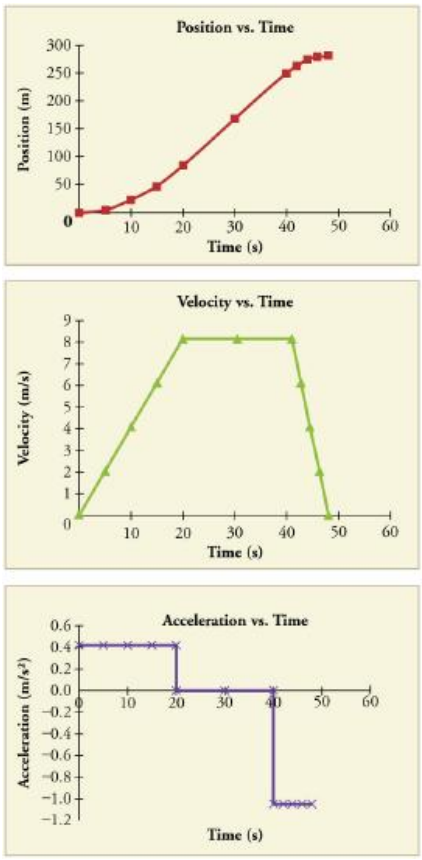


Figure 5.1.5.9: (a) Position of the train over time. Notice that the train's position changes slowly at the beginning of the journey, then more and more quickly as it picks up speed. Its position then changes more slowly as it slows down at the end of the journey. In the middle of the journey, while the velocity remains constant, the position changes at a constant rate. (b) Velocity of the train over time. The train's velocity increases as it accelerates at the beginning of the journey. It remains the same in the middle of the journey (where there is no acceleration). It decreases as the train slows down at the end of the journey. (c) The acceleration of the train over time. The train has positive acceleration as it speeds up at the beginning of the journey. It has no acceleration as it travels at constant velocity in the middle of the journey. Its acceleration is negative as it slows down at the end of the journey.

Example 5.1.5.6: Calculating Average Velocity: The Subway Train

What is the average velocity of the train in part b of Example 5.1.5.2, and shown again below, if it takes 5.00 min to make its trip?

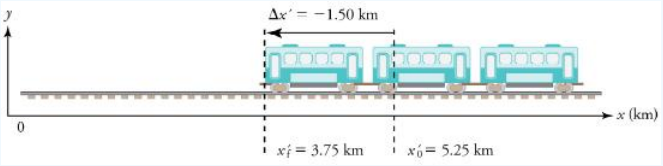


Figure 5.1.5.10

Strategy

Average velocity is displacement divided by time. It will be negative here, since the train moves to the left and has a negative displacement.

Solution

1. Identify the knowns. $x'_{\mathrm{f}} = 3.75\ \mathrm{km},\ x'_0 = 5.25\ \mathrm{km},\ \Delta t = 5.00\ \mathrm{min}.$

2. Determine displacement, $\Delta x'$. We found $\Delta x'$ to be **−1.5 km** in Example 5.1.5.2.

3. Solve for average velocity.

$$\bar{v} = \frac{\Delta x'}{\Delta t} = \frac{-1.50 \text{ km}}{5.00 \text{ min}}$$

4. Convert units.

$$\bar{v} = \frac{\Delta x'}{\Delta t} = \left(\frac{-1.50 \text{ km}}{5.00 \text{ min}}\right)\left(\frac{60 \text{ min}}{1 \text{ h}}\right) = -18.0 \text{ km/h}$$

Discussion

The negative velocity indicates motion to the left.

Example 5.1.5.7: Calculating Deceleration: The Subway Train

Finally, suppose the train in Figure 5.1.5.10 slows to a stop from a velocity of 20.0 km/h in 10.0 s. What is its average acceleration?

Strategy

Once again, let's draw a sketch:

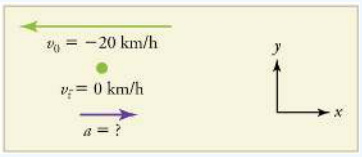


Figure 5.1.5.11

As before, we must find the change in velocity and the change in time to calculate average acceleration.

Solution

1. Identify the knowns. $v_0 = -20 \text{ km/h},\ v_f = 0 \text{ km/h},\ \Delta t = 10.0 \text{ s}$.

2. Calculate Δv. The change in velocity here is actually positive, since

$$\Delta v = v_f - v_0 = 0 - (-20 \text{ km/h}) = +20 \text{ km/h}$$

3. Solve for $\bar{a}$.

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{+20.0 \text{ km/h}}{10.0 \text{ s}}$$

4. Convert units.

$$\bar{a} = \left(\frac{+20.0 \text{ km/h}}{10.0 \text{ s}}\right)\left(\frac{10^3 \text{ m}}{1 \text{ km}}\right)\left(\frac{1 \text{ h}}{3600 \text{ s}}\right) = +0.556 \text{ m/s}^2$$

Discussion

The plus sign means that acceleration is to the right. This is reasonable because the train initially has a negative velocity (to the left) in this problem and a positive acceleration opposes the motion (and so it is to the right).

Sign and Direction

Perhaps the most important thing to note about these examples is the signs of the answers. In our chosen coordinate system, plus means the quantity is to the right and minus means it is to the left. This is easy to imagine for displacement and velocity. But it is a little less obvious for acceleration. Most people interpret negative acceleration as the slowing of an object. This was not the case in Example 5.1.5.7, where a positive acceleration slowed a negative velocity. The crucial distinction was that the acceleration was in the opposite direction from the velocity. In fact, a negative acceleration will *increase* a negative velocity. For example, the train moving to the left in Figure 5.1.5.10 is sped up by an acceleration to the left. In that case, both v and a are negative. The plus and minus signs give the directions of the accelerations. If acceleration has the same sign as the change in velocity, the object is speeding up. If acceleration has the opposite sign of the change in velocity, the object is slowing down.

Exercise 5.1.5.1

An airplane lands on a runway traveling east. Describe its acceleration.

Answer

If we take east to be positive, then the airplane has negative acceleration, as it is accelerating toward the west. It is also slowing down: its acceleration is opposite in direction to its velocity.

Section Summary

- Acceleration is the rate at which velocity changes. In symbols, **average acceleration** $\bar{a}$ is

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{v_{\mathrm{f}} - v_0}{t_{\mathrm{f}} - t_0}$$

- The SI unit for acceleration is $\mathrm{m/s^2}$.
- Acceleration is a vector, and thus has a both a magnitude and direction.
- Acceleration can be caused by either a change in the magnitude or the direction of the velocity.
- Instantaneous acceleration a is the acceleration at a specific instant in time.
- When an acceleration is in a direction opposite to that of the velocity of an object, the object slows down.

Glossary

acceleration
the rate of change in velocity; the change in velocity over time

average acceleration
the change in velocity divided by the time over which it changes

instantaneous acceleration
acceleration at a specific point in time

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5.1.6: Motion Equations for Constant Acceleration in One Dimension

Learning Objectives

- Calculate displacement of an object that is not accelerating, given initial position and velocity.
- Calculate final velocity of an accelerating object, given initial velocity, acceleration, and time.
- Calculate displacement and final position of an accelerating object, given initial position, initial velocity, time, and acceleration.



Figure 5.1.6.1: Kinematic equations can help us describe and predict the motion of moving objects such as these kayaks racing in Newbury, England. (credit: Barry Skeates, Flickr)

We might know that the greater the acceleration of, say, a car moving away from a stop sign, the greater the displacement in a given time. But we have not developed a specific equation that relates acceleration and displacement. In this section, we develop some convenient equations for kinematic relationships, starting from the definitions of displacement, velocity, and acceleration already covered.

Notation: *t*, *x*, *v*, *a*

First, let us make some simplifications in notation. Taking the initial time to be zero, as if time is measured with a stopwatch, is a great simplification. Since elapsed time is $\Delta t = t_{\mathrm{f}} - t_0$, taking $t_0 = 0$ means that $\Delta t = t_{\mathrm{f}}$, the final time on the stopwatch. When initial time is taken to be zero, we use the subscript 0 to denote initial values of position and velocity. That is, x_0 *is the initial position* and v_0 *is the initial velocity*. We put no subscripts on the final values. That is, t *is the final time*, x *is the final position*, and v *is the final velocity*. This gives a simpler expression for elapsed time—now, $\Delta t = t$. It also simplifies the expression for displacement, which is now $\Delta x = x - x_0$. Also, it simplifies the expression for change in velocity, which is now $\Delta v = v - v_0$. To summarize, using the simplified notation, with the initial time taken to be zero,

$$\left.\begin{array}{l} \Delta t = t \\ \Delta x = x - x_0 \\ \Delta v = v - v_0 \end{array}\right\}$$

where *the subscript 0 denotes an initial value and the absence of a subscript denotes a final value* in whatever motion is under consideration.

We now make the important assumption that *acceleration is constant*. This assumption allows us to avoid using calculus to find instantaneous acceleration. Since acceleration is constant, the average and instantaneous accelerations are equal. That is,

$$\bar{a} = a = \text{ constant}$$

so we use the symbol a for acceleration at all times. Assuming acceleration to be constant does not seriously limit the situations we can study nor degrade the accuracy of our treatment. For one thing, acceleration *is* constant in a great number of situations. Furthermore, in many other situations we can accurately describe motion by assuming a constant acceleration equal to the average acceleration for that motion. Finally, in motions where acceleration changes drastically, such as a car accelerating to top speed and then braking to a stop, the motion can be considered in separate parts, each of which has its own constant acceleration.

SOLVING FOR DISPLACEMENT (Δx) AND FINAL POSITION (x) FROM AVERAGE VELOCITY WHEN ACCELERATION (a) IS CONSTANT

To get our first two new equations, we start with the definition of average velocity:

$$\bar{v} = \frac{\Delta x}{\Delta t}.$$

Substituting the simplified notation for Δx and Δt yields

$$\bar{v} = \frac{x - x_0}{t}.$$

Solving for x yields

$$x = x_0 + \bar{v}t,$$

where the average velocity is

$$\bar{v} = \frac{v_0 + v}{2} (\text{constant } a).$$

The equation $\bar{v} = \frac{v_0+v}{2}$ reflects the fact that, when acceleration is constant, v is just the simple average of the initial and final velocities. For example, if you steadily increase your velocity (that is, with constant acceleration) from 30 to 60 km/h, then your average velocity during this steady increase is 45 km/h. Using the equation $\bar{v} = \frac{v_0+v}{2}$ to check this, we see that

$$\bar{v} = \frac{v_0 + v}{2} = \frac{30 \text{ km/h} + 60 \text{ km/h}}{2} = 45 \text{ km/h},$$

which seems reasonable.

Example 5.1.6.1: Calculating Displacement: How Far does the Jogger Run?

A jogger runs down a straight stretch of road with an average velocity of 4.00 m/s for 2.00 min. What is his final position, taking his initial position to be zero?

Strategy

Draw a sketch.

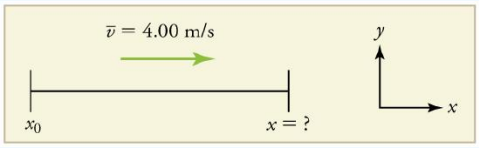


Figure 5.1.6.2

The final position x is given by the equation

$$x = x_0 + \bar{v}t.$$

To find x, we identify the values of x_0, $\bar{v}$, and t from the statement of the problem and substitute them into the equation.

Solution

1. Identify the knowns. $\bar{v} = 4.00 \text{ m/s}, \ \Delta t = 2.00 \text{ min}$, and $x_0 = 0 \text{ m}$.

2. Enter the known values into the equation.

$$x = x_0 + \bar{v}t = 0 + (4.00 \text{ m/s})(120 \text{ s}) = 480 \text{ m}$$

Discussion

Velocity and final displacement are both positive, which means they are in the same direction.

The equation $x = x_0 + \bar{v}t$ gives insight into the relationship between displacement, average velocity, and time. It shows, for example, that displacement is a linear function of average velocity. (By linear function, we mean that displacement depends on $\bar{v}$ rather than on $\bar{v}$ raised to some other power, such as $\bar{v}^2$. When graphed, linear functions look like straight lines with a constant slope.) On a car trip, for example, we will get twice as far in a given time if we average 90 km/h than if we average 45 km/h.

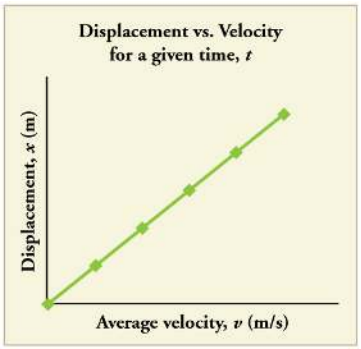


Figure 5.1.6.3: There is a linear relationship between displacement and average velocity. For a given time t, an object moving twice as fast as another object will move twice as far as the other object.

SOLVING FOR FINAL VELOCITY

We can derive another useful equation by manipulating the definition of acceleration.

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

Substituting the simplified notation for Δv and Δt gives us

$$a = \frac{v - v_0}{t} (\text{ constant } a).$$

Solving for v yields

$$v = v_0 + at (\text{ constant } a).$$

Example 5.1.6.2: Calculating Final Velocity: An Airplane Slowing Down after Landing

An airplane lands with an initial velocity of 70.0 m/s and then slows down at $1.50\ \text{m/s}^2$ for 40.0 s. What is its final velocity?

Strategy

Draw a sketch. We draw the acceleration vector in the direction opposite the velocity vector because the plane is slowing down.

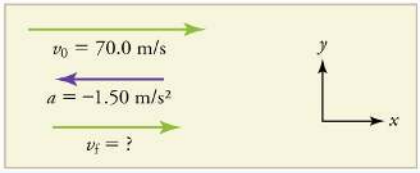


Figure 5.1.6.4

Solution

1. Identify the knowns. $v_0 = 70.0\ \text{m/s},\ a = -1.50\ \text{m/s}^2,\ t = 40.0\ \text{s}$.

2. Identify the unknown. In this case, it is final velocity, v_f.

3. Determine which equation to use. We can calculate the final velocity using the equation $v = v_0 + at$.

4. Plug in the known values and solve.

$$v = v_0 + at = 70.0\ \text{m/s} + \left(-1.50\ \text{m/s}^2\right)(40.0\ \text{s}) = 10.0\ \text{m/s}$$

Discussion

The final velocity is much less than the initial velocity, as desired when slowing down, but still positive. With jet engines, reverse thrust could be maintained long enough to stop the plane and start moving it backward. That would be indicated by a

negative final velocity, which is not the case here.



Figure 5.1.6.5: The airplane lands with an initial velocity of 70.0 m/s and slows to a final velocity of 10.0 m/s before heading for the terminal. Note that the acceleration is negative because its direction is opposite to its velocity, which is positive.

In addition to being useful in problem solving, the equation $v = v_0 + at$ gives us insight into the relationships among velocity, acceleration, and time. From it we can see, for example, that

- final velocity depends on how large the acceleration is and how long it lasts
- if the acceleration is zero, then the final velocity equals the initial velocity $(v = v_0)$, as expected (i.e., velocity is constant)
- if a is negative, then the final velocity is less than the initial velocity

All of these observations fit our intuition, and it is always useful to examine basic equations in light of our intuition and experiences to check that they do indeed describe nature accurately.

MAKING CONNECTIONS: REAL-WORLD CONNECTION



Figure 5.1.6.6: The Space Shuttle *Endeavor* blasts off from the Kennedy Space Center in February 2010. (credit: Matthew Simantov, Flickr)

An intercontinental ballistic missile (ICBM) has a larger average acceleration than the Space Shuttle and achieves a greater velocity in the first minute or two of flight (actual ICBM burn times are classified—short-burn-time missiles are more difficult for an enemy to destroy). But the Space Shuttle obtains a greater final velocity, so that it can orbit the earth rather than come directly back down as an ICBM does. The Space Shuttle does this by accelerating for a longer time.

SOLVING FOR FINAL POSITION WHEN VELOCITY IS NOT CONSTANT (a≠0)

We can combine the equations above to find a third equation that allows us to calculate the final position of an object experiencing constant acceleration. We start with

$$v = v_0 + at.$$

Adding v_0 to each side of this equation and dividing by 2 gives

$$\frac{v_0 + v}{2} = v_0 + \frac{1}{2}at.$$

Since $\frac{v_0+v}{2} = \bar{v}$ for constant acceleration, then

$$\bar{v} = v_0 + \frac{1}{2}at.$$

Now we substitute this expression for $\bar{v}$ into the equation for displacement, $x = x_0 + \bar{v}t$, yielding

$$x = x_0 + v_0 t + \frac{1}{2}at^2 (\text{ constant } a).$$

Example 5.1.6.3: Calculating Displacement of an Accelerating Object: Dragsters

Dragsters can achieve average accelerations of $26.0\ \text{m/s}^2$. Suppose such a dragster accelerates from rest at this rate for 5.56 s. How far does it travel in this time?



Figure 5.1.6.7: U.S. Army Top Fuel pilot Tony "The Sarge" Schumacher begins a race with a controlled burnout. (credit: Lt. Col. William Thurmond. Photo Courtesy of U.S. Army.)

Strategy

Draw a sketch.

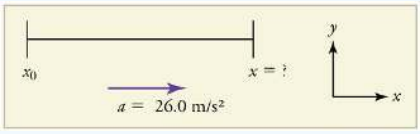


Figure 5.1.6.8

We are asked to find displacement, which is x if we take x_0 to be zero. (Think about it like the starting line of a race. It can be anywhere, but we call it 0 and measure all other positions relative to it.) We can use the equation $x = x_0 + v_0t + \frac{1}{2}at^2$ once we identify v_0, a, and t from the statement of the problem.

Solution

1. Identify the knowns. Starting from rest means that $v_0 = 0$, a is given as $26.0\ \text{m/s}^2$ and t is given as 5.56 s.

2. Plug the known values into the equation to solve for the unknown x:

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

Since the initial position and velocity are both zero, this simplifies to

$$x = \frac{1}{2}at^2.$$

Substituting the identified values of a and t gives

$$x = \frac{1}{2}\left(26.0\ \text{m/s}^2\right)(5.56\ \text{s})^2,$$

yielding

$$x = 402\ \text{m}.$$

Discussion

If we convert 402 m to miles, we find that the distance covered is very close to one quarter of a mile, the standard distance for drag racing. So the answer is reasonable. This is an impressive displacement in only 5.56 s, but top-notch dragsters can do a quarter mile in even less time than this.

What else can we learn by examining the equation $x = x_0 + v_0t + \frac{1}{2}at^2$ We see that:

- displacement depends on the square of the elapsed time when acceleration is not zero. In Example 5.1.6.3, the dragster covers only one fourth of the total distance in the first half of the elapsed time
- if acceleration is zero, then the initial velocity equals average velocity $(v_0 = \bar{v})$ and $x = x_0 + v_0t + \frac{1}{2}at^2$ becomes $x = x_0 + v_0t$

SOLVING FOR FINAL VELOCITY WHEN VELOCITY IS NOT CONSTANT (a≠0)

A fourth useful equation can be obtained from another algebraic manipulation of previous equations.

If we solve $v = v_0 + at$ for t, we get

$$t = \frac{v - v_0}{a}.$$

Substituting this and $\bar{v} = \frac{v_0 + v}{2}$ into $x = x_0 + \bar{v}t$, we get

$$v^2 = v_0^2 + 2a\,(x - x_0)\,(\text{ constant } a).$$

Example 5.1.6.4: Calculating Final Velocity: Dragsters

Calculate the final velocity of the dragster in Example 5.1.6.3 without using information about time.

Strategy

Draw a sketch.

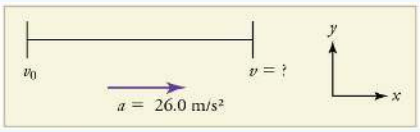


Figure 5.1.6.9

The equation $v^2 = v_0^2 + 2a\,(x - x_0)$ is ideally suited to this task because it relates velocities, acceleration, and displacement, and no time information is required.

Solution

1. Identify the known values. We know that $v_0 = 0$, since the dragster starts from rest. Then we note that $x - x_0 = 402$ m (this was the answer in Example 5.1.6.3). Finally, the average acceleration was given to be $a = 26.0\ \text{m/s}^2$.

2. Plug the knowns into the equation $v^2 = v_0^2 + 2a\,(x - x_0)$ and solve for v.

$$v^2 = 0 + 2\left(26.0\ \text{m/s}^2\right)(402\ \text{m}).$$

Thus

$$v^2 = 2.09 \times 10^4\ \text{m}^2/\text{s}^2.$$

To get v, we take the square root:

$$v = \sqrt{2.09 \times 10^4\ \text{m}^2/\text{s}^2} = 145\ \text{m/s}.$$

Discussion

145 m/s is about 522 km/h or about 324 mi/h, but even this breakneck speed is short of the record for the quarter mile. Also, note that a square root has two values; we took the positive value to indicate a velocity in the same direction as the acceleration.

An examination of the equation $v^2 = v_0^2 + 2a\,(x - x_0)$ can produce further insights into the general relationships among physical quantities:

- The final velocity depends on how large the acceleration is and the distance over which it acts
- For a fixed magnitude of acceleration, a car that is going twice as fast doesn't simply stop in twice the distance—it takes much further to stop. (This is why we have reduced speed zones near schools.)

Putting Equations Together

In the following examples, we further explore one-dimensional motion, but in situations requiring slightly more algebraic manipulation. The examples also give insight into problem-solving techniques. The box below provides easy reference to the equations needed.

SUMMARY OF KINEMATIC EQUATIONS (CONSTANT a)

$$x = x_0 + \bar{v}t$$
$$\bar{v} = \frac{v_0 + v}{2}$$
$$v = v_0 + at$$
$$x = x_0 + v_0 t + \frac{1}{2}at^2$$
$$v^2 = v_0^2 + 2a\left(x - x_0\right)$$

Example 5.1.6.5: Calculating Displacement: How Far Does a Car Go When Coming to a Halt?

On dry concrete, suppose a car can slow down at a rate of $7.00\ \mathrm{m/s^2}$, whereas on wet concrete the maximum magnitude of acceleration is only $5.00\ \mathrm{m/s^2}$. Find the distances necessary to stop a car moving at 30.0 m/s (about 110 km/h) (a) on dry concrete and (b) on wet concrete. (c) Repeat both calculations, finding the displacement from the point where the driver sees a traffic light turn red, taking into account his reaction time of 0.500 s to get his foot on the brake.

Strategy

Draw a sketch.

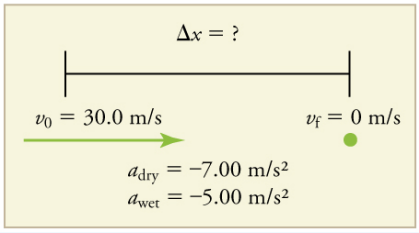


Figure 5.1.6.10

In order to determine which equations are best to use, we need to list all of the known values and identify exactly what we need to solve for. We shall do this explicitly in the next several examples, using tables to set them off.

Solution for (a)

1. Identify the knowns and what we want to solve for. We know that $v_0 = 30.0\ \mathrm{m/s}$; $v = 0$; $a = -7.00\ \mathrm{m/s^2}$ (a is negative because it is in a direction opposite to velocity). We take x_0 to be 0. We are looking for displacement Δx, or $x - x_0$.

2. Identify the equation that will help up solve the problem. The best equation to use is

$$v^2 = v_0^2 + 2a\left(x - x_0\right).$$

This equation is best because it includes only one unknown, x. We know the values of all the other variables in this equation. (There are other equations that would allow us to solve for x, but they require us to know the stopping time, t, which we do not know. We could use them but it would entail additional calculations.)

3. Rearrange the equation to solve for x.

$$x - x_0 = \frac{v^2 - v_0^2}{2a}$$

4. Enter known values.

$$x - 0 = \frac{0^2 - (30.0\ \mathrm{m/s})^2}{2\left(-7.00\ \mathrm{m/s^2}\right)}$$

Thus,

$$x = 64.3 \text{ m on dry concrete.}$$

Solution for (b)

This part can be solved in exactly the same manner as Part A. The only difference is that the acceleration is -5.00 m/s^2. The result is

$$x_{\text{wet}} = 90.0 \text{ m on wet concrete. .}$$

Solution for (c)

Once the driver reacts, the stopping distance is the same as it is in Parts A and B for dry and wet concrete. So to answer this question, we need to calculate how far the car travels during the reaction time, and then add that to the stopping time. It is reasonable to assume that the velocity remains constant during the driver's reaction time.

1. Identify the knowns and what we want to solve for. We know that $\bar{v} = 30.0 \text{ m/s}$; $t_{\text{reaction}} = 0.500 \text{ s}$; $a_{\text{reaction}} = 0$. We take $x_{\text{0-reaction}}$ to be 0. We are looking for $x_{reaction}$.

2. Identify the best equation to use.

$x = x_0 + \bar{v}t$ works well because the only unknown value is x, which is what we want to solve for.

3. Plug in the knowns to solve the equation.

$$x = 0 + (30.0 \text{ m/s})(0.500 \text{ s}) = 15.0 \text{ m.}$$

This means the car travels 15.0 m while the driver reacts, making the total displacements in the two cases of dry and wet concrete 15.0 m greater than if he reacted instantly.

4. Add the displacement during the reaction time to the displacement when braking.

$$x_{\text{braking}} + x_{\text{reaction}} = x_{\text{total}}$$

a. 64.3 m + 15.0 m = 79.3 m when dry
b. 90.0 m + 15.0 m = 105 m when wet

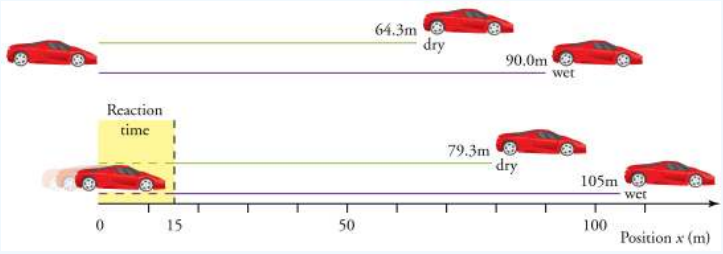


Figure 5.1.6.11: The distance necessary to stop a car varies greatly, depending on road conditions and driver reaction time. Shown here are the braking distances for dry and wet pavement, as calculated in this example, for a car initially traveling at 30.0 m/s. Also shown are the total distances traveled from the point where the driver first sees a light turn red, assuming a 0.500 s reaction time.

Discussion

The displacements found in this example seem reasonable for stopping a fast-moving car. It should take longer to stop a car on wet rather than dry pavement. It is interesting that reaction time adds significantly to the displacements. But more important is the general approach to solving problems. We identify the knowns and the quantities to be determined and then find an appropriate equation. There is often more than one way to solve a problem. The various parts of this example can in fact be solved by other methods, but the solutions presented above are the shortest.

With the basics of kinematics established, we can go on to many other interesting examples and applications. In the process of developing kinematics, we have also glimpsed a general approach to problem solving that produces both correct answers and insights into physical relationships.

MAKING CONNECTIONS: TAKE-HOME EXPERIMENT—BREAKING NEWS

We have been using SI units of meters per second squared to describe some examples of acceleration of cars, runners, and trains. To achieve a better feel for these numbers, one can measure the braking acceleration of a car doing a slow (and safe) stop. Recall that, for average acceleration, $\bar{a} = \Delta v/\Delta t$. While traveling in a car, slowly apply the brakes as you come up to a stop sign. Have a passenger note the initial speed in miles per hour and the time taken (in seconds) to stop. From this, calculate the acceleration in miles per hour per second. Convert this to meters per second squared and compare with other accelerations mentioned in this chapter. Calculate the distance traveled in braking.

Exercise 5.1.6.1

A manned rocket accelerates at a rate of $20\ \text{m/s}^2$ during launch. How long does it take the rocket reach a velocity of 400 m/s?

Answer

To answer this, choose an equation that allows you to solve for time t, given only a, v_0, and v.

$$v = v_0 + at$$

Rearrange to solve for t.

$$t = \frac{v - v_0}{a} = \frac{400\ \text{m/s} - 0\ \text{m/s}}{20\ \text{m/s}^2} = 20\ \text{s}$$

Section Summary

- To simplify calculations we take acceleration to be constant, so that $\bar{a} = a$ at all times.
- We also take initial time to be zero.
- Initial position and velocity are given a subscript 0; final values have no subscript. Thus,

$$\left.\begin{aligned} \Delta t &= t \\ \Delta x &= x - x_0 \\ \Delta v &= v - v_0 \end{aligned}\right\}$$

- The following kinematic equations for motion with constant a are useful:

$$\begin{aligned} x &= x_0 + \bar{v}t \\ \bar{v} &= \frac{v_0 + v}{2} \\ v &= v_0 + at \\ x &= x_0 + v_0 t + \frac{1}{2}at^2 \\ v^2 &= v_0^2 + 2a\left(x - x_0\right) \end{aligned}$$

- In vertical motion, y is substituted for x.

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5.1.7: Falling Objects

Learning Objectives

- Describe the effects of gravity on objects in motion.
- Describe the motion of objects that are in free fall.
- Calculate the position and velocity of objects in free fall.

Falling objects form an interesting class of motion problems. For example, we can estimate the depth of a vertical mine shaft by dropping a rock into it and listening for the rock to hit the bottom. By applying the kinematics developed so far to falling objects, we can examine some interesting situations and learn much about gravity in the process.

Gravity

The most remarkable and unexpected fact about falling objects is that, if air resistance and friction are negligible, then in a given location all objects fall toward the center of Earth with the *same constant acceleration, independent of their mass.* This experimentally determined fact is unexpected, because we are so accustomed to the effects of air resistance and friction that we expect light objects to fall slower than heavy ones.

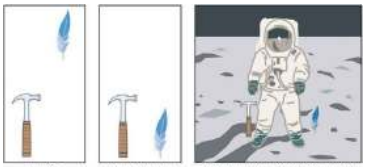


Figure 5.1.7.1: A hammer and a feather will fall with the same constant acceleration if air resistance is considered negligible. This is a general characteristic of gravity not unique to Earth, as astronaut David R. Scott demonstrated on the Moon in 1971, where the acceleration due to gravity is only $1.67\ \mathrm{m/s^2}$.

In the real world, air resistance can cause a lighter object to fall slower than a heavier object of the same size. A tennis ball will reach the ground after a hard baseball dropped at the same time. (It might be difficult to observe the difference if the height is not large.) Air resistance opposes the motion of an object through the air, while friction between objects—such as between clothes and a laundry chute or between a stone and a pool into which it is dropped—also opposes motion between them. For the ideal situations of these first few chapters, an object *falling without air resistance or friction* is defined to be in **free-fall**.

The force of gravity causes objects to fall toward the center of Earth. The acceleration of free-falling objects is therefore called the **acceleration due to gravity**. The acceleration due to gravity is *constant*, which means we can apply the kinematics equations to any falling object where air resistance and friction are negligible. This opens a broad class of interesting situations to us. The acceleration due to gravity is so important that its magnitude is given its own symbol, g. It is constant at any given location on Earth and has the average value

$$g = 9.80\ \mathrm{m/s^2}.$$

Although g varies from $9.78\ \mathrm{m/s^2}$ to $9.83\ \mathrm{m/s^2}$, depending on latitude, altitude, underlying geological formations, and local topography, the average value of $9.80\ \mathrm{m/s^2}$ will be used in this text unless otherwise specified. The direction of the acceleration due to gravity is *downward (towards the center of Earth)*. In fact, its direction *defines* what we call vertical. Note that whether the acceleration a in the kinematic equations has the value $+g$ or $-g$ depends on how we define our coordinate system. If we define the upward direction as positive, then $a = -g = -9.80\ \mathrm{m/s^2}$, and if we define the downward direction as positive, then $a = g = 9.80\ \mathrm{m/s^2}$. In certain examples and homework exercises, slightly inaccurate but more convenient value of $g \simeq 10\ \mathrm{m/s^2}$ will be used with appropriate specifications.

One-Dimensional Motion Involving Gravity

The best way to see the basic features of motion involving gravity is to start with the simplest situations and then progress toward more complex ones. So we start by considering straight up and down motion with no air resistance or friction. These assumptions mean that the velocity (if there is any) is vertical. If the object is dropped, we know the initial velocity is zero. Once the object has left contact with whatever held or threw it, the object is in free-fall. Under these circumstances, the motion is one-dimensional and

has constant acceleration of magnitude g. We will also represent vertical displacement with the symbol y and use x for horizontal displacement.

KINEMATIC EQUATIONS FOR OBJECTS IN FREE-FALL

$$v = v_0 - gt$$

$$y = y_0 + v_0 t - \frac{1}{2} g t^2$$

$$v^2 = v_0^2 - 2g\,(y - y_0)$$

Example 5.1.7.1: Calculating Position and Velocity of a Falling Object: A Rock Thrown Upward

A person standing on the edge of a high cliff throws a rock straight up with an initial velocity of 13.0 m/s. The rock misses the edge of the cliff as it falls back to earth. Calculate the position and velocity of the rock 1.00 s, 2.00 s, and 3.00 s after it is thrown, neglecting the effects of air resistance.

Strategy

Draw a sketch.

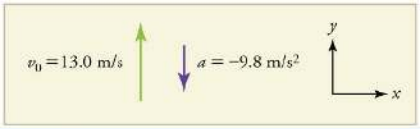


Figure 5.1.7.2

We are asked to determine the position y at various times. It is reasonable to take the initial position y_0 to be zero. This problem involves one-dimensional motion in the vertical direction. We use plus and minus signs to indicate direction, with up being positive and down negative. Since up is positive, and the rock is thrown upward, the initial velocity must be positive too. The acceleration due to gravity is downward, so a is negative. It is crucial that the initial velocity and the acceleration due to gravity have opposite signs. Opposite signs indicate that the acceleration due to gravity opposes the initial motion and will slow and eventually reverse it.

Since we are asked for values of position and velocity at three times, we will refer to these as y_1 and v_1; y_2 and v_2; and y_3 and v_3.

Solution for Position y_1

1. Identify the knowns. We know that $y_0 = 0;\ v_0 = 13.0\ \text{m/s};\ a = -g = -9.80\ \text{m/s}^2$; and $t = 1.00$ s.

2. Identify the best equation to use. We will use $y = y_0 + v_0 t + \frac{1}{2} a t^2$ because it includes only one unknown, y (or y_1, here), which is the value we want to find.

3. Plug in the known values and solve for y_1.

$$y_1 = 0 + (13.0\ \text{m/s})(1.00\ \text{s}) + \frac{1}{2}\left(-9.80\ \text{m/s}^2\right)(1.00\ \text{s})^2 = 8.10\ \text{m}$$

Discussion

The rock is 8.10 m above its starting point at $t = 1.00$ s, since $y_1 > y_0$. It could be *moving* up or down; the only way to tell is to calculate v_1 and find out if it is positive or negative.

Solution for Velocity v_1

1. Identify the knowns. We know that $y_0 = 0;\ v_0 = 13.0\ \text{m/s};\ a = -g = -9.80\ \text{m/s}^2$; and $t = 1.00s$. We also know from the solution above that $y_1 = 8.10$ m.

2. Identify the best equation to use. The most straightforward is $v = v_0 - gt$ (from $v = v_0 + at$, where a = gravitational acceleration $= -g$).

3. Plug in the knowns and solve.

$$v_1 = v_0 - gt = 13.0\ \text{m/s} - \left(9.80\ \text{m/s}^2\right)(1.00\ \text{s}) = 3.20\ \text{m/s}$$

Discussion

The positive value for v_1 means that the rock is still heading upward at t=**1.00s**. However, it has slowed from its original 13.0 m/s, as expected.

Solution for Remaining Times

The procedures for calculating the position and velocity at t = **2.00 s** and **3.00 s** are the same as those above. The results are summarized in Table 5.1.7.1 and illustrated in Figure 5.1.7.3.

Table 5.1.7.1: Results

Time, *t*	Position, *y*	Velocity, *v*	Acceleration, *a*
1.00 s	8.10 m	3.20 m	$-9.80\ \text{m/s}^2$
2.00 s	6.40 m	−6.60 m	$-9.80\ \text{m/s}^2$
3.00 s	−5.10 m	−16.4 m	$-9.80\ \text{m/s}^2$

Graphing the data helps us understand it more clearly.

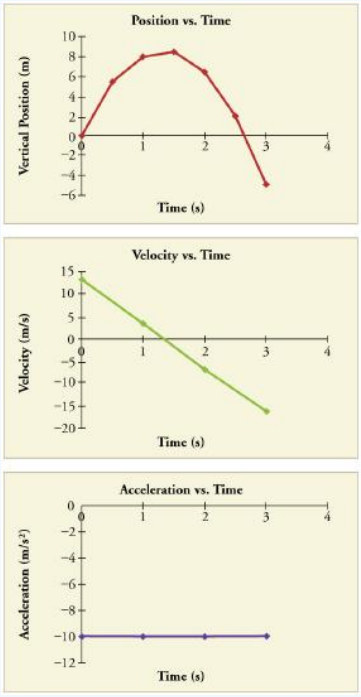


Figure 5.1.7.3: Vertical position, vertical velocity, and vertical acceleration vs. time for a rock thrown vertically up at the edge of a cliff. Notice that velocity changes linearly with time and that acceleration is constant. *Misconception Alert!* Notice that the position vs. time graph shows vertical position only. It is easy to get the impression that the graph shows some horizontal motion—the shape of the graph looks like the path of a projectile. But this is not the case; the horizontal axis is *time*, not space. The actual path of the rock in space is straight up, and straight down.

Discussion

The interpretation of these results is important. At 1.00 s the rock is above its starting point and heading upward, since y_1 and v_1 are both positive. At 2.00 s, the rock is still above its starting point, but the negative velocity means it is moving downward. At 3.00 s, both y_3 and v_3 are negative, meaning the rock is below its starting point and continuing to move downward. Notice that when the rock is at its highest point (at 1.5 s), its velocity is zero, but its acceleration is still $-9.80\ \text{m/s}^2$. Its acceleration is $-9.80\ \text{m/s}^2$ for the whole trip—while it is moving up and while it is moving down. Note that the values for y are the positions

(or displacements) of the rock, not the total distances traveled. Finally, note that free-fall applies to upward motion as well as downward. Both have the same acceleration—the acceleration due to gravity, which remains constant the entire time. Astronauts training in the famous Vomit Comet, for example, experience free-fall while arcing up as well as down, as we will discuss in more detail later.

MAKING CONNECTIONS: TAKE-HOME EXPERIMENT—REACTION TIME

A simple experiment can be done to determine your reaction time. Have a friend hold a ruler between your thumb and index finger, separated by about 1 cm. Note the mark on the ruler that is right between your fingers. Have your friend drop the ruler unexpectedly, and try to catch it between your two fingers. Note the new reading on the ruler. Assuming acceleration is that due to gravity, calculate your reaction time. How far would you travel in a car (moving at 30 m/s) if the time it took your foot to go from the gas pedal to the brake was twice this reaction time?

Example 5.1.7.2: Calculating Velocity of a Falling Object: A Rock Thrown Down

What happens if the person on the cliff throws the rock straight down, instead of straight up? To explore this question, calculate the velocity of the rock when it is 5.10 m below the starting point, and has been thrown downward with an initial speed of 13.0 m/s.

Strategy

Draw a sketch.

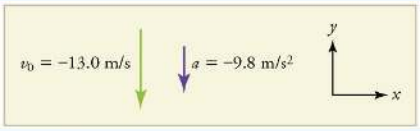


Figure 5.1.7.4

Since up is positive, the final position of the rock will be negative because it finishes below the starting point at $y_0 = 0$. Similarly, the initial velocity is downward and therefore negative, as is the acceleration due to gravity. We expect the final velocity to be negative since the rock will continue to move downward.

Solution

1. Identify the knowns. $y_0 = 0;\ y_1 = -5.10\ \text{m};\ v_0 = -13.0\ \text{m/s};\ a = -g = -9.80\ \text{m/s}^2$.

2. Choose the kinematic equation that makes it easiest to solve the problem. The equation $v^2 = v_0^2 + 2a\,(y - y_0)$ works well because the only unknown in it is v. (We will plug y_1 in for y.)

3. Enter the known values

$$v^2 = (-13.0\ \text{m/s})^2 + 2\,(-9.80\ \text{m/s}^2)\,(-5.10\ \text{m} - 0\ \text{m}) = 268.96\ \text{m}^2/\text{s}^2,$$

where we have retained extra significant figures because this is an intermediate result.

Taking the square root, and noting that a square root can be positive or negative, gives

$$v = \pm 16.4\ \text{m/s}.$$

The negative root is chosen to indicate that the rock is still heading down. Thus,

$$v = -16.4\ \text{m/s}.$$

Discussion

Note that *this is exactly the same velocity the rock had at this position when it was thrown straight upward with the same initial speed*. (See Example 5.1.7.1 and Figure 5.1.7.5 (a).) This is not a coincidental result. Because we only consider the acceleration due to gravity in this problem, the *speed* of a falling object depends only on its initial speed and its vertical position relative to the starting point. For example, if the velocity of the rock is calculated at a height of 8.10 m above the starting point (using the

method from Example 5.1.7.1) when the initial velocity is 13.0 m/s straight up, a result of $\pm 3.20\ \mathrm{m/s}$ is obtained. Here both signs are meaningful; the positive value occurs when the rock is at 8.10 m and heading up, and the negative value occurs when the rock is at 8.10 m and heading back down. It has the same *speed* but the opposite direction.

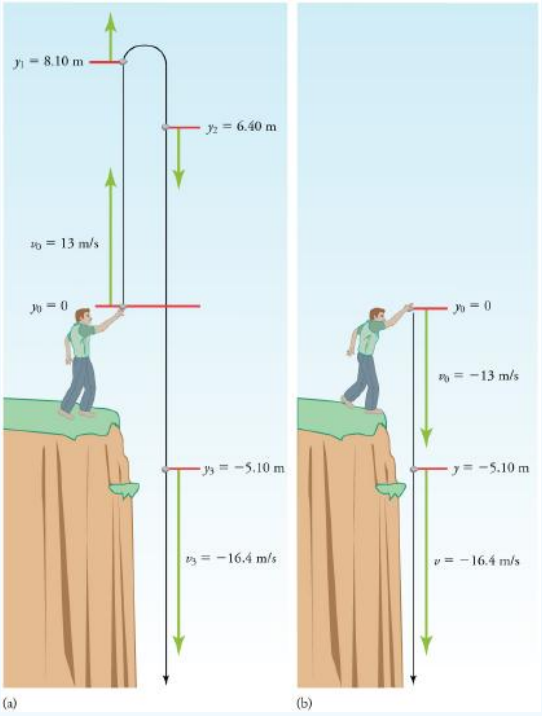


Figure 5.1.7.5: (a) A person throws a rock straight up, as explored in Example 5.1.7.1. The arrows are velocity vectors at 0, 1.00, 2.00, and 3.00 s. (b) A person throws a rock straight down from a cliff with the same initial speed as before, as in Example 5.1.7.2. Note that at the same distance below the point of release, the rock has the same velocity in both cases.

Another way to look at it is this: In Example 5.1.7.1, the rock is thrown up with an initial velocity of **13.0 m/s**. It rises and then falls back down. When its position is $y = 0$ on its way back down, its velocity is **−13.0 m/s**. That is, it has the same speed on its way down as on its way up. We would then expect its velocity at a position of $y = -5.10\mathrm{m}$ to be the same whether we have thrown it upwards at **+13.0 m/s** or thrown it downwards at **−13.0 m/s**. The velocity of the rock on its way down from $y = 0$ is the same whether we have thrown it up or down to start with, as long as the speed with which it was initially thrown is the same.

Example 5.1.7.3: Find g from Data on a Falling Object

The acceleration due to gravity on Earth differs slightly from place to place, depending on topography (e.g., whether you are on a hill or in a valley) and subsurface geology (whether there is dense rock like iron ore as opposed to light rock like salt beneath you.) The precise acceleration due to gravity can be calculated from data taken in an introductory physics laboratory course. An object, usually a metal ball for which air resistance is negligible, is dropped and the time it takes to fall a known distance is measured. See, for example, Figure 5.1.7.6. Very precise results can be produced with this method if sufficient care is taken in measuring the distance fallen and the elapsed time.

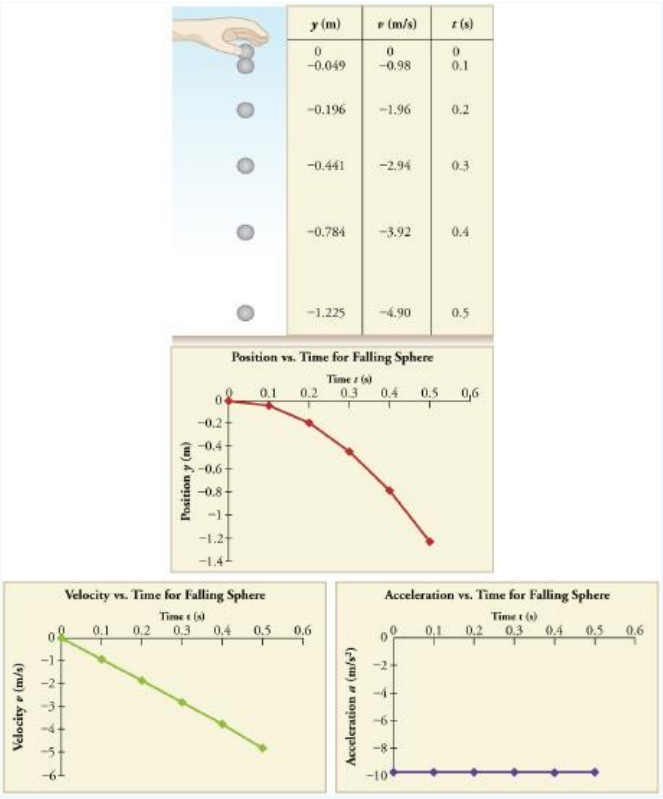


Figure 5.1.7.6: Positions and velocities of a metal ball released from rest when air resistance is negligible. Velocity is seen to increase linearly with time while displacement increases with time squared. Acceleration is a constant and is equal to gravitational acceleration.

Suppose the ball falls 1.0000 m in 0.45173 s. Assuming the ball is not affected by air resistance, what is the precise acceleration due to gravity at this location?

Strategy

Draw a sketch.

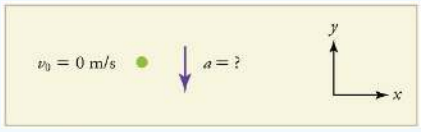


Figure 5.1.7.7

We need to solve for acceleration a. Note that in this case, displacement is downward and therefore negative, as is acceleration.

Solution

1. Identify the knowns. $y_0 = 0;\ y = -1.0000\ \text{m};\ t = 0.45173;\ v_0 = 0.$.

2. Choose the equation that allows you to solve for a using the known values.

$$y = y_0 + v_0 t + \frac{1}{2}at^2$$

3. Substitute 0 for v_0 and rearrange the equation to solve for a. Substituting 0 for v_0 yields

$$y = y_0 + \frac{1}{2}at^2.$$

Solving for a gives

$$a = \frac{2\,(y - y_0)}{t^2}.$$

4. Substitute known values yields

$$a = \frac{2(-1.0000\ \text{m} - 0)}{(0.45173\ \text{s})^2} = -9.8010\ \text{m/s}^2,$$

so, because $a = -g$ with the directions we have chosen,

$$g = 9.8010\ \text{m/s}^2.$$

Discussion

The negative value for a indicates that the gravitational acceleration is downward, as expected. We expect the value to be somewhere around the average value of $9.80\ \text{m/s}^2$, so $9.8010\ \text{m/s}^2$ makes sense. Since the data going into the calculation are relatively precise, this value for g is more precise than the average value of $9.80\ \text{m/s}^2$; it represents the local value for the acceleration due to gravity.

Exercise 5.1.7.1

A chunk of ice breaks off a glacier and falls 30.0 meters before it hits the water. Assuming it falls freely (there is no air resistance), how long does it take to hit the water?

Answer

We know that initial position $y_0 = 0$, final position $y = -30.0\ \text{m}$, and $a = -g = -9.80\ \text{m/s}^2$. We can then use the equation $y = y_0 + v_0 t + \frac{1}{2}at^2$ to solve for t. Inserting $a = -g$, we obtain

$$\begin{aligned} y &= 0 + 0 - \frac{1}{2}gt^2 \\ t^2 &= \frac{2y}{-g} \\ t &= \pm\sqrt{\frac{2y}{-g}} = \pm\sqrt{\frac{2(-30.0\ \text{m})}{-9.80\ \text{m/s}^2}} = \pm\sqrt{6.12\ \text{s}^2} = 2.47\ \text{s} \approx 2.5\ \text{s} \end{aligned}$$

where we take the positive value as the physically relevant answer. Thus, it takes about 2.5 seconds for the piece of ice to hit the water.

Section Summary

- An object in free-fall experiences constant acceleration if air resistance is negligible.
- On Earth, all free-falling objects have an acceleration due to gravity g, which averages

$$g = 9.80\ \text{m/s}^2.$$

- Whether the acceleration a should be taken as $+g$ or $-g$ is determined by your choice of coordinate system. If you choose the upward direction as positive,$a = -g = -9.80\ \text{m/s}^2$ is negative. In the opposite case, $a = +\text{g} = 9.80\ \text{m/s}^2$ is positive. Since acceleration is constant, the kinematic equations above can be applied with the appropriate $+g$ or $-g$ substituted for a.
- For objects in free-fall, up is normally taken as positive for displacement, velocity, and acceleration.

Glossary

free-fall

the state of movement that results from gravitational force only

acceleration due to gravity

acceleration an object undergoes while in free-fall

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5.1.8: Projectile Motion

Learning Objectives

- Identify and explain the properties of a projectile, such as acceleration due to gravity, range, and trajectory.
- Apply the principle of independence of motion to solve projectile motion problems.

Projectile motion is the **motion** of an object thrown or projected into the air, subject to only the acceleration of gravity. The object is called a **projectile**, and its path is called its **trajectory**. The motion of falling objects is a simple one-dimensional type of projectile motion in which there is no horizontal movement. In this section, we consider two-dimensional projectile motion, such as that of a football or other object for which **air resistance** *is negligible*.

The most important fact to know here is that *motions along perpendicular axes are independent* and thus can be considered separately. In particular, it is often convenient to consider vertical and horizontal motions separately, or independently. The key to analyzing two-dimensional projectile motion is to break it into two motions, one along the horizontal axis and the other along the vertical. And we will assume all forces except gravity are negligible (that is, we ignore forces due to air resistance, wind, friction, etc.). The vertical component of acceleration is, then, $a_y = -g = -9.80\ \mathrm{m/s^2}$, where we take upward direction as the positive y direction. And because there is no force in the horizontal direction, $a_x = 0$. Figure 5.1.8.1 illustrates this approach to analyzing projectile motion.

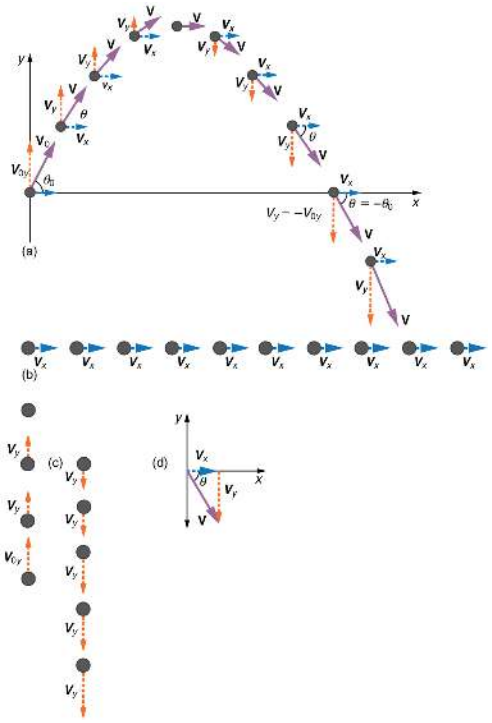


Figure 5.1.8.1: (a) We analyze two-dimensional projectile motion by breaking it into two independent one-dimensional motions along the vertical and horizontal axes. (b) The horizontal motion is simple, because $a_x = 0$ and v_x is thus constant. (c) The velocity in the vertical direction begins to decrease as the object rises; at its highest point, the vertical velocity is zero. As the object falls towards the Earth again, the vertical velocity increases again in magnitude. This is exactly same as in the case of falling objects (or objects thrown directly upward). (d) The *x* - and *y* -motions can be recombined to give the total velocity at any given point on the trajectory.

One of the conceptual aspects of projectile motion we can discuss without a detailed analysis is the range. On level ground, we define **range** to be the horizontal distance R traveled by a projectile. The range of projectiles describes everyday phenomena such as how far a football can be thrown or kicked. Also, investigating the range of projectiles can shed light on other interesting phenomena, such as the orbits of satellites around the Earth. Let us consider projectile range further.

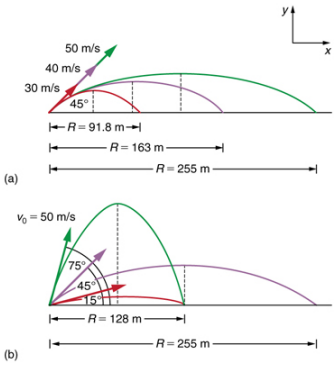


Figure 5.1.8.2: Trajectories of projectiles on level ground. (a) The greater the initial speed v_0, the greater the range for a given initial angle. (b) The effect of initial angle θ_0 on the range of a projectile with a given initial speed. Note that the range is the same for 15° and 75°, although the maximum heights of those paths are different.

How does the initial velocity of a projectile affect its range? It is intuitive to guess that, the greater the initial speed v_0, the greater the range, as shown in Figure 5.1.8.2 (a). The initial angle θ_0 also has a dramatic effect on the range, as illustrated in Figure 5.1.8.2 (b). For a fixed initial speed, such as might be produced by a cannon, the maximum range is obtained with $\theta_0 = 45^\circ$. Interestingly, for every initial angle except 45°, there are two angles that give the same range. The range also depends on the value of the acceleration of gravity g. The lunar astronaut Alan Shepherd was able to drive a golf ball a great distance on the Moon because gravity is weaker there. The range R of a projectile on *level ground* for which air resistance is negligible is given by

$$R = \frac{v_0^2 \sin 2\theta_0}{g},$$

where v_0 is the initial speed and θ_0 is the initial angle relative to the horizontal. This formula (which can be derived using algebra and trigonometry) fits the major features of projectile range as described.

When we speak of the range of a projectile on level ground, we assume that R is very small compared with the circumference of the Earth. If, however, the range is large, the Earth curves away below the projectile and acceleration of gravity changes direction along the path. The range is larger than predicted by the range equation given above because the projectile has farther to fall than it would on level ground. (See Figure 5.1.8.3.) If the initial speed is great enough, the projectile goes into orbit. This possibility was recognized centuries before it could be accomplished. When an object is in orbit, the Earth curves away from underneath the object at the same rate as it falls. The object thus falls continuously but never hits the surface.

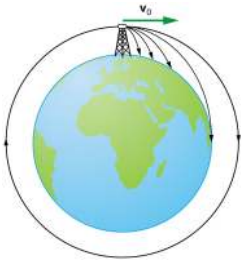


Figure 5.1.8.3: Projectile to satellite. In each case shown here, a projectile is launched from a very high tower to avoid air resistance. With increasing initial speed, the range increases and becomes longer than it would be on level ground because the Earth curves away underneath its path. With a large enough initial speed, orbit is achieved.

Summary

- Projectile motion is the motion of an object through the air that is subject only to the acceleration of gravity.
- The most important fact regarding projectile motion is that motions along vertical direction and the horizontal direction are independent.
- The maximum horizontal distance traveled by a projectile is called the **range**. The range R of a projectile on level ground launched at an angle θ_0 above the horizontal with initial speed v_0 is given by

$$R = \frac{v_0^2 \sin 2\theta_0}{g}.$$

Glossary

centripetal acceleration
the acceleration of an object moving in a circle, directed toward the center

ultracentrifuge
a centrifuge optimized for spinning a rotor at very high speeds

uniform circular motion
an object moving in a circular path at constant speed

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5.1.9: Centripetal Acceleration

Learning Objectives

- Explain what centripetal acceleration is.
- Use the formula for centripetal acceleration in simple situations.

We defined acceleration as a change in velocity, either in its magnitude or in its direction, or both. When an object moves along a circular path, the direction of its velocity changes constantly, so there is always an associated acceleration, even if the speed of the object is constant. You experience this acceleration yourself when you turn a corner in your car. What you notice is a sideways acceleration because you and the car are changing direction. The sharper the curve and the greater your speed, the more noticeable this acceleration will become. In this section we briefly examine the direction and magnitude of that acceleration.

Figure 5.1.9.1 shows an object moving in a circular path at constant speed, called **uniform circular motion**. The direction of the instantaneous velocity is shown at two points along the path. Acceleration is in the direction of the change in velocity, which points directly toward the center of rotation (the center of the circular path). This pointing is shown with the vector diagram in the figure. We call the acceleration of an object moving in uniform circular motion (resulting from a net external force) the **centripetal acceleration**(a_c); centripetal means "toward the center" or "center seeking."

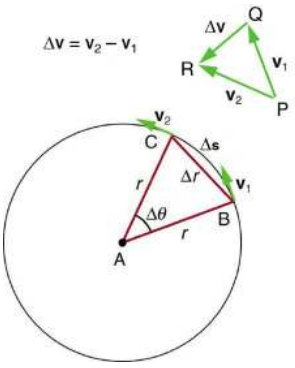


Figure 5.1.9.1: The directions of the velocity of an object at two different points are shown, and the change in velocity $\Delta \mathbf{v}$ is seen to point directly toward the center of curvature. (See small inset.) Because $\mathbf{a}_c = \Delta \mathbf{v}/\Delta t$, the acceleration is also toward the center; a_c is called centripetal acceleration. (For small time differences, $\Delta\theta$ is very small, and the arc length Δs is approximately equal to the chord length Δr.)

The direction of centripetal acceleration is toward the center of curvature, but what is its magnitude? If we use the geometry shown in Figure 5.1.9.1 along with some kinematics equations, we can obtain (detailed derivation skipped)

$$a_c = \frac{v^2}{r}, \tag{5.1.9.1}$$

which is the acceleration of an object in a circle of radius r at a speed v. Verify for yourself that a_c has unit of $\mathrm{m/s^2}$, as expected for acceleration.

We see in Equation (5.1.9.1) that centripetal acceleration is greater at high speeds and in sharp curves (smaller radius), as you have noticed when driving a car. But it is a bit surprising that a_c is proportional to speed squared, implying, for example, that it is four times as hard to take a curve at 100 km/h than at 50 km/h. A sharp corner has a small radius, so that a_c is greater for tighter turns, as you have probably noticed.

Section Summary

- Centripetal acceleration a_c is the acceleration experienced while in uniform circular motion. It always points toward the center of rotation. It is perpendicular to the linear velocity v and has the magnitude

$$a_c = \frac{v^2}{r}.$$

- The unit of centripetal acceleration is $\mathrm{m/s^2}$.

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5.1.E: Kinematics (Exercise)

Conceptual Questions

1.1: Displacement

1. Give an example in which there are clear distinctions among distance traveled, displacement, and magnitude of displacement. Specifically identify each quantity in your example.

2. Under what circumstances does distance traveled equal magnitude of displacement? What is the only case in which magnitude of displacement and displacement are exactly the same?

3. Bacteria move back and forth by using their flagella (structures that look like little tails). Speeds of up to $50\ \mu\text{m/s}\ \ (50 \times 10^{-6}\ \text{m/s})$ have been observed. The total distance traveled by a bacterium is large for its size, while its displacement is small. Why is this?

1.2: Vectors, Scalars, and Coordinate Systems

4. A student writes, "*A bird that is diving for prey has a speed of* −10 m/s." What is wrong with the student's statement? What has the student actually described? Explain.

5. What is the speed of the bird in Exercise 2.2.4?

6. Acceleration is the change in velocity over time. Given this information, is acceleration a vector or a scalar quantity? Explain.

7. A weather forecast states that the temperature is predicted to be −5ºC the following day. Is this temperature a vector or a scalar quantity? Explain.

1.3: Time, Velocity, and Speed

8. Give an example (but not one from the text) of a device used to measure time and identify what change in that device indicates a change in time.

9. There is a distinction between average speed and the magnitude of average velocity. Give an example that illustrates the difference between these two quantities.

10. Does a car's odometer measure position or displacement? Does its speedometer measure speed or velocity?

11. If you divide the total distance traveled on a car trip (as determined by the odometer) by the time for the trip, are you calculating the average speed or the magnitude of the average velocity? Under what circumstances are these two quantities the same?

12. How are instantaneous velocity and instantaneous speed related to one another? How do they differ?

1.4: Acceleration

13. Is it possible for speed to be constant while acceleration is not zero? Give an example of such a situation.

14. Is it possible for velocity to be constant while acceleration is not zero? Explain.

15. Give an example in which velocity is zero yet acceleration is not.

16. If a subway train is moving to the left (has a negative velocity) and then comes to a stop, what is the direction of its acceleration? Is the acceleration positive or negative?

17. Plus and minus signs are used in one-dimensional motion to indicate direction. What is the sign of an acceleration that reduces the magnitude of a negative velocity? Of a positive velocity?

1.5: Motion Equations for Constant Acceleration in One Dimension

18. In a constant-acceleration motion, how does the position change? How does the velocity change?

19. Describe the relationship between the position and the velocity in a constant-acceleration motion.

20. Describe the relationship between the velocity and the acceleration in a constant-acceleration motion.

21. In a constant-acceleration motion starting from rest, how does the distance traveled change with the duration of motion? If the motion continues for double the time (total), how much does the distance traveled increase (total)?

1.6: Falling Objects

22. What is the acceleration of a rock thrown straight upward on the way up? At the top of its flight? On the way down?

23. An object that is thrown straight up falls back to Earth. This is one-dimensional motion. (a) When is its velocity zero? (b) Does its velocity change direction? (c) Does the acceleration due to gravity have the same sign on the way up as on the way down?

24. Suppose you throw a rock nearly straight up at a coconut in a palm tree, and the rock misses on the way up but hits the coconut on the way down. Neglecting air resistance, how does the speed of the rock when it hits the coconut on the way down compare with what it would have been if it had hit the coconut on the way up? Is it more likely to dislodge the coconut on the way up or down? Explain.

25. If an object is thrown straight up and air resistance is negligible, then its speed when it returns to the starting point is the same as when it was released. If air resistance were not negligible, how would its speed upon return compare with its initial speed? How would the maximum height to which it rises be affected?

26. The severity of a fall depends on your speed when you strike the ground. All factors but the acceleration due to gravity being the same, how many times higher could a safe fall on the Moon be than on Earth (gravitational acceleration on the Moon is about 1/6 that of the Earth)?

27. How many times higher could an astronaut jump on the Moon than on Earth if his takeoff speed is the same in both locations (gravitational acceleration on the Moon is about 1/6 of g on Earth)?

1.7: Projectile Motion

28. Answer the following questions for projectile motion on level ground assuming negligible air resistance (the initial angle being neither 0° nor 90°): (a) Is the velocity ever zero? (b) When is the velocity a minimum? A maximum? (c) Can the velocity ever be the same as the initial velocity at a time other than at $t = 0$? (d) Can the speed ever be the same as the initial speed at a time other than at $t = 0$?

29. Answer the following questions for projectile motion on level ground assuming negligible air resistance (the initial angle being neither 0° nor 90°): (a) Is the acceleration ever zero? (b) Is the acceleration ever in the same direction as a component of velocity? (c) Is the acceleration ever opposite in direction to a component of velocity?

30. For a fixed initial speed, the range of a projectile is determined by the angle at which it is fired. For all but the maximum, there are two angles that give the same range. Considering factors that might affect the ability of an archer to hit a target, such as wind, explain why the smaller angle (closer to the horizontal) is preferable. When would it be necessary for the archer to use the larger angle? Why does the punter in a football game use the higher trajectory?

31. During a lecture demonstration, a professor places two coins on the edge of a table. She then flicks one of the coins horizontally off the table, simultaneously nudging the other over the edge. Describe the subsequent motion of the two coins, in particular discussing whether they hit the floor at the same time.

1.8: Centripetal Acceleration

32. Give examples of centripetal acceleration from everyday experience.

33. A satellite in a circular orbit around the Earth is undergoing a centripetal acceleration. Explain how this description is consistent with the description that the satellite in free-fall.

34. Can centripetal acceleration change the speed of circular motion? Explain.

Problems & Exercises

1.1: Displacement

35.

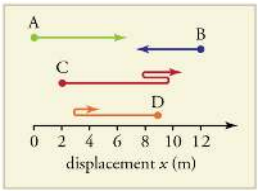


Figure 5.1.E.1

Find the following for path A in Figure 5.1.E.1: (a) The distance traveled. (b) The magnitude of the displacement from start to finish. (c) The displacement from start to finish.

Answer

(a) 7 m

(b) 7 m

(c) +7 m

36. Find the following for path B in Figure 5.1.E.1: (a) The distance traveled. (b) The magnitude of the displacement from start to finish. (c) The displacement from start to finish.

37. Find the following for path C in Figure 5.1.E.1: (a) The distance traveled. (b) The magnitude of the displacement from start to finish. (c) The displacement from start to finish.

Answer

(a) 13 m

(b) 9 m

(c) +9 m

38. Find the following for path D in Figure 5.1.E.1: (a) The distance traveled. (b) The magnitude of the displacement from start to finish. (c) The displacement from start to finish.

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SECTION OVERVIEW

5.2: Dynamics

5.2.1: Introduction to Dynamics- Newton’s Laws of Motion

5.2.2: Development of Force Concept

5.2.3: Newton’s First Law of Motion- Inertia

5.2.4: Newton's Second Law of Motion- Force and Acceleration

5.2.5: Newton’s Third Law of Motion- Symmetry in Forces

5.2.6: Normal Force and Tension

5.2.7: Spring Force- Hooke’s Law

5.2.8: Friction

5.2.9: Newton’s Universal Law of Gravitation

5.2.10: Centripetal Force

5.2.E: Dynamics (Exercise)

Thumbnail: For every action there is a reaction. (CC BY-SA 3.0; Benjamin Crowell)

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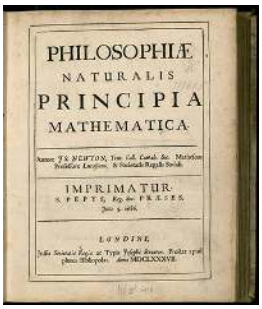
5.2.1: Introduction to Dynamics- Newton's Laws of Motion



Figure 5.2.1.1: Newton's laws of motion describe the motion of the dolphin's path. (credit: Jin Jang)

Motion draws our attention. Motion itself can be beautiful, causing us to marvel at the forces needed to achieve spectacular motion, such as that of a dolphin jumping out of the water, or a pole vaulter, or the flight of a bird, or the orbit of a satellite. The study of motion is kinematics, but kinematics only *describes* the way objects move—their velocity and their acceleration. **Dynamics** considers the forces that affect the motion of moving objects and systems. Newton's laws of motion are the foundation of dynamics. These laws provide an example of the breadth and simplicity of principles under which nature functions. They are also universal laws in that they apply to similar situations on Earth as well as in space.

Issac Newton's (1642–1727) laws of motion were just one part of the monumental work that has made him legendary. The development of Newton's laws marks the transition from the Renaissance into the modern era. This transition was characterized by a revolutionary change in the way people thought about the physical universe. For many centuries natural philosophers had debated the nature of the universe based largely on certain rules of logic with great weight given to the thoughts of earlier classical philosophers such as Aristotle (384–322 BC). Among the many great thinkers who contributed to this change were Newton and Galileo.


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR.

Figure 5.2.1.2: Issac Newton's monumental work, *Philosophiae Naturalis Principia Mathematica*, was published in 1687. It proposed scientific laws that are still used today to describe the motion of objects. (credit: Service commun de la documentation de l'Université de Strasbourg)

Galileo was instrumental in establishing *observation* as the absolute determinant of truth, rather than "logical" argument. Galileo's use of the telescope was his most notable achievement in demonstrating the importance of observation. He discovered moons orbiting Jupiter and made other observations that were inconsistent with certain ancient ideas and religious dogma. For this reason, and because of the manner in which he dealt with those in authority, Galileo was tried by the Inquisition and punished. He spent the

final years of his life under a form of house arrest. Because others before Galileo had also made discoveries by *observing* the nature of the universe, and because repeated observations verified those of Galileo, his work could not be suppressed or denied. After his death, his work was verified by others, and his ideas were eventually accepted by the church and scientific communities.

Galileo also contributed to the formation of what is now called Newton's first law of motion. Newton made use of the work of his predecessors, which enabled him to develop laws of motion, discover the law of gravity, invent calculus, and make great contributions to the theories of light and color. It is amazing that many of these developments were made with Newton working alone, without the benefit of the usual interactions that take place among scientists today.

It was not until the advent of modern physics early in the 20th century that it was discovered that Newton's laws of motion produce a good approximation to motion only when the objects are moving at speeds much, much less than the speed of light and when those objects are larger than the size of most molecules (about 10^{-9} m in diameter). These constraints define the realm of classical mechanics. At the beginning of the 20th century, Albert Einstein (1879–1955) developed the theory of relativity and, along with many other scientists, developed quantum theory. This theory does not have the constraints present in classical physics. All of the situations we consider in this chapter are in the realm of classical physics.

MAKING CONNECTIONS: PAST AND PRESENT PHILOSOPHY

The importance of observation and the concept of *cause and effect* were not always so entrenched in human thinking. This realization was a part of the evolution of modern physics from natural philosophy. The achievements of Galileo, Newton, Einstein, and others were key milestones in the history of scientific thought. Most of the scientific theories that are described in this book descended from the work of these scientists.

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5.2.2: Development of Force Concept

Learning Objectives

- Understand the definition of force.

Dynamics is the study of the forces that cause objects and systems to move. To understand this, we need a working definition of force. Our intuitive definition of **force**—that is, a push or a pull—is a good place to start. We know that a push or pull has both magnitude and direction (therefore, it is a vector quantity) and can vary considerably in each regard. For example, a cannon exerts a strong force on a cannonball that is launched into the air. In contrast, Earth exerts only a tiny downward pull on a flea.

A more quantitative definition of force can be based on some standard force, just as distance is measured in units relative to a standard distance. One possibility is to stretch a spring a certain fixed distance, as illustrated in Figure 5.2.2.1, and use the force it exerts to pull itself back to its relaxed shape—called a *restoring force*—as a standard. The magnitude of all other forces can be stated as multiples of this standard unit of force. Many other possibilities exist for standard forces. Some alternative definitions of force will be given later in this chapter.

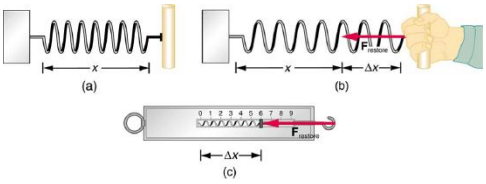


Figure 5.2.2.1: The force exerted by a stretched spring can be used as a standard unit of force. (a) This spring has a length x when undistorted. (b) When stretched a distance Δx, the spring exerts a restoring force, $\mathbf{F}_{\text{restore}}$, which is reproducible. (c) A spring scale is one device that uses a spring to measure force. The force $\mathbf{F}_{\text{restore}}$ is exerted on whatever is attached to the hook. Here $\mathbf{F}_{\text{restore}}$ has a magnitude of 6 units in the force standard being employed.

TAKE-HOME EXPERIMENT: FORCE STANDARDS

To investigate force standards and cause and effect, get two identical rubber bands. Hang one rubber band vertically on a hook. Find a small household item that could be attached to the rubber band using a paper clip, and use this item as a weight to investigate the stretch of the rubber band. Measure the amount of stretch produced in the rubber band with one, two, and four of these (identical) items suspended from the rubber band. What is the relationship between the number of items and the amount of stretch? How large a stretch would you expect for the same number of items suspended from two rubber bands? What happens to the amount of stretch of the rubber band (with the weights attached) if the weights are also pushed to the side with a pencil?

Section Summary

- **Dynamics** is the study of how forces affect the motion of objects.
- **Force** is a push or pull that can be defined in terms of various standards, and it is a vector having both magnitude and direction.

Glossary

dynamics

the study of how forces affect the motion of objects and systems

force

a push or pull on an object with a specific magnitude and direction; can be represented by vectors; can be expressed as a multiple of a standard force

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5.2.3: Newton's First Law of Motion- Inertia

Learning Objectives

- Define mass and inertia.
- Understand Newton's first law of motion.

Experience suggests that an object at rest will remain at rest if left alone, and that an object in motion tends to slow down and stop unless some effort is made to keep it moving. What **Newton's first law of motion** states, however, is the following:

NEWTON'S FIRST LAW OF MOTION

A body at rest remains at rest, or, if in motion, remains in motion at a constant velocity unless acted on by a net external force.

Note the repeated use of the verb "remains." We can think of this law as preserving the status quo of motion.

Rather than contradicting our experience, **Newton's first law of motion** states that there must be a *cause* (which is a net external force) *for there to be any change in velocity (either a change in magnitude or direction)*. We will define *net external force* in the next section. An object sliding across a table or floor slows down due to the net force of friction acting on the object. If friction disappeared, would the object still slow down?

The idea of cause and effect is crucial in accurately describing what happens in various situations. For example, consider what happens to an object sliding along a rough horizontal surface. The object quickly grinds to a halt. If we spray the surface with talcum powder to make the surface smoother, the object slides farther. If we make the surface even smoother by rubbing lubricating oil on it, the object slides farther yet. Extrapolating to a frictionless surface, we can imagine the object sliding in a straight line indefinitely. Friction is thus the *cause* of the slowing (consistent with Newton's first law). The object would not slow down at all if friction were completely eliminated. Consider an air hockey table. When the air is turned off, the puck slides only a short distance before friction slows it to a stop. However, when the air is turned on, it creates a nearly frictionless surface, and the puck glides long distances without slowing down. Additionally, if we know enough about the friction, we can accurately predict how quickly the object will slow down. Friction is an external force.

Newton's first law is completely general and can be applied to anything from an object sliding on a table to a satellite in orbit to blood pumped from the heart. Experiments have thoroughly verified that any change in velocity (speed or direction) must be caused by an external force. The idea of *generally applicable or universal laws* is important not only here—it is a basic feature of all laws of physics. Identifying these laws is like recognizing patterns in nature from which further patterns can be discovered. The genius of Galileo, who first developed the idea for the first law, and Newton, who clarified it, was to ask the fundamental question, "What is the cause?" Thinking in terms of cause and effect is a worldview fundamentally different from the typical ancient Greek approach when questions such as "Why does a tiger have stripes?" would have been answered in Aristotelian fashion, "That is the nature of the beast." True perhaps, but not a useful insight.

Mass

The property of a body to remain at rest or to remain in motion with constant velocity is called **inertia**. Newton's first law is often called the **law of inertia**. As we know from experience, some objects have more inertia than others. It is obviously more difficult to change the motion of a large boulder than that of a basketball, for example. The inertia of an object is measured by its **mass**. Roughly speaking, mass is a measure of the amount of "stuff" (or matter) in something. The quantity or amount of matter in an object is determined by the numbers of atoms and molecules of various types it contains. Unlike weight, mass does not vary with location. The mass of an object is the same on Earth, in orbit, or on the surface of the Moon. In practice, it is very difficult to count and identify all of the atoms and molecules in an object, so masses are not often determined in this manner. Operationally, the masses of objects are determined by comparison with the standard kilogram.

Exercise 5.2.3.1

Which has more mass: a kilogram of cotton balls or a kilogram of gold?

Answer

They are equal. A kilogram of one substance is equal in mass to a kilogram of another substance. The quantities that might differ between them are volume and density.

Section Summary

- **Newton's first law of motion** states that a body at rest remains at rest, or, if in motion, remains in motion at a constant velocity unless acted on by a net external force. This is also known as the **law of inertia**.
- **Inertia** is the tendency of an object to remain at rest or remain in motion. Inertia is related to an object's mass.
- **Mass** is the quantity of matter in a substance.

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5.2.4: Newton's Second Law of Motion- Force and Acceleration

Learning Objectives

- Define net force, external force, and system.
- Understand Newton's second law of motion.
- Apply Newton's second law to determine the weight of an object.

Newton's second law of motion is closely related to Newton's first law of motion. It mathematically states the cause and effect relationship between force and changes in motion. Newton's second law of motion is more quantitative and is used extensively to calculate what happens in situations involving a force. Before we can write down Newton's second law as a simple equation giving the exact relationship of force, mass, and acceleration, we need to sharpen some ideas that have already been mentioned.

First, what do we mean by a change in motion? The answer is that a change in motion is equivalent to a change in velocity. A change in velocity means, by definition, that there is an **acceleration**. Newton's first law says that a net external force causes a change in motion; thus, we see that a *net external force causes acceleration*.

Another question immediately arises. What do we mean by an external force? An intuitive notion of external is correct—an **external force** acts from outside the **system** of interest. For example, in Figure 5.2.4.1(a) the system of interest is the wagon plus the child in it. The two forces exerted by the other children are external forces. An internal force acts between elements of the system. Again looking at Figure 5.2.4.1(a), the force the child in the wagon exerts to hang onto the wagon is an internal force between elements of the system of interest. Only external forces affect the motion of a system, according to Newton's first law. (The internal forces actually cancel, as we shall see in the next section.) *You must define the boundaries of the system before you can determine which forces are external*. Sometimes the system is obvious, whereas other times identifying the boundaries of a system is more subtle. The concept of a system is fundamental to many areas of physics, as is the correct application of Newton's laws. This concept will be revisited many times on our journey through physics.

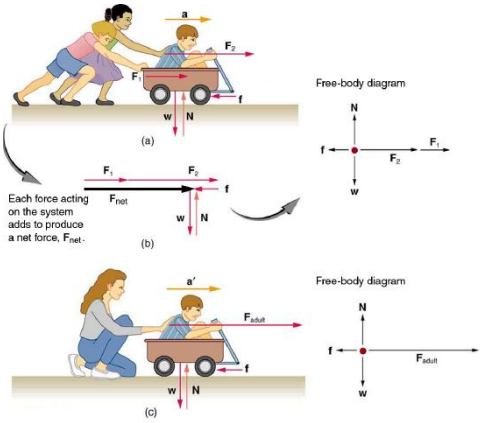


Figure 5.2.4.1: Different forces exerted on the same mass produce different accelerations. (a) Two children push a wagon with a child in it. Arrows representing all external forces are shown. The system of interest is the wagon and its rider. The weight w of the system and the support of the ground N are also shown for completeness and are assumed to cancel. The vector f represents the friction acting on the wagon, and it acts to the left, opposing the motion of the wagon. (b) All of the external forces acting on the system add together to produce a net force, $\boldsymbol{F}_{\text{net}}$. The free-body diagram shows all of the forces acting on the system of interest. The dot represents the center of mass of the system. Each force vector extends from this dot. Because there are two forces acting to the right, we draw the vectors collinearly. (c) A larger net external force produces a larger acceleration ($|\boldsymbol{a}'| > |\boldsymbol{a}|$) when an adult pushes the child.

Figure 5.2.4.1 is our first example of a **free-body diagram**, which is a technique used to illustrate all the external forces acting on a body. The body is represented by a single isolated point (or free body), and only those forces acting on the body from the outside (external forces) are shown. Free-body diagrams are very useful in analyzing forces acting on a system and are employed extensively in the study and application of Newton's laws of motion.

Now, it seems reasonable that acceleration should be directly proportional to and in the same direction as the net (total) external force acting on a system. This assumption has been verified experimentally and is illustrated in Figure 5.2.4.1. In part (a), a smaller

force causes a smaller acceleration than the larger force illustrated in part (c). For completeness, the vertical forces are also shown; they are assumed to cancel since there is no acceleration in the vertical direction. The vertical forces are the weight w and the support of the ground N, and the horizontal force f represents the force of friction. These will be discussed in more detail in later sections. For now, we will say that friction is a force that opposes the motion past each other of objects that are touching. Figure 5.2.4.1(b) shows how vectors representing the external forces add together to produce a net force, $\boldsymbol{F}_{\text{net}}$.

To obtain an equation for Newton's second law, we first write the relationship of acceleration and net external force as the proportionality

$$\boldsymbol{a} \propto \boldsymbol{F}_{\text{net}}$$

where the symbol $\propto$ means "proportional to," and $\boldsymbol{F}_{\text{net}}$ is the **net external force**, the vector sum of all external forces. This proportionality states what we have said in words—*acceleration is directly proportional to the net external force*. Once the system of interest is chosen, it is important to identify the external forces, so that the internal forces can be ignored (again, as we will see later, they exactly cancel out, allowing for a tremendous simplification).

Now, hopefully it also seems reasonable that acceleration should be inversely proportional to the mass of the system. That is, if the system has more "stuff", then for the same net external force applied, the acceleration is less. And indeed, as illustrated in Figure 5.2.4.2, the same net external force applied to a car produces a much smaller acceleration than when applied to a basketball. The proportionality is written as

$$a \propto \frac{1}{m}$$

where m is the mass of the system. In fact, this is how we will *define* mass. That is, for an object B to have double the mass of an object A, the same net external force applied on object B produces half the acceleration it does on object A.

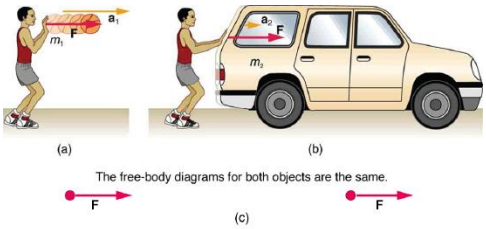


Figure 5.2.4.2: The same force exerted on systems of different masses produces different accelerations. (a) A basketball player pushes on a basketball to make a pass. (The effect of gravity on the ball is ignored.) (b) The same player exerts an identical force on a stalled SUV and produces a far smaller acceleration (even if friction is negligible). (c) The free-body diagrams are identical, permitting direct comparison of the two situations. A series of patterns for the free-body diagram will emerge as you do more problems.

As it turns out, the acceleration of an object depends only on the net external force and the mass of the object. Combining the two proportionalities just given yields Newton's second law of motion.

NEWTON'S SECOND LAW OF MOTION

The acceleration of a system is directly proportional to and in the same direction as the net external force acting on the system, and inversely proportional to its mass.

In equation form, Newton's second law of motion is

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$$

This is often written in the more familiar form

$$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a},$$

with the vector notation indicating that the net external force is in the same direction as acceleration. When only the magnitude of force and acceleration are considered, this equation is simply (note the lack of vector notations)

$$F_{\text{net}} = ma.$$

Although these equations are really the same, the first gives more insight into what Newton's second law means. The law is a *cause and effect relationship* among three quantities. That is, acceleration is *caused* by a net external force, not vice versa, as the second equation might mistakenly imply.

Units of Force

$F_{\text{net}} = ma$ is used to define the units of force in terms of the three basic units for mass, length, and time. The SI unit of force is called the **newton** (abbreviated N) and 1 N is the force needed to accelerate a system of mass 1 kg at the rate of $1\ \text{m/s}^2$. Putting these together,

$$1\ \text{N} = 1\ \text{kg} \cdot \text{m/s}^2.$$

While almost the entire world uses the newton for the unit of force, in the United States the most familiar unit of force is the pound (lb), where 1 N = 0.225 lb.

Weight and the Gravitational Force

When an object is dropped, it accelerates toward the center of Earth. Newton's second law states that a net force on an object is responsible for its acceleration. If air resistance is negligible, the net force on a falling object is the gravitational force, commonly called its **weight**, w. Weight can be denoted as a vector w because it has a direction; *down* is, by definition, the direction of gravity, so w is directed downward. The magnitude of weight is denoted as w. Galileo was instrumental in showing that, in the absence of air resistance, all objects fall with the same acceleration g. Using Galileo's result and Newton's second law, we can derive an equation for the magnitude of weight.

Consider an object with mass m falling downward toward Earth. It experiences only the downward force of gravity, which has magnitude w. Newton's second law states that the magnitude of the net external force on an object is $F_{\text{net}} = ma$.

Since the object experiences only the downward force of gravity, $F_{\text{net}} = w$. We know that the acceleration of an object due to gravity is g, or $a = g$. Substituting these into Newton's second law gives

Definition: WEIGHT

This is the equation for *weight*—the gravitational force on a mass m:

$$w = mg.$$

Since $g = 9.80\ \text{m/s}^2$ on Earth, the weight of a 1.0 kg object on Earth is 9.8 N, as we see:

$$w = mg = (1.0\ \text{kg})\left(9.80\ \text{m/s}^2\right) = 9.8\ \text{N}.$$

When the net external force on an object is its weight, we say that it is in **free-fall**. That is, the only force acting on the object is the force of gravity. In the real world, when objects fall downward toward Earth, they are never truly in free-fall because there is always some upward force from the air acting on the object.

The acceleration due to gravity g varies slightly over the surface of Earth, so that the weight of an object depends on location and is not an intrinsic property of the object. Weight varies dramatically if one leaves Earth. On the Moon, for example, the acceleration due to gravity is only $1.67\ \text{m/s}^2$. A 1.0-kg mass thus has a weight of 9.8 N on Earth and only about 1.7 N on the Moon.

The broadest definition of weight in this sense is that *the weight of an object is the gravitational force on it from the nearest large body*, such as Earth, the Moon, the Sun, and so on. This is the most common and useful definition of weight in physics. It differs dramatically, however, from the definition of weight used by NASA and the popular media in relation to space travel and exploration. When they speak of "weightlessness" and "microgravity," they are really referring to the phenomenon we call "free-fall" in physics. We shall use the above definition of weight, and we will make careful distinctions between free-fall and actual weightlessness.

It is important to be aware that weight and mass are very different physical quantities, although they are closely related. Mass is the quantity of matter (how much "stuff") and does not vary, whereas weight is the gravitational force and does vary depending on gravity. It is tempting to equate the two, since most of our examples take place on Earth, where the weight of an object only varies

a little with the location of the object. Furthermore, the terms *mass* and *weight* are used interchangeably in everyday language; for example, our medical records often show our "weight" in kilograms, but never in the correct units of newtons.

COMMON MISCONCEPTIONS: MASS VS. WEIGHT

Mass and weight are often used interchangeably in everyday language. However, in science, these terms are distinctly different from one another. Mass is a measure of how much matter is in an object. The typical measure of mass is the kilogram (or the "slug" in English units). Weight, on the other hand, is a measure of the force of gravity acting on an object. Weight is equal to the mass of an object (m) multiplied by the acceleration due to gravity (g). Like any other force, weight is measured in terms of newtons (or pounds in English units). This interchangeable use is why you might have heard an expression such as, "1 kilogram is 2.2 pounds." The *correct* statement is "1 kilogram mass weighs 2.2 pounds on Earth."

Assuming the mass of an object is kept intact, it will remain the same, regardless of its location. However, because weight depends on the acceleration due to gravity, the weight of an object *can change* when the object enters into a region with stronger or weaker gravity. For example, the acceleration due to gravity on the Moon is $1.67\ \mathrm{m/s^2}$ (which is much less than the acceleration due to gravity on Earth, $9.80\ \mathrm{m/s^2}$). If you measured your weight on Earth and then measured your weight on the Moon, you would find that you "weigh" much less, even though you do not look any skinnier. This is because the force of gravity is weaker on the Moon. In fact, when people say that they are "losing weight," they really mean that they are losing "mass" (which in turn causes them to weigh less).

TAKE-HOME EXPERIMENT: MASS AND WEIGHT

What do bathroom scales measure? When you stand on a bathroom scale, what happens to the scale? It depresses slightly. The scale contains springs that compress in proportion to your weight—similar to rubber bands expanding when pulled. The springs provide a measure of your weight (for an object which is not accelerating). This is a force in newtons (or pounds). In most countries, the measurement in newtons is divided by 9.80 to give a reading in mass units of kilograms. The scale measures weight but is calibrated to provide information about mass. While standing on a bathroom scale, push down on a table next to you. What happens to the reading? Why? Would your scale measure the same "mass" on Earth as on the Moon?

Example 5.2.4.1: What Acceleration Can a Person Produce when Pushing a Lawn Mower?

Suppose that the net external force (push minus friction) exerted on a lawn mower is 51 N (about 11 lb) parallel to the ground. The mass of the mower is 24 kg. What is its acceleration?



Figure 5.2.4.3: The net force on a lawn mower is 51 N to the right. At what rate does the lawn mower accelerate to the right?

Strategy

Since F_{net} and m are given, the acceleration can be calculated directly from Newton's second law as stated in $F_{\mathrm{net}} = ma$.

Solution

The magnitude of the acceleration a is $a = \frac{F_{\mathrm{net}}}{m}$. Entering known values gives

$$a = \frac{51\ \mathrm{N}}{24\ \mathrm{kg}}$$

Substituting the units $\mathrm{kg \cdot m/s^2}$ for N yields

$$a = \frac{51 \text{ kg} \cdot \text{m/s}^2}{24 \text{ kg}} = 2.1 \text{ m/s}^2.$$

Discussion

The direction of the acceleration is the same direction as that of the net force, which is parallel to the ground. There is no information given in this example about the individual external forces acting on the system, but we can say something about their relative magnitudes. For example, the force exerted by the person pushing the mower forward must be greater than the friction opposing the motion (directed backward) to result in a forward net force, and the vertical forces must cancel if there is to be no acceleration in the vertical direction. The acceleration found is small enough to be reasonable for a person pushing a mower. When the person reaches the top speed, the acceleration will be zero (no change of velocity) and the force exerted by the person pushing the mower will be equal to the friction opposing the motion.

Example 5.2.4.2: What Rocket Thrust Accelerates This Sled?

Prior to manned space flights, rocket sleds were used to test aircraft, missile equipment, and physiological effects on human subjects at high speeds. They consisted of a platform that was mounted on one or two rails and propelled by several rockets. Calculate the magnitude of force exerted by each rocket, called its thrust T, for the four-rocket propulsion system shown in Figure 5.2.4.4. The sled's initial acceleration is 49 m/s^2 the mass of the system is 2100 kg, and the force of friction opposing the motion is known to be 650 N.

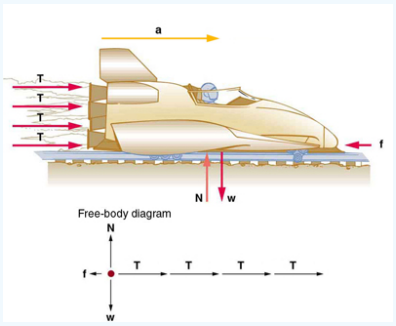


Figure 5.2.4.4: A sled experiences a rocket thrust that accelerates it to the right. Each rocket creates an identical thrust T. As in other situations where there is only horizontal acceleration, the vertical forces cancel. The ground exerts an upward force N on the system which balances out the weight force, w. The system here is the sled, its rockets, and rider, so none of the internal forces *between* these objects are considered. f represents the friction force (figure not drawn to scale).

Strategy

Although there are forces acting vertically and horizontally, we assume the vertical forces cancel since there is no vertical acceleration. This leaves us with only horizontal forces and a simpler one-dimensional problem. Directions are indicated with plus or minus signs, with right taken as the positive direction. See the free-body diagram in the figure.

Solution

Since acceleration, mass, and the force of friction are given, we start with Newton's second law and look for ways to find the thrust of the engines. Since we have defined the direction of the force and acceleration as acting "to the right," we need to consider only the magnitudes of these quantities in the calculations. Hence we begin with

$$F_{\text{net}} = ma,$$

where F_{net} is the net force along the horizontal direction. We can see from Figure 5.2.4.4 that the engine thrusts add, while friction opposes the thrust. In equation form, the net external force is

$$F_{\text{net}} = 4T - f.$$

Substituting this into Newton's second law gives

$$F_{\text{net}} = ma = 4T - f.$$

Using a little algebra, we solve for the total thrust $4T$:

$$4T = ma + f.$$

Substituting known values yields

$$4T = ma + f = (2100\ \text{kg})\left(49\ \text{m/s}^2\right) + 650\ \text{N}.$$

So the total thrust is

$$4T = 1.04 \times 10^5\ \text{N},$$

and the individual thrusts are

$$T = \frac{1.04 \times 10^5\ \text{N}}{4} = 2.6 \times 10^4\ \text{N}.$$

Discussion

The numbers are quite large, so to put the result in perspective, note that acceleration of $49\ \text{m/s}^2$ is approximately 5 times the gravitational acceleration on Earth. It's a large acceleration, which requires a large net external force to produce.

Experiments such as this were performed in the early 1960s to test the limits of human endurance and the setup designed to protect human subjects in jet fighter emergency ejections. Speeds of 1000 km/h were obtained, with accelerations of 45 g's. (Recall that g, the acceleration due to gravity, is $9.80\ \text{m/s}^2$. When we say that an acceleration is g's, it is $45 \times 9.80\ \text{m/s}^2$, which is approximately $440\ \text{m/s}^2$. While living subjects are not used any more, land speeds of 10,000 km/h have been obtained with rocket sleds. In this example, as in the preceding one, the system of interest is obvious. We will see in later examples that choosing the system of interest is crucial—and the choice is not always obvious.

Newton's second law of motion gives a relationship among acceleration, force, and mass. It can help us make predictions. Each of those physical quantities can be defined independently, so the second law tells us something basic and universal about nature. The next section introduces the third and final law of motion.

Section Summary

- Acceleration, a, is defined as a rate of change in velocity, resulting from a change in the magnitude and/or the direction of the velocity.
- An external force is one acting on a system from outside the system, as opposed to internal forces, which act between components within the system.
- Newton's second law of motion states that the acceleration of a system is directly proportional to and in the same direction as the net external force acting on the system, and inversely proportional to its mass.
- In equation form, Newton's second law of motion is $\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m}$, often written in the more familiar form: $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$.
- The weight w of an object is defined as the force of gravity acting on an object of mass mm. Given acceleration due to gravity g, the magnitude of weight is:

$$w = mg$$

Glossary

acceleration
the rate at which an object's velocity changes over a period of time

free-fall
a situation in which the only force acting on an object is the force due to gravity

external force
a force acting on an object or system that originates outside of the object or system

net external force
the vector sum of all external forces acting on an object or system; causes a mass to accelerate

free-body diagram

a sketch showing all of the external forces acting on an object or system; the system is represented by a dot, and the forces are represented by vectors extending outward from the dot

Newton's second law of motion

The acceleration of a system is directly proportional to and in the same direction as the net external force acting on the system, and inversely proportional to its mass.

system

the object or the group of objects under consideration

weight

the force due to gravity; $w = mg$ for objects on Earth

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5.2.5: Newton's Third Law of Motion- Symmetry in Forces

Learning Objectives

- Understand Newton's third law of motion.
- Apply Newton's third law to define systems and solve problems of motion.

Whenever one body exerts a force on another—the first also experiences a force (equal in magnitude and opposite in direction). Numerous common experiences, such as stubbing a toe or throwing a ball, confirm this. It is precisely stated in **Newton's third law of motion**.

NEWTON'S THIRD LAW OF MOTION

Whenever one body exerts a force on a second body, the first body experiences a force by the second body that is equal in magnitude and opposite in direction to the force that it itself exerts.

This law represents a certain *symmetry in nature*: Forces always occur in pairs, and one body cannot exert a force on another without experiencing a force itself. We sometimes refer to this law loosely as "action-reaction," where the force exerted is the action and the force experienced as a consequence is the reaction. Newton's third law has practical uses in analyzing the origin of forces and understanding which forces are external to a system.

We can readily see Newton's third law at work by taking a look at how people move about. Consider a swimmer pushing off from the side of a pool, as illustrated in Figure 5.2.5.1. She pushes against the pool wall with her feet and accelerates in the direction *opposite* to that of her push. The wall has exerted an equal and opposite force back on the swimmer. You might think that two equal and opposite forces would cancel, but they do not *because they act on different bodies*. In this case, there are two bodies to consider: the swimmer and the wall. If we define the swimmer as the system of interest, as in the figure, then $\boldsymbol{F}_{\text{wall on feet}}$ is an external force on this system and affects its motion. The swimmer moves in the direction of $\boldsymbol{F}_{\text{wall on feet}}$. In contrast, the force $\boldsymbol{F}_{\text{feet on wall}}$ acts on the wall and not on our system of interest. Thus $\boldsymbol{F}_{\text{feet on wall}}$ does not affect the motion of the system and does not counteract $\boldsymbol{F}_{\text{wall on feet}}$. Note that the swimmer pushes the wall in the direction opposite to that in which she wishes to move. The reaction force by the wall on her pushes her in the desired direction.

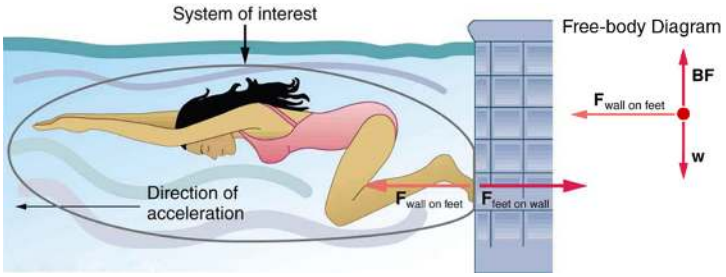


Figure 5.2.5.1: When the swimmer exerts a force $\boldsymbol{F}_{\text{feet on wall}}$ on the wall, she accelerates in the direction opposite to that of her push. This means the net external force on her is in the direction opposite to $\boldsymbol{F}_{\text{feet on wall}}$. This opposition occurs because, in accordance with Newton's third law of motion, the wall exerts a force $\boldsymbol{F}_{\text{wall on feet}}$ on her, equal in magnitude but in the direction opposite to the one she exerts on it. The line around the swimmer indicates the system of interest. Note that $\boldsymbol{F}_{\text{feet on wall}}$ does not act on this system (the swimmer) and, thus, does not cancel $\boldsymbol{F}_{\text{wall on feet}}$. Thus the free-body diagram shows only $\boldsymbol{F}_{\text{wall on feet}}$, w, the gravitational force, and **BF**, the buoyant force of the water supporting the swimmer's weight. The vertical forces w and **BF** cancel since there is no vertical motion.

Other examples of Newton's third law are easy to find. As a professor paces in front of a whiteboard, she exerts a force backward on the floor. The floor exerts a reaction force forward on the professor that causes her to accelerate forward. Similarly, a car accelerates because the ground pushes forward on the drive wheels in reaction to the drive wheels pushing backward on the ground. You can see evidence of the wheels pushing backward when tires spin on a gravel road and throw rocks backward. In another example, rockets move forward by expelling gas backward at high velocity. This means the rocket exerts a large backward force on the gas in the rocket combustion chamber, and the gas therefore exerts a large reaction force forward on the rocket. This reaction force is called **thrust**. It is a common misconception that rockets propel themselves by pushing on the ground or on the air behind them. The rockets propel themselves by pushing their own exhaust gases, and that is how they work even in a vacuum. Helicopters

create lift by pushing air down, thereby experiencing an upward reaction force. Birds and airplanes also fly by exerting force on air in a direction opposite to that of whatever force they need. For example, the wings of a bird force air downward and backward in order to get lift and move forward. An octopus propels itself in the water by ejecting water through a funnel from its body, similar to a jet ski. In a situation similar to Sancho's, professional cage fighters experience reaction forces when they punch, sometimes breaking their hand by hitting an opponent's body.

Example 5.2.5.1: Getting Up To Speed: Choosing the Correct System

A physics professor pushes a cart of demonstration equipment to a lecture hall, as seen in Figure 5.2.5.2. Her mass is 65.0 kg, the cart's is 12.0 kg, and the equipment's is 7.0 kg. Calculate the acceleration produced when the professor exerts a backward force of 150 N on the floor. All forces opposing the motion, such as friction on the cart's wheels and air resistance, total 24.0 N.

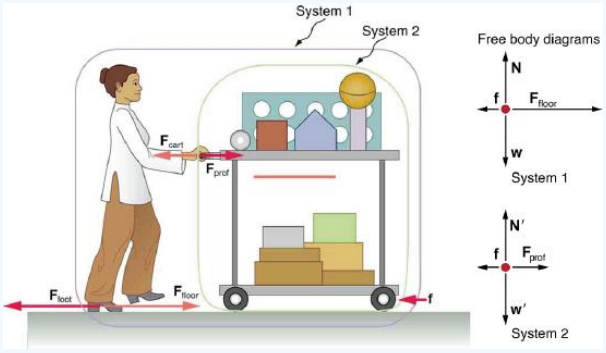


Figure 5.2.5.2: A professor pushes a cart of demonstration equipment. The lengths of the arrows are proportional to the magnitudes of the forces (except for **f**, since it is too small to draw to scale). Different questions are asked in each example; thus, the system of interest must be defined differently for each. System 1 is appropriate for this example, since it asks for the acceleration of the entire group of bodies. Only $\boldsymbol{F}_{\text{floor}}$ and f are external forces acting on System 1 along the line of motion. All other forces either cancel or act on the outside world. System 2 is appropriate for Example 5.2.5.2 so that $\boldsymbol{F}_{\text{prof}}$ will be an external force and enter into Newton's second law.

Strategy

Since they accelerate as a unit, we define the system to be the professor, cart, and equipment. This is System 1 in Figure 5.2.5.2. The professor pushes backward with a force $\boldsymbol{F}_{\text{foot}}$ of 150 N. According to Newton's third law, the floor exerts a forward reaction force $\boldsymbol{F}_{\text{floor}}$ of 150 N on System 1. Because all motion is horizontal, we can assume there is no net force in the vertical direction, and treat this as a one-dimensional problem in the horizontal direction. As noted, f opposes the motion and is thus in the opposite direction of $\boldsymbol{F}_{\text{floor}}$. Note that we do not include the forces $\boldsymbol{F}_{\text{prof}}$ or $\boldsymbol{F}_{\text{cart}}$ because these are internal forces, and we do not include $\boldsymbol{F}_{\text{foot}}$ because it acts on the floor, not on the system. There are no other significant forces acting on System 1. If the net external force can be found from all this information, we can use Newton's second law to find the acceleration as requested. See the free-body diagram in the figure.

Solution

Newton's second law is given by

$$a = \frac{F_{\text{net}}}{m}.$$

The net external force on System 1 is deduced from Figure 5.2.5.2 and the discussion above to be

$$F_{\text{net}} = F_{\text{floor}} - f = 150 \text{ N} - 24.0 \text{ N} = 126 \text{ N}.$$

The mass of System 1 is

$$m = (65.0 + 12.0 + 7.0)\text{kg} = 84 \text{ kg}.$$

These values of F_{net} and m produce an acceleration of

$$a = \frac{F_{\text{net}}}{m},$$
$$a = \frac{126\ \text{N}}{84\ \text{kg}} = 1.5\ \text{m/s}^2$$

Discussion

None of the forces between components of System 1, such as between the professor's hands and the cart, contribute to the net external force because they are internal to System 1. Another way to look at this is to note that forces between components of a system cancel because they are equal in magnitude and opposite in direction. For example, the force exerted by the professor on the cart results in an equal and opposite force back on her. In this case both forces act on the same system and, therefore, cancel. Thus internal forces (between components of a system) cancel. Choosing System 1 was crucial to solving this problem.

Example 5.2.5.2: Force on the Cart—Choosing a New System

Calculate the force the professor exerts on the cart in Figure 5.2.5.2 using data from the previous example if needed.

Strategy

If we now define the system of interest to be the cart plus equipment (System 2 in Figure 5.2.5.2), then the net external force on System 2 is the force the professor exerts on the cart minus friction. The force she exerts on the cart, $\mathbf{F}_{\text{prof}}$, is an external force acting on System 2. $\mathbf{F}_{\text{prof}}$ was internal to System 1, but it is external to System 2 and will enter Newton's second law for System 2.

Solution

Newton's second law can be used to find $\mathbf{F}_{\text{prof}}$. Starting with

$$a = \frac{F_{\text{net}}}{m}$$

and noting that the magnitude of the net external force on System 2 is

$$F_{\text{net}} = F_{\text{prof}} - f,$$

we solve for $\mathbf{F}_{\text{prof}}$, the desired quantity:

$$F_{\text{prof}} = F_{\text{net}} + f.$$

The value of f is given, so we must calculate net F_{net}. That can be done since both the acceleration and mass of System 2 are known. Using Newton's second law we see that

$$F_{\text{net}} = ma,$$

where the mass of System 2 is 19.0 kg (m= 12.0 kg + 7.0 kg) and its acceleration was found to be $a = 1.5\ \text{m/s}^2$ in the previous example. Thus,

$$F_{\text{net}} = ma,$$
$$F_{\text{net}} = (19.0\ \text{kg})\left(1.5\ \text{m/s}^2\right) = 29\ \text{N}.$$

Now we can find the desired force:

$$F_{\text{prof}} = F_{\text{net}} + f,$$
$$F_{\text{prof}} = 29\ \text{N} + 24.0\ \text{N} = 53\ \text{N}.$$

Discussion

It is interesting that this force is significantly less than the 150-N force the professor exerted backward on the floor. Not all of that 150-N force is transmitted to the cart; some of it accelerates the professor.

The choice of a system is an important analytical step both in solving problems and in thoroughly understanding the physics of the situation (which is not necessarily the same thing).

COMMON MISCONCEPTION: REACTION VS. RESULT

The phrases "action" and "reaction" in reference to the pair of forces described by Newton's third law often leads to unfortunate misunderstandings regarding the nature of the reaction force. Because of the common English usage of the word "reaction" (root word: react)—for example, in film, "reaction shot" means a shot of actors' faces as they react to an event that just happened—many students intuitively guess that there is a cause-and-effect relationship between "action force" and "reaction force."

There is no such relationship. Newton's third law describes *symmetry* in forces. Action force and reaction force are symmetric—they occur simultaneously; they are two sides of one and the same interaction. Action force does not cause reaction force, no more than the head of a coin causes the tail of the coin (they merely occur together, always). Here's a quick check to see if you understood the pairing of action force and reaction force correctly: try swapping the labels. That is, if you originally called A "action force" and B "reaction force", try calling B "action force" and A "reaction force." Does this re-labeling make some sense? If not, chances are, you have mis-identified the pair of action force and reaction force. (Here, a little weirdness is O.K., but if it feels like complete nonsense to swap the labels—like reversal of a cause-and-effect relationship—that tells you you used "reaction" in the common English usage, not how the word is used in Newton's third law.)

Section Summary

- **Newton's third law of motion** represents a basic symmetry in nature. It states: Whenever one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that the first body exerts.
- A **thrust** is a reaction force that pushes a body forward in response to a backward force. Rockets, airplanes, and cars are pushed forward by a thrust reaction force.

Glossary

Newton's third law of motion

Whenever one body exerts a force on a second body, the first body experiences a force by the second body that is equal in magnitude and opposite in direction to the force that it itself exerts.

thrust

a reaction force that pushes a body forward; rockets, airplanes, and cars are pushed forward by a thrust, a reaction force to propellants pushed backward

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5.2.6: Normal Force and Tension

Learning Objectives

- Define normal force.
- Explain the relationship between normal force and apparent weight.
- Describe properties of tension force.
- Apply Newton's laws of motion to analyze forces.

Forces are given many names, such as push, pull, thrust, lift, weight, friction, and tension. Traditionally, forces have been grouped into several categories and given names relating to their source, how they are transmitted, or their effects. The most important of these categories are discussed in this section, together with some interesting applications. Further examples of forces are discussed later in this text.

Normal Force

Weight (also called force of gravity) is a pervasive force that acts at all times and must be counteracted to keep an object from falling. You definitely notice that you must support the weight of a heavy object by pushing up on it when you hold it stationary, as illustrated in Figure 5.2.6.1(a). But how do inanimate objects like a table support the weight of a mass placed on them, such as shown in Figure 5.2.6.1(b)? When the bag of dog food is placed on the table, the table actually sags slightly under the load. This would be noticeable if the load were placed on a card table, but even rigid objects deform when a force is applied to them. Unless the object is deformed beyond its limit, it will exert a restoring force much like a deformed spring (or trampoline or diving board). The greater the deformation, the greater the restoring force. So when the load is placed on the table, the table sags until the restoring force becomes as large as the weight of the load. At this point the net external force on the load is zero. That is the situation when the load is stationary on the table. The table sags quickly, and the sag is slight so we do not notice it. But it is similar to the sagging of a trampoline when you climb onto it.

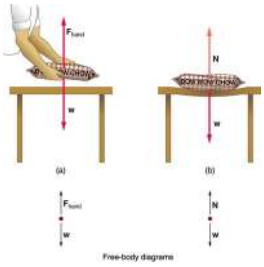


Figure 5.2.6.1: (a) The person holding the bag of dog food must supply an upward force $\boldsymbol{F}_{\text{hand}}$ equal in magnitude and opposite in direction to the weight of the food w. (b) The card table sags when the dog food is placed on it, much like a stiff trampoline. Elastic restoring forces in the table grow as it sags until they supply a force **N** equal in magnitude and opposite in direction to the weight of the load.

We must conclude that whatever supports a load, be it animate or not, must supply an upward force equal to the weight of the load, as we assumed in a few of the previous examples. The force supporting a load is perpendicular to the surface of contact between the load and its support, and this force is called a **normal force**, often indicated with symbol **N** (Please do not confuse this with the abbreviation for newton, the unit of force, N). The word *normal* means perpendicular to a surface. The normal force is not always equal to the object's weight, if there are other forces acting on the object, or if the object is accelerating, so that the net force is not zero.

Normal force also goes by another name, **apparent weight**. This is because all the forces you feel, especially your sensation of weight, are directly attributed to contact forces, such as the normal force. When NASA astronauts are weightlessly floating in the International Space Station, their actual weight (gravitational force on them by the Earth) is not zero, but their apparent weight (sensation of weight due to contact forces) is zero.

Tension

A **tension** is a force along the length of a medium, especially a force carried by a flexible medium, such as a rope or cable. The word “tension” comes from a Latin word meaning “to stretch.” Not coincidentally, the flexible cords that carry muscle forces to

other parts of the body are called *tendons*. Any flexible connector, such as a string, rope, chain, wire, or cable, can exert pulls only parallel to its length; thus, a force carried by a flexible connector is a tension with direction parallel to the connector. It is important to understand that tension is a pull in a connector. In contrast, consider the phrase: "You can't push a rope." The tension force pulls outward along the two ends of a rope.

Consider a person holding a mass on a rope as shown in Figure 5.2.6.2.

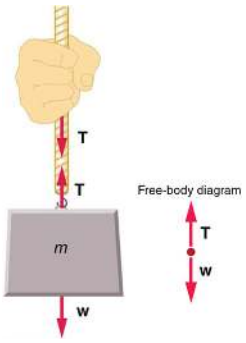


Figure 5.2.6.2: When a perfectly flexible connector (one requiring no force to bend it) such as this rope transmits a force ***T***, that force must be parallel to the length of the rope, as shown. The pull such a flexible connector exerts is a tension. Note that the rope pulls with equal force but in opposite directions on the hand and the supported mass (neglecting the weight of the rope). This is an example of Newton's third law. The rope is the medium that carries the equal and opposite forces between the two objects. The tension anywhere in the rope between the hand and the mass is equal. Once you have determined the tension in one location, you have determined the tension at all locations along the rope.

Tension in the rope must equal the weight of the supported mass, as we can prove using Newton's second law. If the 5.00-kg mass in the figure is stationary, then its acceleration is zero, and thus $\boldsymbol{F}_{\text{net}} = 0$. The only external forces acting on the mass are its weight w and the tension ***T*** supplied by the rope. Thus,

$$F_{\text{net}} = T - w = 0,$$

where ***T*** and w are the magnitudes of the tension and weight and their signs indicate direction, with up being positive here. Thus, just as you would expect, the tension equals the weight of the supported mass:

$$T = w = mg.$$

For a 5.00-kg mass, then (neglecting the mass of the rope) we see that

$$T = mg = (5.00 \text{ kg})\left(9.80 \text{ m/s}^2\right) = 49.0 \text{ N}.$$

If we cut the rope and insert a spring, the spring would extend a length corresponding to a force of 49.0 N, providing a direct observation and measure of the tension force in the rope.

Flexible connectors are often used to transmit forces around corners, such as in a hospital traction system, a finger joint, or a bicycle brake cable. If there is no friction, the tension is transmitted undiminished. Only its direction changes, and it is always parallel to the flexible connector. This is illustrated in Figure 5.2.6.3 (a) and (b).

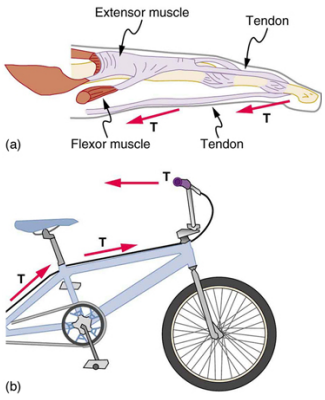


Figure 5.2.6.3: (a) Tendons in the finger carry force ***T*** from the muscles to other parts of the finger, usually changing the force's direction, but not its magnitude (the tendons are relatively friction free). (b) The brake cable on a bicycle carries the tension ***T*** from the handlebars to the brake mechanism. Again, the direction but not the magnitude of ***T*** is



changed. **Figure** 5.2.6.4: Unless an infinite tension is exerted, any flexible connector—such as the chain at the bottom of the picture—will sag under its own weight, giving a characteristic curve when the weight is evenly distributed along the length, known as a catenary curve. Suspension bridges—such as the Golden Gate Bridge shown in this image—are essentially very heavy flexible connectors. The weight of the bridge is evenly distributed along the length of flexible connectors, usually cables, which take on the characteristic shape. (credit: Leaflet, Wikimedia Commons)

Normal force and tension are examples of forces that are determined not by a specific formula but by enforcing a constraint on motion state of a body. In the example of the bag on a table above, the normal force is equal to weight, because that is the value needed to ensure that the acceleration of the bag is zero. What happens if the body experiences a non-zero acceleration? We will consider example below of a person standing on a scale (which measures his apparent weight) while riding in an elevator.

Example 5.2.6.1: What Does the Bathroom Scale Read in an Elevator?

Figure 5.2.6.5 shows a 75.0-kg man (weight of about 165 lb.) standing on a bathroom scale in an elevator. Calculate the scale reading: (a) if the elevator accelerates upward at a rate of $1.20\ \mathrm{m/s^2}$, and (b) if the elevator moves upward at a constant speed of 1 m/s.

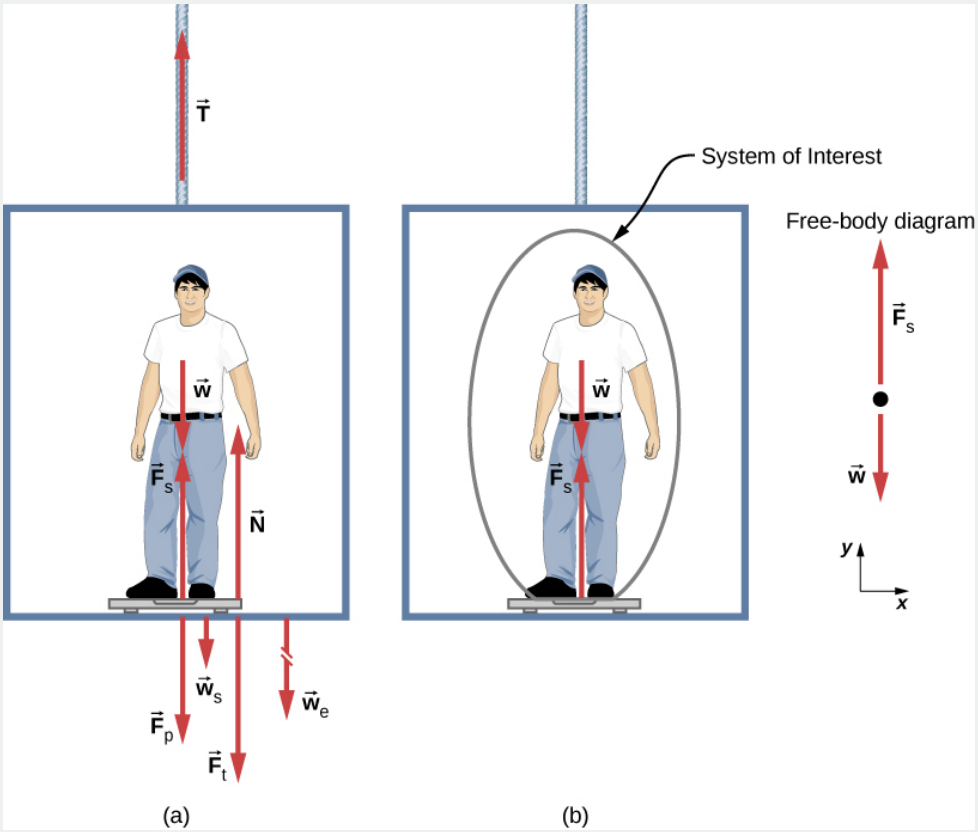


Figure 5.2.6.5: (a) The various forces acting when a person stands on a bathroom scale in an elevator. The arrows are approximately correct for when the elevator is accelerating upward—broken arrows represent forces too large to be drawn to scale. $\vec{\mathbf{T}}$ is the tension in the supporting cable, $\vec{\mathbf{w}}$ is the weight of the person, $\vec{\mathbf{w}}_{\mathrm{s}}$ is the weight of the scale, $\vec{\mathbf{w}}_{\mathrm{e}}$ is the weight of the elevator, $\vec{\mathbf{F}}_{\mathrm{s}}$ is the force of the scale on the person, $\vec{\mathbf{F}}_{\mathrm{P}}$ is the force of the person on the scale, $\vec{\mathbf{F}}_{\mathrm{t}}$ is the force of the scale on the floor of the elevator,

and $\vec{\mathbf{N}}$ is the force of the floor upward on the scale. (b) The free-body diagram shows only the external forces acting *on* the designated system of interest—the person—and is the diagram we use for the solution of the problem.

Strategy

If the scale at rest is accurate, its reading equals $\vec{\mathbf{F}}_{\mathrm{P}}$, the magnitude of the force the person exerts downward on it. Figure 5.2.6.5(a) shows the numerous forces acting on the elevator, scale, and person. It makes this one-dimensional problem look much more formidable than if the person is chosen to be the system of interest and a free-body diagram is drawn, as in Figure 5.2.6.5(b). Analysis of the free-body diagram using Newton's laws can produce answers to both Figure 5.2.6.5(a) and (b) of this example, as well as some other questions that might arise. The only forces acting on the person are his weight $\vec{\mathbf{w}}$ and the upward force of the scale $\vec{\mathbf{F}}_{\mathrm{s}}$. According to Newton's third law, $\vec{\mathbf{F}}_{\mathrm{P}}$ and $\vec{\mathbf{F}}_{\mathrm{s}}$ are equal in magnitude and opposite in direction, so that we need to find F_s in order to find what the scale reads. We can do this, as usual, by applying Newton's second law,

$$\vec{\mathbf{F}}_{\mathrm{net}} = m\vec{\mathbf{a}}.$$

From the free-body diagram, we see that the net force $\vec{\mathbf{F}}_{\mathrm{net}}$ is sum of the scale force $\vec{\mathbf{F}}_{\mathrm{s}}$ and the weight $\vec{\mathbf{w}}$. Since the scale force and the weight are pointing in opposite directions, in terms of the magnitudes of the vectors,

$$F_{\mathrm{net}} = F_s - w = ma.$$

Solving for F_s gives us an equation with only one unknown:

$$F_{\mathrm{s}} = ma + w,$$

or, because $w = mg$, simply

$$F_{\mathrm{s}} = ma + mg.$$

No assumptions were made about the acceleration, so this solution should be valid for a variety of accelerations in addition to those in this situation. (*Note:* We are considering the case when the elevator is accelerating upward. If the elevator is accelerating downward, Newton's second law becomes $F_s - w = -ma$.)

Solution

a. We have $a = 1.20\ \mathrm{m/s^2}$, so that

$$F_{\mathrm{s}} = (75.0\ \mathrm{kg})\left(9.80\ \mathrm{m/s^2}\right) + (75.0\ \mathrm{kg})\left(1.20\ \mathrm{m/s^2}\right)$$

yielding

$$F_{\mathrm{s}} = 825\ \mathrm{N}.$$

b. Now, what happens when the elevator reaches a constant upward velocity? Will the scale still read more than his weight? For any constant velocity—up, down, or stationary—acceleration is zero because $a = \frac{\Delta v}{\Delta t}$ and $\Delta v = 0$. Thus,

$$F_{\mathrm{s}} = ma + mg = 0 + mg$$

or

$$F_{\mathrm{s}} = (75.0\ \mathrm{kg})\left(9.80\ \mathrm{m/s^2}\right),$$

which gives

$$F_{\mathrm{s}} = 735\ \mathrm{N}.$$

Significance

The scale reading in Figure 5.2.6.5(a) is about 185 lb. What would the scale have read if he were stationary? Since his acceleration would be zero, the force of the scale would be equal to his weight:

$$F_{\text{net}} = ma = 0 = F_{\text{s}} - w$$
$$F_{\text{s}} = w = mg$$
$$F_{\text{s}} = (75.0 \text{ kg})\left(9.80 \text{ m/s}^2\right) = 735 \text{ N}.$$

Thus, the scale reading in the elevator is greater than his 735-N (165-lb.) weight. This means that the scale is pushing up on the person with a force greater than his weight, as it must in order to accelerate him upward. Clearly, the greater the acceleration of the elevator, the greater the scale reading, consistent with what you feel in rapidly accelerating versus slowly accelerating elevators. In Figure 5.2.6.5(b), the scale reading is 735 N, which equals the person's weight. This is the case whenever the elevator has a constant velocity—moving up, moving down, or stationary.

Section Summary

- When objects rest on a surface, the surface applies a force to the object that supports the weight of the object. This supporting force acts perpendicular to and away from the surface. It is called a normal force, and it also goes by the name "apparent weight."
- *When objects rest on a non-accelerating horizontal surface*, the magnitude of the normal force is equal to the weight of the object:

$$N = mg.$$

- The pulling force that acts along a stretched flexible connector, such as a rope or cable, is called tension, ***T***. When a rope supports the weight of an object that is at rest, the tension in the rope is equal to the weight of the object:

$$T = mg.$$

Glossary

normal force
the force that a surface applies to an object to support the weight of the object; acts perpendicular to the surface on which the object rests

apparent weight
sensation of weight due to contact forces; usually the same as normal force

tension
the pulling force that acts along a medium, especially a stretched flexible connector, such as a rope or cable; when a rope supports the weight of an object, the force on the object due to the rope is called a tension force

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5.2.7: Spring Force- Hooke's Law

Learning Objectives

- Describe the restoring force and displacement.
- Explain oscillatory motion under a spring force.

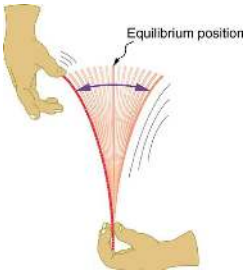


Figure 5.2.7.1: When displaced from its vertical equilibrium position, this plastic ruler oscillates back and forth because of the restoring force opposing displacement. When the ruler is on the left, there is a force to the right, and vice versa.

Newton's first law implies that an object oscillating back and forth is experiencing forces. Without force, the object would move in a straight line at a constant speed rather than oscillate. Consider, for example, plucking a plastic ruler to the left as shown in Figure 5.2.7.1. The deformation of the ruler creates a force in the opposite direction, known as a **restoring force**. Once released, the restoring force causes the ruler to move back toward its stable equilibrium position, where the net force on it is zero. However, by the time the ruler gets there, it gains momentum and continues to move to the right, producing the opposite deformation. It is then forced to the left, back through equilibrium, and the process is repeated until dissipative forces dampen the motion. These forces remove mechanical energy from the system, gradually reducing the motion until the ruler comes to rest.

The simplest oscillations occur when the restoring force is directly proportional to displacement. This is called Hooke's law force, or spring force:

$$F = -kx.$$

Here, F is the restoring force, x is the displacement from equilibrium or **deformation**, and k is a constant related to the difficulty in deforming the system. The minus sign indicates the restoring force is in the direction opposite to the displacement.

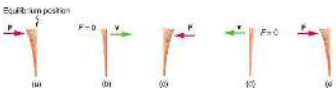


Figure 5.2.7.2: (a) The plastic ruler has been released, and the restoring force is returning the ruler to its equilibrium position. (b) The net force is zero at the equilibrium position, but the ruler has momentum and continues to move to the right. (c) The restoring force is in the opposite direction. It stops the ruler and moves it back toward equilibrium again. (d) Now the ruler has momentum to the left. (e) In the absence of damping (caused by frictional forces), the ruler reaches its original position. From there, the motion will repeat itself.

The **spring constant** k is related to the rigidity (or stiffness) of a system—the larger the spring constant, the greater the restoring force, and the stiffer the system. The units of k are newtons per meter (N/m). Figure 5.2.7.3 shows a graph of the absolute value of the restoring force versus the displacement for a system that can be described by Hooke's law—a simple spring in this case. The slope of the graph equals the spring constant k in newtons per meter.

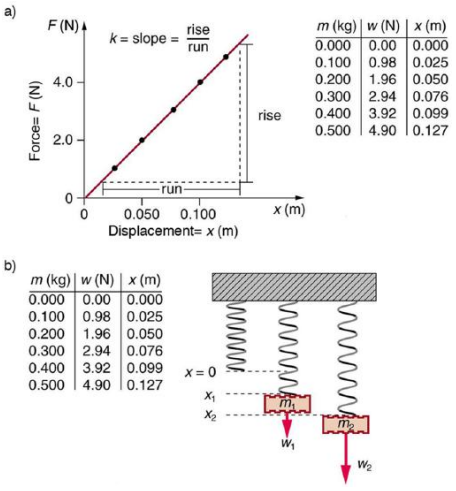


Figure 5.2.7.3: (a) A graph of absolute value of the restoring force versus displacement is displayed. The fact that the graph is a straight line means that the system obeys Hooke's law. The slope of the graph is the spring constant k. (b) The data in the graph were generated by measuring the displacement of a spring from equilibrium while supporting various weights. The restoring force equals the weight supported, if the mass is stationary.

Example 5.2.7.1: How Stiff Are Car Springs?



Figure 5.2.7.4: The mass of a car increases due to the introduction of a passenger. This affects the displacement of the car on its suspension system. (credit: exfordy on Flickr)

What is the spring constant for the suspension system of a car that settles 1.20 cm when an 80.0-kg person gets in?

Strategy

Consider the car to be in its equilibrium position $x = 0$ before the person gets in. The car then settles down 1.20 cm, which means it is displaced to a position $x = -1.20 \times 10^{-2}$ m. At that point, the springs supply a restoring force F equal to the person's weight $w = mg = (80.0 \text{ kg})\,(9.80 \text{ m/s}^2) = 784$ N. We take this force to be F in Hooke's law. Knowing F and x, we can then solve the spring constant k.

Solution

1. Solve Hooke's law, $F = -kx$, for k:

$$k = -\frac{F}{x}.$$

Substitute known values and solve k:

$$k = -\frac{784 \text{ N}}{-1.20 \times 10^{-2} \text{ m}} = 6.53 \times 10^{4} \text{ N/m}.$$

Discussion

Note that F and x have opposite signs because they are in opposite directions—the restoring force is up, and the displacement is down. Also, note that the car would oscillate up and down when the person got in if it were not for damping (due to frictional

forces) provided by shock absorbers. Bouncing cars are a sure sign of bad shock absorbers.

Section Summary

- An oscillation is a back and forth motion of an object between two points of deformation.
- An oscillation may create a wave, which is a disturbance that propagates from where it was created.
- The simplest type of oscillations and waves are related to systems that can be described by Hooke's law:

$$F = -kx,$$

where F is the restoring force, x is the displacement from equilibrium or deformation, and k is the spring constant of the system.

Glossary

deformation
displacement from equilibrium

spring constant
a constant related to the rigidity of a system: the larger the spring constant, the more rigid the system; the spring constant is represented by *k*

restoring force
force acting in opposition to the force caused by a deformation

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5.2.8: Friction

Learning Objectives

- Discuss the general characteristics of friction.
- Describe the various types of friction.
- Explain effect of friction on motion.

Friction is a force that is around us all the time that opposes relative motion between systems in contact but also allows us to move (which you have discovered if you have ever tried to walk on ice). While a common force, the behavior of friction is actually very complicated and is still not completely understood. We have to rely heavily on observations for whatever understandings we can gain. However, we can still deal with its more elementary general characteristics and understand the circumstances in which it behaves.

Definition: FRICTION

Friction is a force that opposes relative motion between systems in contact.

One of the simpler characteristics of friction is that it is parallel to the contact surface between systems and always in a direction that opposes motion or attempted motion of the systems relative to each other. If two systems are in contact and moving relative to one another, then the friction between them is called **kinetic friction**. For example, friction slows a hockey puck sliding on ice. But when objects are stationary, **static friction** can act between them; the static friction is usually greater than the kinetic friction between the objects.

Definition: KINETIC FRICTION

If two systems are in contact and moving relative to one another, then the friction between them is called kinetic friction.

Imagine, for example, trying to slide a heavy crate across a concrete floor—you may push harder and harder on the crate and not move it at all. This means that the static friction responds to what you do—it increases to be equal to and in the opposite direction of your push. But if you finally push hard enough, the crate seems to slip suddenly and starts to move. Once in motion it is easier to keep it in motion than it was to get it started, indicating that the kinetic friction force is less than the static friction force. If you add mass to the crate, say by placing a box on top of it, you need to push even harder to get it started and also to keep it moving. Furthermore, if you oiled the concrete you would find it to be easier to get the crate started and keep it going (as you might expect).

Figure 5.2.8.1 is a crude pictorial representation of how friction occurs at the interface between two objects. Close-up inspection of these surfaces shows them to be rough. So when you push to get an object moving (in this case, a crate), you must raise the object until it can skip along with just the tips of the surface hitting, break off the points, or do both. A considerable force can be resisted by friction with no apparent motion. The harder the surfaces are pushed together (such as if another box is placed on the crate), the more force is needed to move them. Part of the friction is due to adhesive forces between the surface molecules of the two objects, which explain the dependence of friction on the nature of the substances. Adhesion varies with substances in contact and is a complicated aspect of surface physics. Once an object is moving, there are fewer points of contact (fewer molecules adhering), so less force is required to keep the object moving. At small but nonzero speeds, friction is nearly independent of speed.

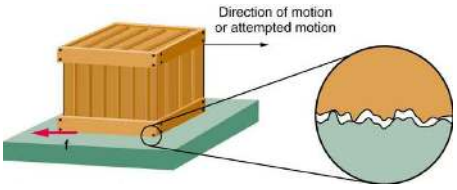


Figure 5.2.8.1: Frictional forces, such as f, always oppose motion or attempted motion between objects in contact. Friction arises in part because of the roughness of the surfaces in contact, as seen in the expanded view. In order for the object to move, it must rise to where the peaks can skip along the bottom surface. Thus a force is required just to set the object in motion. Some of the peaks will be broken off, also requiring a force to maintain motion. Much of the friction is actually due to attractive forces between molecules making up the two objects, so that even perfectly smooth surfaces are not

friction-free. Such adhesive forces also depend on the substances the surfaces are made of, explaining, for example, why rubber-soled shoes slip less than those with leather soles.

The magnitude of the frictional force has two forms: one for static situations (static friction), the other for when there is motion (kinetic friction).

When there is no motion between the objects, the **magnitude of static friction $\mathbf{f_s}$** is

$$f_s \leq \mu_s N,$$

where μ_s is the coefficient of static friction and ***N*** is the magnitude of the normal force (the force perpendicular to the surface).

MAGNITUDE OF STATIC FRICTION

Magnitude of static friction f_s is

$$f_s \leq \mu_s N,$$

where μ_s is the coefficient of static friction and N is the magnitude of the normal force.

The symbol $\leq$ means *less than or equal to*, implying that static friction can have a minimum and a maximum value of $\mu_s N$. Static friction is a responsive force that increases to be equal and opposite to whatever force is exerted, up to its maximum limit. Once the applied force exceeds $f_{s(max)}$, the object will move. Thus

$$f_{s(max)} = \mu_s N.$$

Once an object is moving, the **magnitude of kinetic friction** f_k is given by

$$f_k = \mu_k N,$$

where μ_k is the coefficient of kinetic friction. A system in which $f_k = \mu_k N$ is described as a system in which *friction behaves simply*.

MAGNITUDE OF KINETIC FRICTION

The magnitude of kinetic friction f_k is given by

$$f_k = \mu_k N,$$

where μ_k is the coefficient of kinetic friction.

As seen in Table 5.2.8.1, the coefficients of kinetic friction are less than their static counterparts. That values of μ in Table 5.2.8.1 are stated to only one or, at most, two digits is an indication of the approximate description of friction given by the above two equations.

Table 5.2.8.1: Coefficients of Static and Kinetic Friction

System	Static friction μ_s	Kinetic friction μ_k
Rubber on dry concrete	1.0	0.7
Rubber on wet concrete	0.7	0.5
Wood on wood	0.5	0.3
Waxed wood on wet snow	0.14	0.1
Metal on wood	0.5	0.3
Steel on steel (dry)	0.6	0.3
Steel on steel (oiled)	0.05	0.03
Teflon on steel	0.04	0.04
Bone lubricated by synovial fluid	0.016	0.015
Shoes on wood	0.9	0.7
Shoes on ice	0.1	0.05
Ice on ice	0.1	0.03
Steel on ice	0.4	0.02

The equations given earlier include the dependence of friction on materials and the normal force. The direction of friction is always opposite that of motion, parallel to the surface between objects, and perpendicular to the normal force. For example, if the crate you try to push (with a force parallel to the floor) has a mass of 100 kg, then the normal force would be equal to its weight, $W = mg = (100\ \text{kg})\,(9.80\ \text{m/s}^2) = 980\ \text{N}$, perpendicular to the floor. If the coefficient of static friction is 0.45, you would have to exert a force parallel to the floor greater than $f_{s(\max)} = \mu_s N = (0.45)(980\ \text{N}) = 440\ \text{N}$ to move the crate. Once there is motion, friction is less and the coefficient of kinetic friction might be 0.30, so that a force of only 290 N ($f_k = \mu_k N = (0.30)(980\ \text{N}) = 290\ \text{N}$) would keep it moving at a constant speed. If the floor is lubricated, both coefficients are considerably less than they would be without lubrication. Coefficient of friction is a unit less quantity with a magnitude usually between 0 and 1.0. The coefficient of the friction depends on the two surfaces that are in contact.

TAKE-HOME EXPERIMENT

Find a small plastic object (such as a food container) and slide it on a kitchen table by giving it a gentle tap. Now spray water on the table, simulating a light shower of rain. What happens now when you give the object the same-sized tap? Now add a few drops of (vegetable or olive) oil on the surface of the water and give the same tap. What happens now? This latter situation is particularly important for drivers to note, especially after a light rain shower. Why?

Many people have experienced the slipperiness of walking on ice. However, many parts of the body, especially the joints, have much smaller coefficients of friction—often three or four times less than ice. A joint is formed by the ends of two bones, which are connected by thick tissues. The knee joint is formed by the lower leg bone (the tibia) and the thighbone (the femur). The hip is a ball (at the end of the femur) and socket (part of the pelvis) joint. The ends of the bones in the joint are covered by cartilage, which provides a smooth, almost glassy surface. The joints also produce a fluid (synovial fluid) that reduces friction and wear. A damaged or arthritic joint can be replaced by an artificial joint (Figure 5.2.8.2). These replacements can be made of metals (stainless steel or titanium) or plastic (polyethylene), also with very small coefficients of friction.



Figure 5.2.8.2: Artificial knee replacement is a procedure that has been performed for more than 20 years. In this figure, we see the post-op X-rays of the right knee joint replacement. (credit: Mike Baird, Flickr)

Other natural lubricants include saliva produced in our mouths to aid in the swallowing process, and the slippery mucus found between organs in the body, allowing them to move freely past each other during heartbeats, during breathing, and when a person moves. Artificial lubricants are also common in hospitals and doctor's clinics. For example, when ultrasonic imaging is carried out, the gel that couples the transducer to the skin also serves to lubricate the surface between the transducer and the skin—thereby reducing the coefficient of friction between the two surfaces. This allows the transducer to move freely over the skin.

We have discussed that when an object rests on a horizontal surface, there is a normal force supporting it equal in magnitude to its weight. Furthermore, simple friction is always proportional to the normal force.

MAKING CONNECTIONS: SUBMICROSCOPIC EXPLANATIONS OF FRICTION

The simpler aspects of friction dealt with so far are its macroscopic (large-scale) characteristics. Great strides have been made in the atomic-scale explanation of friction during the past several decades. Researchers are finding that the atomic nature of friction seems to have several fundamental characteristics. These characteristics not only explain some of the simpler aspects of friction—they also hold the potential for the development of nearly friction-free environments that could save hundreds of billions of dollars in energy which is currently being converted (unnecessarily) to heat.

Figure 5.2.8.3 illustrates one macroscopic characteristic of friction that is explained by microscopic (small-scale) research. We have noted that friction is proportional to the normal force, but not to the area in contact, a somewhat counterintuitive notion. When two rough surfaces are in contact, the actual contact area is a tiny fraction of the total area since only high spots touch. When a greater normal force is exerted, the actual contact area increases, and it is found that the friction is proportional to this area.

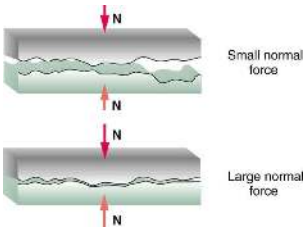


Figure 5.2.8.3: Two rough surfaces in contact have a much smaller area of actual contact than their total area. When there is a greater normal force as a result of a greater applied force, the area of actual contact increases as does friction.

But the atomic-scale view promises to explain far more than the simpler features of friction. The mechanism for how heat is generated is now being determined. In other words, why do surfaces get warmer when rubbed? Essentially, atoms are linked with one another to form lattices. When surfaces rub, the surface atoms adhere and cause atomic lattices to vibrate—essentially creating sound waves that penetrate the material. The sound waves diminish with distance and their energy is converted into heat. Chemical reactions that are related to frictional wear can also occur between atoms and molecules on the surfaces. Figure 5.2.8.4 shows how the tip of a probe drawn across another material is deformed by atomic-scale friction. The force needed to drag the tip can be measured and is found to be related to shear stress, which will be discussed later in this chapter. The variation in shear stress is

remarkable (more than a factor of 10^{12}) and difficult to predict theoretically, but shear stress is yielding a fundamental understanding of a large-scale phenomenon known since ancient times—friction.

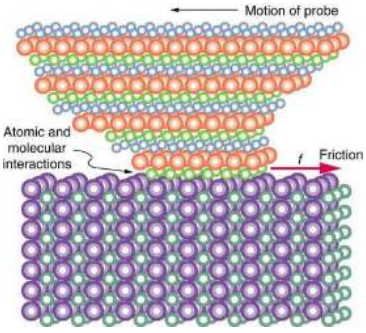


Figure 5.2.8.4: The tip of a probe is deformed sideways by frictional force as the probe is dragged across a surface. Measurements of how the force varies for different materials are yielding fundamental insights into the atomic nature of friction.

Section Summary

- Friction is a contact force between systems that opposes the motion or attempted motion between them. Simple friction is proportional to the normal force ***N*** pushing the systems together. (A normal force is always perpendicular to the contact surface between systems.) Friction depends on both of the materials involved. The magnitude of static friction f_{s} between systems stationary relative to one another is given by

$$f_{\text{s}} \leq \mu_{\text{s}} N,$$

  where μ_{s} is the coefficient of static friction, which depends on both of the materials.
- The kinetic friction force f_{k} between systems moving relative to one another is given by

$$f_{\text{k}} = \mu_{\text{k}} N,$$

  where μ_{k} is the coefficient of kinetic friction, which also depends on both materials.

Glossary

friction
a force that opposes relative motion or attempts at motion between systems in contact

kinetic friction
a force that opposes the motion of two systems that are in contact and moving relative to one another

static friction
a force that opposes the motion of two systems that are in contact and are not moving relative to one another

magnitude of static friction
$f_{\text{s}} \leq \mu_{\text{s}} N$, where μ_{s} is the coefficient of static friction and N is the magnitude of the normal force

magnitude of kinetic friction
$f_{\text{k}} = \mu_{\text{k}} N$, where μ_{k} is the coefficient of kinetic friction

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5.2.9: Newton's Universal Law of Gravitation

Learning Objectives

- Explain Earth's gravitational force.
- Describe the gravitational effect of the Moon on Earth.
- Explain sensation of weightlessness in space.

What do aching feet, a falling apple, and the orbit of the Moon have in common? Each is caused by the gravitational force. Our feet are strained by supporting our weight—the force of Earth's gravity on us. An apple falls from a tree because of the same force acting a few meters above Earth's surface. And the Moon orbits Earth because gravity is able to supply the necessary centripetal force at a distance of hundreds of millions of meters. In fact, the same force causes planets to orbit the Sun, stars to orbit the center of the galaxy, and galaxies to cluster together. Gravity is another example of underlying simplicity in nature. It is the weakest of the four basic forces found in nature, and in some ways the least understood. It is a force that acts at a distance, without physical contact, and is expressed by a formula that is valid everywhere in the universe, for masses and distances that vary from the tiny to the immense.

Sir Isaac Newton was the first scientist to precisely define the gravitational force, and to show that it could explain both falling bodies and astronomical motions. See Figure 5.2.9.1. But Newton was not the first to suspect that the same force caused both our weight and the motion of planets. His forerunner Galileo Galilei had contended that falling bodies and planetary motions had the same cause. Some of Newton's contemporaries, such as Robert Hooke, Christopher Wren, and Edmund Halley, had also made some progress toward understanding gravitation. But Newton was the first to propose an exact mathematical form and to use that form to show that the motion of heavenly bodies should be conic sections—circles, ellipses, parabolas, and hyperbolas. This theoretical prediction was a major triumph—it had been known for some time that moons, planets, and comets follow such paths, but no one had been able to propose a mechanism that caused them to follow these paths and not others.



Figure 5.2.9.1: According to early accounts, Newton was inspired to make the connection between falling bodies and astronomical motions when he saw an apple fall from a tree and realized that if the gravitational force could extend above the ground to a tree, it might also reach the Sun. The inspiration of Newton's apple is a part of worldwide folklore and may even be based in fact. Great importance is attached to it because Newton's universal law of gravitation and his laws of motion answered very old questions about nature and gave tremendous support to the notion of underlying simplicity and unity in nature. Scientists still expect underlying simplicity to emerge from their ongoing inquiries into nature.

The gravitational force is relatively simple. It is always attractive, and it depends only on the masses involved and the distance between them. Stated in modern language, **Newton's universal law of gravitation** states that every particle in the universe attracts every other particle with a force along a line joining them. The force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

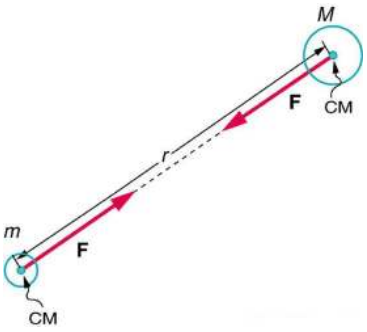


Figure 5.2.9.2: Gravitational attraction is along a line joining the centers of mass of these two bodies. The magnitude of the force is the same on each, consistent with Newton's third law.

MISCONCEPTION ALERT

The magnitude of the force on each object (one has larger mass than the other) is the same, consistent with Newton's third law.

The bodies we are dealing with tend to be large. To simplify the situation we assume that the body acts as if its entire mass is concentrated at one specific point called the **center of mass** (CM). For two bodies having masses m and M with a distance r between their centers of mass, the equation for Newton's universal law of gravitation is

$$F = G\frac{mM}{r^2},$$

where F is the magnitude of the gravitational force and G is a proportionality factor called the **gravitational constant**. G is a universal gravitational constant—that is, it is thought to be the same everywhere in the universe. It has been measured experimentally to be

$$G = 6.673 \times 10^{-11}\frac{\text{N} \cdot \text{m}^2}{\text{kg}^2}$$

in SI units. Note that the units of G are such that a force in newtons is obtained from $F = G\frac{mM}{r^2}$, when considering masses in kilograms and distance in meters. For example, two 1.000 kg masses separated by 1.000 m will experience a gravitational attraction of 6.673×10^{-11} N. This is an extraordinarily small force. The small magnitude of the gravitational force is consistent with everyday experience. We are unaware that even large objects like mountains exert gravitational forces on us. In fact, our body weight is the force of attraction of the *entire Earth* on us with a mass of 5.98×10^{24} kg.

Recall that the acceleration due to gravity g is about $9.80\ \text{m/s}^2$ on Earth. We can now determine why this is so. The weight of an object *mg* is the gravitational force between it and Earth. Substituting *mg* for F in Newton's universal law of gravitation gives

$$mg = G\frac{mM}{r^2},$$

where M is the mass of the object, M is the mass of Earth, and r is the distance to the center of Earth (the distance between the centers of mass of the object and Earth). See Figure 5.2.9.3. The mass M of the object cancels, leaving an equation for g:

$$g = G\frac{M}{r^2}.$$

Substituting known values for Earth's mass and radius (to three significant figures),

$$g = \left(6.67 \times 10^{-11}\frac{\text{N} \cdot \text{m}^2}{\text{kg}^2}\right) \times \frac{5.98 \times 10^{24}\ \text{kg}}{\left(6.38 \times 10^{6}\ \text{m}\right)^2},$$

and we obtain a value for the acceleration of a falling body:

$$g = 9.80\ \text{m/s}^2.$$

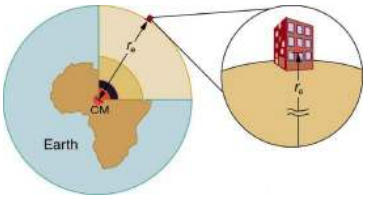


Figure 5.2.9.3: The distance between the centers of mass of Earth and an object on its surface is very nearly the same as the radius of Earth, because Earth is so much larger than the object.

This is the expected value *and is independent of the body's mass*. Newton's law of gravitation takes Galileo's observation that all masses fall with the same acceleration a step further, explaining the observation in terms of a force that causes objects to fall—in fact, in terms of a universally existing force of attraction between masses.

TAKE-HOME EXPERIMENT

Take a marble, a ball, and a spoon and drop them from the same height. Do they hit the floor at the same time? If you drop a piece of paper as well, does it behave like the other objects? Explain your observations.

Example 5.2.9.1: Earth's Gravitational Force on a Mass

(a) Determine the weight of a 5.00 kg rock when on Earth's surface.

(b) Determine the weight of a 5.00 kg rock when 3620 km above the surface of Earth.

Strategy for (a)

Use acceleration due to gravity near Earth's surface and Newton's second law.

Solution for (a)

$$F = mg = 5.00 \text{ kg} \times 9.80 \text{ m/s}^2 = 49.0 \text{ N}$$

Strategy for (b)

Use Newton's universal law of gravitation. Remember that distance is from the center of Earth. In this case the distance is 6380 km + 3620 km = 10,000 km = 1.00×10^7 m.

Solution for (b)

$$F = G\frac{mM}{r^2} = \left(6.673 \times 10^{-11} \frac{\text{N} \cdot \text{m}^2}{\text{kg}^2}\right) \frac{(5.00 \text{ kg})\left(5.98 \times 10^{24} \text{ kg}\right)}{\left(1.00 \times 10^7 \text{ m}\right)^2} = 20.0 \text{ N}$$

Tides

Ocean tides are one very observable result of the Moon's gravity acting on Earth. Figure 5.2.9.4 is a simplified drawing of the Moon's position relative to the tides. Because water easily flows on Earth's surface, a high tide is created on the side of Earth nearest to the Moon, where the Moon's gravitational pull is strongest. Why is there also a high tide on the opposite side of Earth? The answer is that Earth is pulled toward the Moon more than the water on the far side, because Earth is closer to the Moon. So the water on the side of Earth closest to the Moon is pulled away from Earth, and Earth is pulled away from water on the far side. As Earth rotates, the tidal bulge (an effect of the tidal forces between an orbiting natural satellite and the primary planet that it orbits) keeps its orientation with the Moon. Thus there are two tides per day (the actual tidal period is about 12 hours and 25.2 minutes), because the Moon moves in its orbit each day as well).

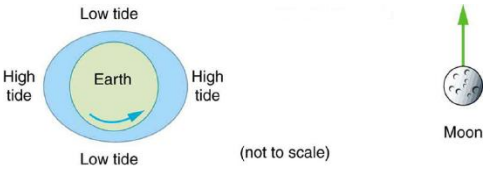


Figure 5.2.9.4: The Moon causes ocean tides by attracting the water on the near side more than Earth, and by attracting Earth more than the water on the far side. The distances and sizes are not to scale. For this simplified representation of the Earth-Moon system, there are two high and two low tides per day at any location, because Earth rotates under the tidal bulge.

The Sun also affects tides, although it has about half the effect of the Moon. However, the largest tides, called spring tides, occur when Earth, the Moon, and the Sun are aligned. The smallest tides, called neap tides, occur when the Sun is at a 90° angle to the Earth-Moon alignment.

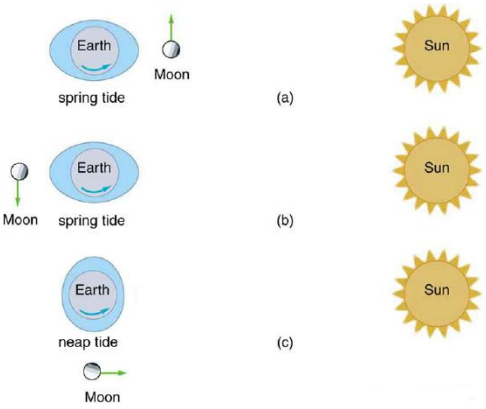


Figure 5.2.9.5: (a, b) Spring tides: The highest tides occur when Earth, the Moon, and the Sun are aligned. (c) Neap tide: The lowest tides occur when the Sun lies at 90° to the Earth-Moon alignment. Note that this figure is not drawn to scale.

Tides are not unique to Earth but occur in many astronomical systems. The most extreme tides occur where the gravitational force is the strongest and varies most rapidly, such as near black holes (see Figure 5.2.9.6). A few likely candidates for black holes have been observed in our galaxy. These have masses greater than the Sun but have diameters only a few kilometers across. The tidal forces near them are so great that they can actually tear matter from a companion star.

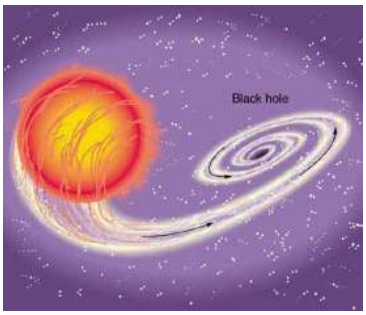


Figure 5.2.9.6: A black hole is an object with such strong gravity that not even light can escape it. This black hole was created by the supernova of one star in a two-star system. The tidal forces created by the black hole are so great that it tears matter from the companion star. This matter is compressed and heated as it is sucked into the black hole, creating light and X-rays observable from Earth.

”Weightlessness” and Microgravity

You may have seen images of astronauts in International Space Station, floating in their environment. What is the effect of “weightlessness” upon an astronaut who is in orbit for months? Or what about the effect of weightlessness upon plant growth? Weightlessness doesn’t mean that an astronaut is not being acted upon by the gravitational force. There is no “zero gravity” in an astronaut’s orbit. The term just means that the astronaut is in free-fall, accelerating with the acceleration due to gravity. If an elevator cable breaks, the passengers inside will be in free fall and will experience weightlessness. You can experience short periods of weightlessness in some rides in amusement parks, and the commercial “zero-G” airplane rides simulate this experience of weightlessness about 20 seconds at a time.



Figure 5.2.9.7: Astronauts experiencing weightlessness on board the International Space Station. (credit: NASA)

Microgravity refers to an environment in which the acceleration of a body due to non-gravitational forces is small compared with that produced by Earth on its surface. Many interesting biology and physics topics have been studied over the past three decades in the presence of microgravity. Of immediate concern is the effect on astronauts of extended times in outer space, such as at the International Space Station. Researchers have observed that muscles will atrophy (waste away) in this environment. There is also a corresponding loss of bone mass. Study continues on cardiovascular adaptation to space flight. On Earth, blood pressure is usually higher in the feet than in the head, because the higher column of blood exerts a downward force on it, due to gravity. When standing, 70% of your blood is below the level of the heart, while in a horizontal position, just the opposite occurs. What difference does the absence of this pressure differential have upon the heart?

Some findings in human physiology in space can be clinically important to the management of diseases back on Earth. On a somewhat negative note, spaceflight is known to affect the human immune system, possibly making the crew members more vulnerable to infectious diseases. Experiments flown in space also have shown that some bacteria grow faster in microgravity than they do on Earth. However, on a positive note, studies indicate that microbial antibiotic production can increase by a factor of two in space-grown cultures. One hopes to be able to understand these mechanisms so that similar successes can be achieved on the ground. In another area of physics space research, inorganic crystals and protein crystals have been grown in outer space that have much higher quality than any grown on Earth, so crystallography studies on their structure can yield much better results.

Plants have evolved with the stimulus of gravity and with gravity sensors. Roots grow downward and shoots grow upward. Plants might be able to provide a life support system for long duration space missions by regenerating the atmosphere, purifying water, and producing food. Some studies have indicated that plant growth and development are not affected by gravity, but there is still uncertainty about structural changes in plants grown in a microgravity environment.

Section Summary

- Newton's universal law of gravitation: Every particle in the universe attracts every other particle with a force along a line joining them. The force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. In equation form, this is

$$F = G\frac{mM}{r^2},$$

  where F is the magnitude of the gravitational force. G is the gravitational constant, given by $G = 6.673 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$.
- Newton's law of gravitation applies universally.

Glossary

gravitational constant, *G*
: a proportionality factor used in the equation for Newton's universal law of gravitation; it is a universal constant—that is, it is thought to be the same everywhere in the universe

center of mass
: the point where the entire mass of an object can be thought to be concentrated

microgravity

an environment in which the acceleration of a body due to non-gravitational forces is small compared with that produced by Earth on its surface

Newton’s universal law of gravitation

every particle in the universe attracts every other particle with a force along a line joining them; the force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them

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5.2.10: Centripetal Force

Learning Objectives

- Explain the role of centripetal force in a uniform circular motion.
- Calculate centripetal force and acceleration for simple situations.

Any force or combination of forces can cause a centripetal or radial acceleration. Just a few examples are the tension in the rope on a tether ball, the force of Earth's gravity on the Moon, friction between roller skates and a rink floor, a banked roadway's force on a car, and forces on the tube of a spinning centrifuge.

Any net force causing uniform circular motion is called a **centripetal force**. The direction of a centripetal force is toward the center of curvature, the same as the direction of centripetal acceleration. According to Newton's second law of motion, net force is mass times acceleration: $F_{\text{net}} = ma$. For uniform circular motion, the acceleration is the centripetal acceleration— $a = a_c$. Thus, the magnitude of centripetal force F_c is

$$F_c = ma_c.$$

By using the expressions for centripetal acceleration a_c from $a_c = \frac{v^2}{r}$, we get an expression for the centripetal force F_c in terms of mass, velocity, and radius of curvature:

$$F_c = m\frac{v^2}{r}.$$

Note that if you solve the first expression for r, you get

$$r = \frac{mv^2}{F_c}.$$

This implies that for a given mass and velocity, a large centripetal force causes a small radius of curvature—that is, a tight curve.

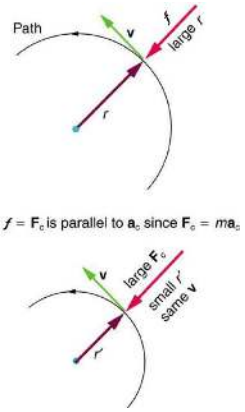


Figure 5.2.10.1: The frictional force supplies the centripetal force and is numerically equal to it. Centripetal force is perpendicular to velocity and causes uniform circular motion. The larger the F_c, the smaller the radius of curvature r and the sharper the curve. The second curve has the same v, but a larger F_c produces a smaller r'.

Example 5.2.10.1: What Coefficient of Friction Do Car Tires Need on a Flat Curve?

(a) Calculate the centripetal force exerted on a 900 kg car that negotiates a 500 m radius curve at 25.0 m/s.

(b) Assuming an unbanked curve, find the minimum static coefficient of friction, between the tires and the road, static friction being the reason that keeps the car from slipping (see Figure 5.2.10.2).

Strategy and Solution for (a)

We know that $F_c = \frac{mv^2}{r}$. Thus,

$$F_c = \frac{mv^2}{r} = \frac{(900\ \text{kg})(25.0\ \text{m/s})^2}{(500\ \text{m})} = 1125\ \text{N}.$$

Strategy for (b)

Figure 5.2.10.2 shows the forces acting on the car on an unbanked (level ground) curve. Friction is to the left, keeping the car from slipping, and because it is the only horizontal force acting on the car, the friction is the centripetal force in this case. We know that the maximum static friction (at which the tires roll but do not slip) is $\mu_s N$, where μ_s is the static coefficient of friction and N is the normal force. The normal force equals the car's weight on level ground, so that $N = mg$. Thus the centripetal force in this situation is

$$F_c = f = \mu_s N = \mu_s mg.$$

Now we have a relationship between centripetal force and the coefficient of friction. Using the expression for F_c

$$F_c = m\frac{v^2}{r},$$
$$m\frac{v^2}{r} = \mu_s mg.$$

We solve this for μ_s, noting that mass cancels, and obtain

$$\mu_s = \frac{v^2}{rg}.$$

Solution for (b)

Substituting the knowns,

$$\mu_s = \frac{(25.0\ \text{m/s})^2}{(500\ \text{m})\,(9.80\ \text{m/s}^2)} = 0.13.$$

(Because coefficients of friction are approximate, the answer is given to only two digits.)

Discussion

The coefficient of friction found in part (b) is much smaller than is typically found between tires and roads. The car will still negotiate the curve if the coefficient is greater than 0.13, because static friction is a responsive force, being able to assume a value less than but no more than $\mu_s N$. A higher coefficient would also allow the car to negotiate the curve at a higher speed, but if the coefficient of friction is less, the safe speed would be less than 25 m/s. Note that mass cancels, implying that in this example, it does not matter how heavily loaded the car is to negotiate the turn. Mass cancels because friction is assumed proportional to the normal force, which in turn is proportional to mass. If the surface of the road were banked, the normal force would be less as will be discussed below.

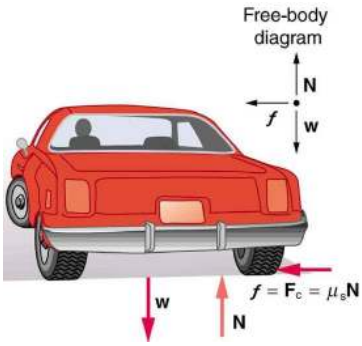


Figure 5.2.10.2: This car on level ground is moving away and turning to the left. The centripetal force causing the car to turn in a circular path is due to friction between the tires and the road. A minimum coefficient of friction is needed, or the car will move in a larger-radius curve and leave the roadway.

In the case of **banked curves**, where the slope of the road helps you negotiate the curve, some or all of the necessary centripetal force is provided by the normal force. See Figure 5.2.10.3. The greater the angle θ, the faster you can take the curve. Race tracks for bikes as well as cars, for example, often have steeply banked curves. In an "ideally banked curve," the angle θ is such that you can

negotiate the curve at a certain speed without the aid of friction between the tires and the road. Conceptually, for **ideal banking**, the net external force equals the horizontal centripetal force in the absence of friction. The components of the normal force N in the horizontal and vertical directions must equal the centripetal force and the weight of the car, respectively.

Figure 5.2.10.3 shows a free body diagram for a car on a frictionless banked curve. If the angle θ is ideal for the speed and radius, then the net external force will equal the necessary centripetal force. The only two external forces acting on the car are its weight w and the normal force of the road N. (A frictionless surface can only exert a force perpendicular to the surface—that is, a normal force.) These two forces must add to give a net external force that is horizontal toward the center of curvature and has magnitude mv^2/r. We omit detailed calculations, which require trigonometry.

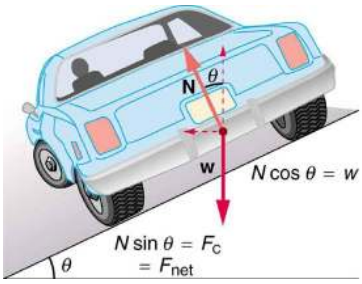


Figure 5.2.10.3: The car on this banked curve is moving away and turning to the left.

Section Summary

- Centripetal force $\mathrm{F_c}$ is any force causing uniform circular motion. It is a "center-seeking" force that always points toward the center of rotation. It is perpendicular to linear velocity v and has magnitude

$$F_\mathrm{c} = ma_\mathrm{c},$$

  which can also be expressed as

$$F_c = m\frac{v^2}{r}.$$

Glossary

centripetal force
any net force causing uniform circular motion

ideal banking
the sloping of a curve in a road, where the angle of the slope allows the vehicle to negotiate the curve at a certain speed without the aid of friction between the tires and the road; the net external force on the vehicle equals the horizontal centripetal force in the absence of friction

banked curve
the curve in a road that is sloping in a manner that helps a vehicle negotiate the curve

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5.2.E: Dynamics (Exercise)

Conceptual Questions

2.1: Development of Force Concept

1. Propose a force standard different from the example of a stretched spring discussed in the text. Your standard must be capable of producing the same force repeatedly.

2. What properties do forces have that allow us to classify them as vectors?

2.2: Newton's First Law of Motion- Inertia

3. How are inertia and mass related?

4. What is the relationship between weight and mass? Which is an intrinsic, unchanging property of a body?

2.3: Newton's Second Law of Motion- Force and Acceleration

5. Which statement is correct? (a) Net force causes motion. (b) Net force causes change in motion. Explain your answer and give an example.

6. Why can we neglect forces such as those holding a body together when we apply Newton's second law of motion?

7. Explain how the choice of the "system of interest" affects which forces must be considered when applying Newton's second law of motion.

8. Describe a situation in which the net external force on a system is not zero, yet its speed remains constant.

9. A system can have a nonzero velocity while the net external force on it *is* zero. Describe such a situation.

10. A rock is thrown straight up. What is the net external force acting on the rock when it is at the top of its trajectory?

11. (a) Give an example of different net external forces acting on the same system to produce different accelerations. (b) Give an example of the same net external force acting on systems of different masses, producing different accelerations. (c) What law accurately describes both effects? State it in words and as an equation.

12. If the acceleration of a system is zero, are no external forces acting on it? What about internal forces? Explain your answers.

13. If a constant, nonzero force is applied to an object, what can you say about the velocity and acceleration of the object?

14. The gravitational force on the basketball in Figure 5.2.E.1 is ignored. When gravity *is* taken into account, what is the direction of the net external force on the basketball—above horizontal, below horizontal, or still horizontal?

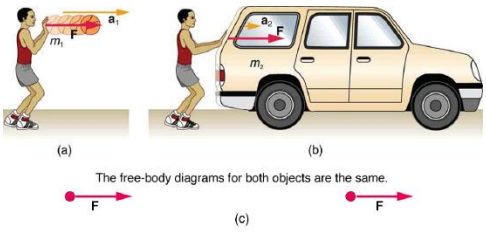


Figure 5.2.E.1: The same force exerted on systems of different masses produces different accelerations. (a) A basketball player pushes on a basketball to make a pass. (The effect of gravity on the ball is ignored.) (b) The same player exerts an identical force on a stalled SUV and produces a far smaller acceleration (even if friction is negligible). (c) The free-body diagrams are identical, permitting direct comparison of the two situations. A series of patterns for the free-body diagram will emerge as you do more problems.

2.4: Newton's Third Law of Motion- Symmetry in Forces

15. When you take off in a jet aircraft, there is a sensation of being pushed back into the seat. Explain why you move backward in the seat—is there really a force backward on you? (The same reasoning explains whiplash injuries, in which the head is apparently thrown backward.)

16. A device used since the 1940s to measure the kick or recoil of the body due to heart beats is the “ballistocardiograph.” What physics principle(s) are involved here to measure the force of cardiac contraction? How might we construct such a device?

17. Describe a situation in which one system exerts a force on another and, as a consequence, experiences a force that is equal in magnitude and opposite in direction. Which of Newton’s laws of motion apply?

18. Why does an ordinary rifle recoil (kick backward) when fired? The barrel of a recoilless rifle is open at both ends. Describe how Newton’s third law applies when one is fired. Can you safely stand close behind one when it is fired?

19. An American football lineman reasons that it is senseless to try to out-push the opposing player, since no matter how hard he pushes he will experience an equal and opposite force from the other player. Use Newton’s laws and draw a free-body diagram of an appropriate system to explain how he can still out-push the opposition if he is strong enough.

20. Newton’s third law of motion tells us that forces always occur in pairs of equal and opposite magnitude. Explain how the choice of the “system of interest” affects whether one such pair of forces cancels.

2.5: Normal Force and Tension

21. Find at least one example of each case from everyday experiences (find an example that is not in the textbook!): (a) a situation where normal force on a person is equal to the person's weight, (b) a situation where normal force on a person is greater than the person's weight, and (c) a situation where normal force on a person is less than the person's weight. Also, can you find an example (that is not in the textbook!) which covers each of all three cases, depending on changing circumstances?

22. As noted in the text, the normal force and the tension force can only act in one direction: the normal force can only push, and the tension force can only pull. The numerical value of the force in these given directions is determined by what force is necessary to keep a body in the observed state of motion (either not accelerating, in presence of other forces, or accelerating at a particular rate). Under certain conditions, the normal force would go to zero (but not negative, as direction can't reverse), as would the tension force.

23. Explain qualitatively what you would see as: (a) the normal force goes to zero, and (b) the tension force goes to zero.

2.6: Spring Force- Hooke’s Law

24. Describe a system which undergoes an oscillation under a Hooke's law force.

25. Imagine an object under a hypothetical force behaving opposite to Hooke's law force. That is, instead of restoring force ($F = -kx$, with the negative sign indicating that the force acts in the opposite direction of displacement), the force reinforces an initial displacement: $F = +kx$. What would happen to this object if it is placed at the equilibrium ($x = 0$) and then very slightly disturbed?

2.7: Friction

26. Define normal force. What is its relationship to friction when friction behaves simply?

27. The glue on a piece of tape can exert forces. Can these forces be a type of simple friction? Explain, considering especially that tape can stick to vertical walls and even to ceilings.

28. When you learn to drive, you discover that you need to let up slightly on the brake pedal as you come to a stop or the car will stop with a jerk. Explain this in terms of the relationship between static and kinetic friction.

29. When you push a piece of chalk across a chalkboard, it sometimes screeches because it rapidly alternates between slipping and sticking to the board. Describe this process in more detail, in particular explaining how it is related to the fact that kinetic friction is less than static friction. (The same slip-grab process occurs when tires screech on pavement.)

2.8: Newton’s Universal Law of Gravitation

30. Action at a distance, such as is the case for gravity, was once thought to be illogical and therefore untrue. What is the ultimate determinant of the truth in physics, and why was this action ultimately accepted?

31. Two friends are having a conversation. Anna says a satellite in orbit is in freefall because the satellite keeps falling toward Earth. Tom says a satellite in orbit is not in freefall because the acceleration due to gravity is not $9.80\ \mathrm{m/s^2}$. Who do you agree with and why?

32. Newton's laws of motion and gravity were among the first to convincingly demonstrate the underlying simplicity and unity in nature. Many other examples have since been discovered, and we now expect to find such underlying order in complex situations. Is there proof that such order will always be found in new explorations?

2.9: Centripetal Force

33. If you wish to reduce the stress (which is related to centripetal force) on high-speed tires, would you use large- or small-diameter tires? Explain.

34. Define centripetal force. Can any type of force (for example, tension, gravitational force, friction, and so on) be a centripetal force? Can any combination of forces be a centripetal force?

35. If centripetal force is directed toward the center, why do you feel that you are 'thrown' away from the center as a car goes around a curve? Explain.

36. Race car drivers routinely cut corners as shown in Figure $5.2.E.2$. Explain how this allows the curve to be taken at the greatest speed.

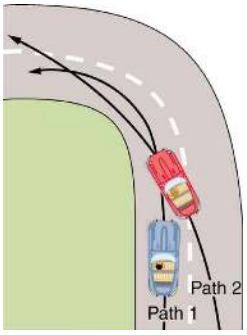
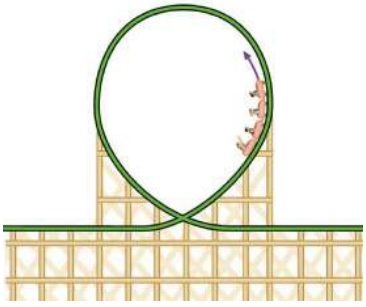


Figure $5.2.E.2$: Two paths around a race track curve are shown. Race car drivers will take the inside path (called cutting the corner) whenever possible because it allows them to take the curve at the highest speed.

37. A number of amusement parks have rides that make vertical loops like the one shown in Figure $5.2.E.3$. For safety, the cars are attached to the rails in such a way that they cannot fall off. If the car goes over the top at just the right speed, gravity alone will supply the centripetal force. What other force acts and what is its direction if:

(a) The car goes over the top at faster than this speed?

(b)The car goes over the top at slower than this speed?


Figure $5.2.E.3$: Amusement rides with a vertical loop are an example of a form of curved motion.

38. What is the direction of the force exerted by the car on the passenger as the car goes over the top of the amusement ride pictured in Figure $5.2.E.3$ under the following circumstances:

(a) The car goes over the top at such a speed that the gravitational force is the only force acting?

(b) The car goes over the top faster than this speed?

(c) The car goes over the top slower than this speed?

39. Suppose a child is riding on a merry-go-round at a distance about halfway between its center and edge. She has a lunch box resting on wax paper, so that there is very little friction between it and the merry-go-round. Which path shown in Figure 5.2.E.4 will the lunch box take when she lets go? The lunch box leaves a trail in the dust on the merry-go-round. Is that trail straight, curved to the left, or curved to the right? Explain your answer.

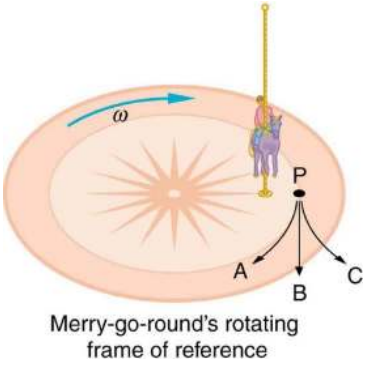


Figure 5.2.E.4: A child riding on a merry-go-round releases her lunch box at point P. This is a view from above the clockwise rotation. Assuming it slides with negligible friction, will it follow path A, B, or C, as viewed from Earth's frame of reference? What will be the shape of the path it leaves in the dust on the merry-go-round?

40. Do you feel yourself thrown to either side when you negotiate a curve that is ideally banked for your car's speed? What is the direction of the force exerted on you by the car seat?

41. Suppose a mass is moving in a circular path on a frictionless table as shown in figure. In the Earth's frame of reference, there is no centrifugal force pulling the mass away from the centre of rotation, yet there is a very real force stretching the string attaching the mass to the nail. Using concepts related to centripetal force and Newton's third law, explain what force stretches the string, identifying its physical origin.

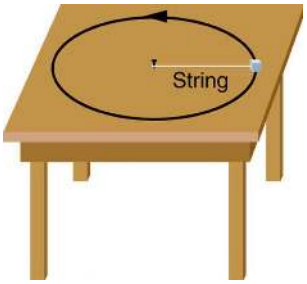


Figure 5.2.E.5: A mass attached to a nail on a frictionless table moves in a circular path. The force stretching the string is real and not fictional. What is the physical origin of the force on the string?

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CHAPTER OVERVIEW

6: Energy

6.1: What is Energy?

6.2: Work and Kinetic Energy

6.3: Potential Energy

6.4: Chemical Energy

6.5: Thermal Energy

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6.1: What is Energy?

Learning Objectives

By the end of this chapter, students will be able to

- List different types of energy
- Explain the connection between force and energy
- Calculate transformations of energy from one type to another



Watts Bar Nuclear Power Plant in East Tennessee. Image from Tennessee Valley Authority (Public Domain).

Energy is the ability of a system to do work. A system has done work if it has exerted a force on another system over some distance. When this happens, energy is transferred from one system to another. At least some of the energy is also transformed from one type to another during this process. One can keep track of how much energy transfers into or out of a system. There are two categories that all energy falls into: kinetic and potential. **Kinetic energy** refers to types of energy associated with motion (Figure 6.1.1, top). For example, a rock rolling down a hill, the wind blowing through trees, water flowing over a dam, and a cyclist riding a bicycle are just a few examples of kinetic energy. **Potential energy** is energy possessed by an object or system due to its position in space relative to another object or system and forces between the two (Figure 6.1.1, bottom). Examples include a rock poised at the top of a hill and water stored behind a dam. Some forms of energy are part kinetic and part potential energy. **Chemical energy** describes the potential of a chemical substance to undergo a chemical reaction and transform other chemical substances; hence it is a form of potential energy. Examples include energy stored in the food you eat and the gasoline that you put in your car. **Nuclear energy** is the energy stored in the nucleus of an atom. This energy can be released in radioactive decay, fission, or fusion. **Radiant energy** is potential energy that is in electromagnetic waves (light). There are many different categories of electromagnetic waves, each with a particular range of values for their energies. Visible light is the most common type of electromagnetic wave that we experience. **Heat (thermal) energy** is energy that moves between objects that have different temperatures. The so-called “useful” types of energy are generally potential energy and kinetic energy. Heat can be utilized to do useful work, but is also where a lot of useful energy is wasted and cannot be used again. For example, when two objects rub together, the force of friction generates heat. We consider that heat to be wasted energy, as it cannot be utilized as useful work. The discussion of thermal energy and its transformations into other forms will be discussed later in this textbook.

Some of the types of energy described above are not unique forms of energy. In reality, the only kinds of energy that exist come from the four fundamental forces in nature. These forces are **gravitational force, electromagnetic force, weak nuclear force,** and **strong nuclear force**. In section 6.2. we will see the connection between force and energy. However, for the remainder of the text, we will ignore the particular types of forces that are the source of energy.



Examples of different forms of **kinetic** energy



Examples of different forms of **potential** energy

Figure 6.1.1*: Examples kinetic (top) and potential (bottom) forms of energy. All images were obtained from Wikimedia commons (public domain).*

Living organisms need energy to perform life-sustaining "work" in order to survive. For nearly all living systems on Earth, the sun is the ultimate source of that energy. Over time, we humans have developed an understanding of energy that has allowed us to harness it for uses well beyond basic survival. The development and evolution of human society is largely attributed to our relationship with energy. The first major advancement in human understanding of energy was the mastery of fire for cooking and heating. Modern civilization is especially dependent on energy and some of its most distinct characteristics such as population growth, environmental impact and climate change are all a consequence of energy use. We use energy to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the comforts and conveniences to which we have grown accustomed in the industrial age. Societal complexity, affluence, and the gap between poor and rich peoples are all related to our level of energy consumption.

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6.2: Work and Kinetic Energy

In this section we will define work and kinetic energy. All of the descriptions below assume a world without friction. Friction is a force, and it can complicate a simple, straight-forward explanation. Unfortunately, our everyday experiences involve friction, and it can be difficult to eliminate it from our thinking about the world.

6.2.1: Work

In physics, the term "work" has a very specific and technical meaning that differs from its everyday use. It is not about effort or exertion, but rather about the transfer of energy. Work is the energy transferred to or from an object when a force acts on it, causing it to move over a distance. To be more precise, three conditions must be met for work to be done:

1. **A force must be applied to an object.** This force can be a push, a pull, gravity, friction, etc.
2. **The object must move or be displaced.** If you push on a wall with all your might, but the wall doesn't budge, you haven't done any work on the wall in the physics sense.
3. **At least part of the force must be in the direction of the displacement.** This is the most crucial part. If you are carrying a box horizontally, you are applying an upward force to support its weight. However, since the motion is horizontal (perpendicular to the force), no work is being done by your lifting force.

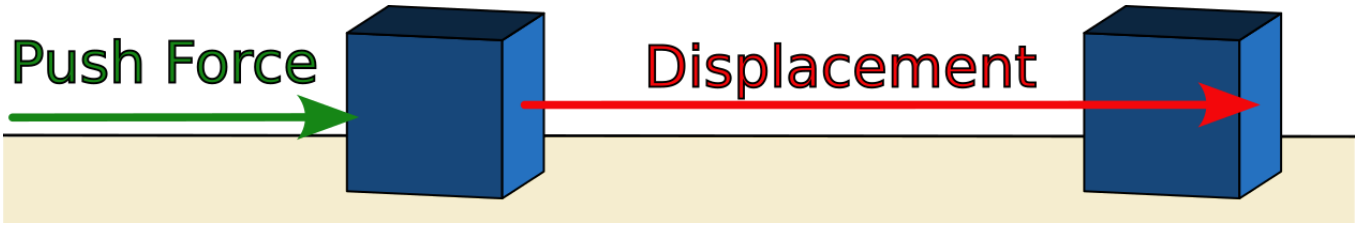


Figure 6.2.1: A schematic of an applied force doing work by displacing an object.

6.2.1.1: Key Aspects of Work

- **Work is a scalar quantity:** Unlike force and displacement which have direction, work does not. It is simply a value that represents a transfer of energy.
- **Positive, Negative, and Zero Work:**
  - **Positive Work:** Occurs when the force has a component in the same direction as the object's motion. This increases the object's energy. For example, pushing a box to make it speed up.
  - **Negative Work:** Occurs when the force has a component in the opposite direction of the object's motion. This removes energy from the object. For example, the force of friction acting on a sliding box is doing negative work, causing it to slow down.
  - **Zero Work:** Occurs when the force is perpendicular to the displacement, or when there is no displacement at all. For example, holding a heavy object still or carrying a briefcase at a constant speed on level ground.

In essence, work is the fundamental link between force and energy. It explains how forces change the energy of a system. The unit for work is the **joule (J)**, which is the same unit used for energy. One joule is defined as the work done by a force of one newton acting over a distance of one meter. Mathematically, we describe work by the equation

$$W = Fd \tag{6.2.1}$$

where W is work, F is the applied force causing a displacement d. It is important that we only consider displacement that is parallel to the applied force. In this text, we will only consider cases where the force and displacement are parallel.

6.2.2: Kinetic Energy

Kinetic energy is the energy that an object possesses due to its **motion**.

Simply put, if something is moving, it has kinetic energy. The amount of kinetic energy an object has depends on two key factors:

1. **Its mass:** A more massive object has more kinetic energy than a less massive object moving at the same speed. A bowling ball, for example, has far more kinetic energy than a tennis ball traveling at the same speed.
2. **Its speed:** This is the most significant factor. Kinetic energy is not just proportional to speed, it is proportional to the **square of the speed**. This means that if you double an object's speed, its kinetic energy increases by a factor of four (2^2). If you triple the speed, the kinetic energy increases by a factor of nine (3^2).

Written as an equation, kinetic energy is

$$KE = \frac{1}{2}mv^2 \tag{6.2.2}$$

where KE is kinetic energy, m is the mass of the object that is moving with a speed v.

6.2.2.1: Examples in Action:

- A moving car possesses a large amount of kinetic energy, which is why it can cause so much damage in a collision.
- A running person, a revolving planet, or a falling drop of rain all have kinetic energy.
- In the work-energy theorem, work done on an object can be understood as a transfer of energy that changes its kinetic energy. When you push a swing to make it move faster, you are doing work on it, and its kinetic energy increases.

In summary, kinetic energy is the energy of motion, and its value is a measure of how much work an object can do as a result of that motion. The faster and more massive an object is, the more kinetic energy it has.

6.2.3: The Work-Energy Theorem

The **work-energy theorem** is a fundamental principle in physics that connects the concepts of work and kinetic energy.

Imagine you have an object, like a box, that is sitting still on the floor. If you want to make it move, you have to push it. This act of pushing the box over a certain distance is what physicists call **work**.

Now, as you push the box, it starts to move faster and faster. The energy an object has because of its motion is called **kinetic energy**. The work-energy theorem simply states that the **total amount of work you do on the box is equal to the change in its kinetic energy.** Mathematically, this is

$$W = Fd = KE_{final} - KE_{initial} \tag{6.2.3}$$

$$W = \frac{1}{2}mv_{final}^2 - \frac{1}{2}mv_{initial}^2 \tag{6.2.4}$$

Let's reiterate work through a few simple scenarios:

- **You do positive work:** If you push the box in the direction it's already moving, you are adding energy to it. The box will speed up, and its kinetic energy will increase. The increase in kinetic energy is exactly equal to the work you performed.
- **You do negative work:** If the box is sliding, and you push against its direction of motion (like trying to slow it down), you are taking energy away from it. The box will slow down, and its kinetic energy will decrease. The decrease in kinetic energy is equal to the negative work you did.
- **You do no work:** If you push on a wall, you're applying a force, but the wall doesn't move. Since there is no displacement, no work is done on the wall, and its kinetic energy remains unchanged (it stays still).

The key takeaway is that work is a transfer of energy. When you do work on an object, you are either giving it kinetic energy or taking it away. The theorem is a powerful way to understand how forces and motion are related, without needing to go into the details of acceleration or time.

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6.3: Potential Energy

Potential energy is the energy an object has stored up due to its position or state. Think of it as "potential" to do work. An object with potential energy isn't moving right now, but it has the ability to move and do something later.

There are a few different types of potential energy, but the two main ones you'll encounter are:

6.3.1: Gravitational Potential Energy

This is the most common type. It's the energy an object stores because of its height above some reference location such as the ground.

Think of it this way:

- **A bowling ball on the top shelf of a closet:** It has a lot of gravitational potential energy because if it falls, it can do some serious damage (like breaking a tile on the floor). If you lift the ball higher, you're increasing its potential energy. All of this potential energy becomes kinetic energy when the ball falls. The further the ball falls, the more kinetic energy gained from the larger initial potential energy. We say that gravity does work on the ball to convert potential energy into kinetic energy.



Figure 6.3.1: A bowling ball falling from a shelf and converting gravitational potential energy to kinetic energy. Image created by Gemini AI.

- **A roller coaster at the top of the first hill:** It's not moving very fast horizontally, but it has a massive amount of potential energy. As it goes down the hill, this potential energy is converted into kinetic energy (energy of motion), which is what makes it go so fast.



Figure 6.3.2: A roller coaster with large potential energy. Image created by Gemini AI.

The formula for gravitational potential energy is $PE = mgh$, where:

- m is the mass of the object (how much "stuff" it's made of)
- g is the acceleration due to gravity (a constant number, usually about 9.8m/s^2 on Earth)
- h is the height of the object

6.3.2: Elastic Potential Energy

This is the energy stored in something that is stretched, compressed, or twisted.

Think of it this way:

- **A stretched rubber band:** It has elastic potential energy. When you let it go, that stored energy is released, and it snaps back to its original shape. You've converted the potential energy into kinetic energy.
- **A compressed spring:** When you press down on a spring, you are storing energy in it. If you let it go, the spring will "spring" back, releasing that stored potential energy. This is how things like trampolines and pogo sticks work.

The formula for elastic potential energy in a spring is $PE = \frac{1}{2}kx^2$, where:

- k is the spring constant (a number that tells you how stiff the spring is)
- x is the distance the spring is stretched or compressed from its resting position.

Chemical potential energy is somewhat connected to elastic potential energy. When chemical bonds are very strong, it is as if they have a large spring constant. Stiff chemical bonds have a lot of chemical potential energy.

6.3.3: The Big Picture

The key takeaway is that potential energy is all about **stored energy**. It's the energy an object has waiting to be used. When that energy is released, it is usually converted into another form of energy, most often kinetic energy (the energy of motion). This constant conversion between potential and kinetic energy is fundamental to understanding how things move and interact in the physical world.

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6.4: Chemical Energy

Chemical energy is a form of **potential energy** that is stored within the bonds of atoms and molecules. Think of it as the "hidden" energy inside a substance, waiting to be released when a chemical reaction takes place. It is important to note that chemical bonds require energy input to break the bonds. All stable chemicals have negative potential energy, that is, the bond sinks the chemical energy down an energy "well". Imagine a rock that has fallen down a literal well. That rock requires energy or work to be done to lift it out. The same is true of chemical bonds. However, when a chemical reaction happens, these bonds are broken and new ones are formed, and this process can either release or absorb energy. If energy is released, the products have lower energy than the reactants. This is an **exothermic** reaction. If energy is absorbed, the products have higher energy than the reactants. This is an **endothermic** reaction. Both kinds of reactions can occur naturally under the right circumstances.

Here are a few ways to think about it with everyday examples.

6.4.0.1: Food: Fuel for Your Body

When you eat food, your body performs a series of chemical reactions to break down the food molecules (like sugars, fats, and proteins). The energy that was stored in the chemical bonds of those food molecules is released. Your body then uses this released energy to power your muscles, keep you warm, and allow your brain to think. This is why we say food is "fuel" for our bodies. The most commonly referred to food reaction is the combustion of glucose, where glucose ($C_6H_{12}O_6$) plus oxygen (O_2) react to from carbon dioxide (CO_2) and water (H_2O). The reaction is written as

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \tag{6.4.1}$$

Example: Chemical Reaction Balancing

The subscripts in a molecule indicate how many atoms of that type are in the molecule. The numbers in front of each molecule indicate the number of molecules needed to balance the reaction. Notice there are sixes in front of the oxygen, carbon dioxide and water. These are to balance the chemical reaction input (reactants) with the output (products). No atoms are created or destroyed in a chemical reaction, but the molecules change. Table 6.4.1 shows the count of each element (carbon, oxygen, and hydrogen) in the reactants and products.

Element	Reactants	Products
Carbon, C	6	6
Oxygen, O	6 + 6(2) = 18	6(2) + 6 = 18
Hydrogen, H	12	6(2) = 12

Table 6.4.1: An accounting of the balance between reactants and products for the combustion reaction of glucose.

6.4.0.1: Batteries: Stored Power

A battery is an excellent example of chemical energy in action. Inside a battery, there are chemicals that are arranged in a specific way. When you connect the battery to a device (like a flashlight), you complete a circuit that allows a chemical reaction to occur. This reaction releases electrons, and this flow of electrons is what we call electricity. The chemical energy stored in the battery is converted into electrical energy. The reaction in a lead acid battery like in your gas-powered automobile is

$$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^- \tag{6.4.2}$$

Exercise 6.4.2

Verify that the equation for the lead acid reaction is balanced.

Answer

- There is one lead (Pb) atom on each side.

- There is one hydrogen (H) atom on each side.
- There is one sulfur (S) atom on each side.
- There are four oxygen (O) atoms on each side.
- We can also balance the charges. There is one negative on the reactant side. There are one positive and two negatives on the product side (1-1-1=-1).

6.4.0.1: Gasoline: Powering Cars

Gasoline is a mixture of hydrocarbons, which are molecules with a lot of energy stored in their chemical bonds. When you turn on your car's engine, a small spark ignites the gasoline, causing a rapid chemical reaction (combustion). This reaction breaks the bonds of the hydrocarbon molecules, releasing a large amount of energy very quickly. This energy pushes the pistons in the engine, which ultimately makes the car's wheels turn. The chemical energy in the gasoline is converted into mechanical energy. The combustion of octane, a key component of gasoline, is

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O \tag{6.4.3}$$

? Exercise 6.4.3

Verify that the equation for the octane combustion reaction is balanced.

Answer

- There are 2x8 = 16 reactant and 16 product carbon (C) atoms.
- There are 2x18 = 36 reactant and 18 product hydrogen (H) atoms.
- There are 25x2 = 50 reactant and 16x2 + 18 = 50 product oxygen (O) atoms.

6.4.0.1: Key Concepts

- **Potential Energy:** A molecule has negative chemical potential energy stored in its bonds. Reactions that make this energy less negative occur naturally and release energy.
- **Chemical Reaction:** This is the process where bonds are broken and new ones are formed. It's the event that releases the stored chemical energy.
- **Exothermic Reaction:** A reaction that releases energy, often in the form of heat, light, or sound. Burning gasoline is a great example.
- **Endothermic Reaction:** A reaction that absorbs energy from its surroundings. An example is an instant cold pack; when you break the inner bag, the chemicals react and absorb heat from the surroundings, making the pack feel cold.

In simple terms, chemical energy is the power source hidden inside a substance, and you need to perform a chemical reaction to unlock it.

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6.5: Thermal Energy

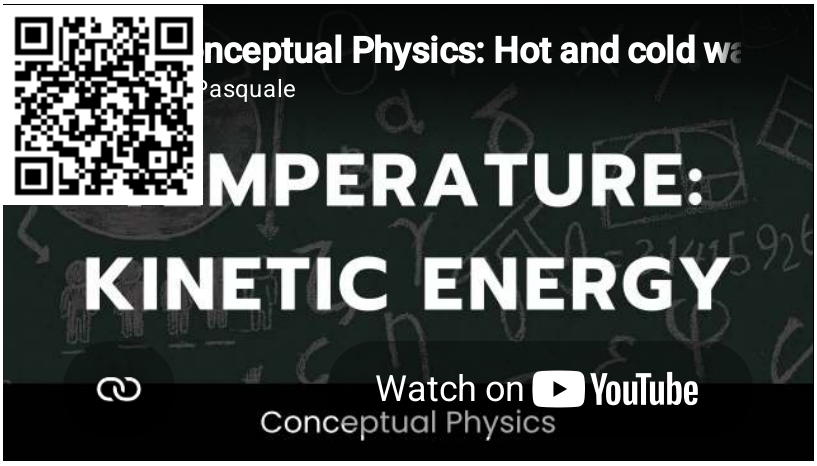
Temperature and heat are important phenomena that start to unlock the ideas of thermodynamics. Temperature is something that impacts our lives greatly as we move throughout the seasons. Heat and specific heat capacity are concepts that allow us to understand climate and cooling systems, among other things. Finally, thermal expansion has far-ranging implications from the existence of aquatic life on this planet, to understanding how objects change their sizes from month to month as temperatures change.

6.5.1: **Temperature**

Temperature quantitatively describes the average translational kinetic energy of the atoms and molecules in a substance. It quantifies the “hotness” or “coldness” of something. The symbol for temperature is the uppercase letter T.

Kinetic energy describes the energy of motion. Therefore, it would be reasonable to expect that a substance at a higher temperature will have more motion than a substance at a lower temperature.

In the video below, there are two beakers filled with water. The beaker on the left is filled with cold water, and the beaker on the right is filled with hot water. (The beaker on the left appears translucent due to the fact that water vapor from the air has condensed on it.)



A drop of blue food dye is dropped into each beaker. After watching for several moments, you can see the food dye swirl around and distribute itself much more rapidly in the beaker of hot water, demonstrating that its motion is much greater than that of the cold water. A photograph of each beaker 30 seconds after the introduction of the food dye is shown in Figure 6.5.1. The dye in the cold beaker (left) has not distributed nearly as much as the dye in the hot beaker (right).

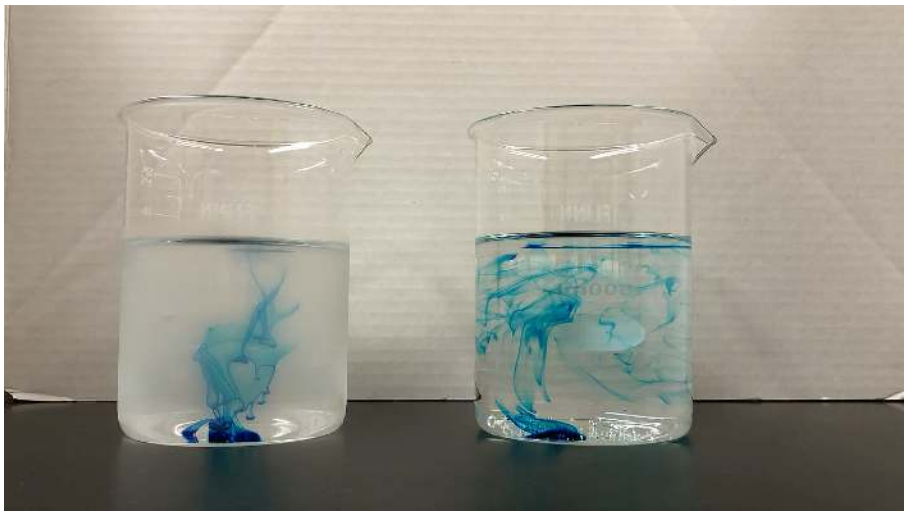


Figure 6.5.1 – A beaker of cold water (left) and hot water (right) are viewed 30 seconds after placing a drop of blue food coloring in each beaker. The dye in the hot water has distributed much more than the dye in the cold water. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.

From a human perspective, temperature is extremely important in helping us determine what to wear when we go outside, and in deciding on what types of indoor and outdoor activities we want to do. Having an objective temperature scale is important in that it cuts out the subjective interpretation of each person's idea of what may be "hot" or "cold." From a physics perspective, an objective temperature scale enables scientists to perform experiments on thermodynamics, climate change, and other important phenomena.

6.5.1.1: Empirical temperature scales

Now that we understand what temperature is, we need a way to measure it. There are two types of temperature scales that can be used: empirical scales and absolute scales.

An empirical scale means that experiments were performed to derive the upper and lower limits of the scale. The Fahrenheit scale was proposed in the 1700s. The limit for the cold end of the temperature scale was a frozen salt water solution. That temperature was denoted as zero. The limit for the hot end of the temperature scale was the temperature of a human body. This temperature was denoted at 96. (This value was chosen because it is easily divisible by many numbers; it has 12 divisors.) The total number of degrees on this scale was therefore 96, creating the original Fahrenheit temperature scale. This rudimentary scale is shown in Figure 6.5.2 .

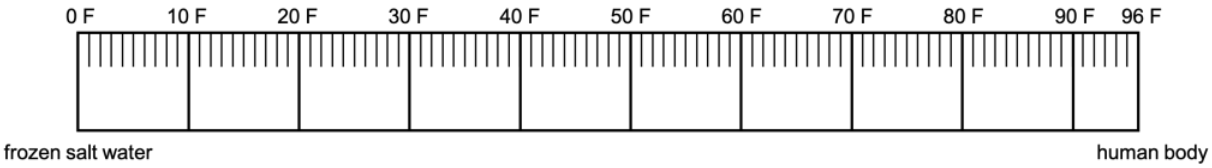


Figure 6.5.2 – The original Fahrenheit scale was developed by setting 0 as the temperature of a frozen salt water solution and setting 96 as the temperature of the human body. This created a total number of 96 degrees between hot and cold. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.

The basis of the Fahrenheit scale isn't terribly scientific because it's not repeatable. Depending on how much salt is placed in the freezing salt water solution, and whether or not the person whose body temperature is measured is sick with a fever, there will be different definitions of 0 and 96 Fahrenheit. Even if we standardize how much salt to place in the water, we are still limited by the variations in human body temperature.

Since the development of the Fahrenheit scale, it has been standardized such that temperature measurements using this scale are now repeatable and scientific. This allows meteorologists (and others) in the United States (one of the only countries in the world that continues to use this scale) to record temperatures in degrees Fahrenheit that are comparable from day to day and over time. While the Fahrenheit scale is admittedly useful as a temperature scale, as we tend to experience the full range of temperatures from zero to one hundred (particularly in varied climates), it was not created with a scientifically sound basis.

The Celsius scale was also developed in the 1700s. The cold end of the temperature scale is established by the freezing point of water at 1 atmosphere of pressure, and is called zero Celsius. (A photograph of a Celsius thermometer reading zero degrees in a bath of ice water is shown in Figure 6.5.3.) The hot end of the temperature scale is established by the boiling point of water at 1 atm of pressure, and is called one hundred Celsius. This means that there are 100 degrees between the cold and hot ends of the Celsius scale. (Note that the original Celsius scale was actually inverted such that 0 degrees indicated the boiling point of water, and 100 degrees indicated the freezing point of water.)

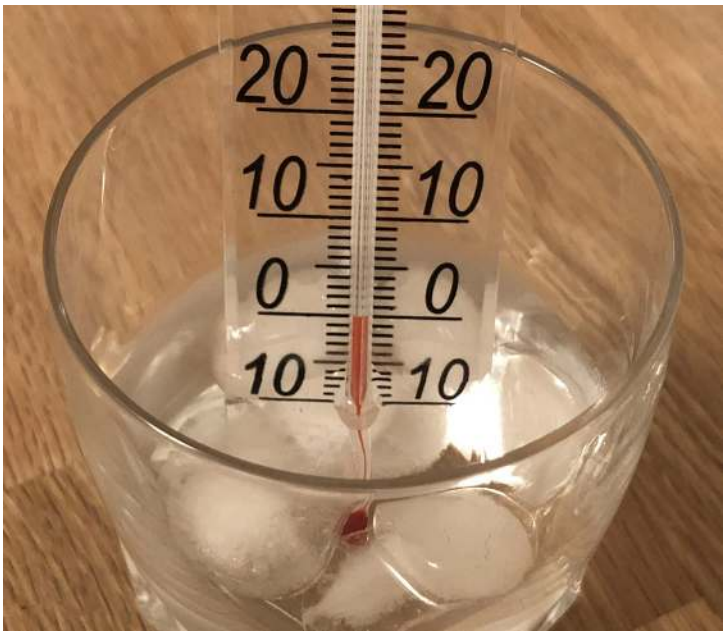


Figure 6.5.3 – A Celsius thermometer reads zero degrees as it is submerged in a container of ice water. Melting ice thermometer, by Ulflund, is licensed under CC0.

The selection of the cold and hot ends of the thermometer establishes the temperature scale and allows us to measure temperatures in between those two extremes. (We can also extrapolate to measure temperatures that are hotter or colder.) This is shown in Figure 6.5.4 .

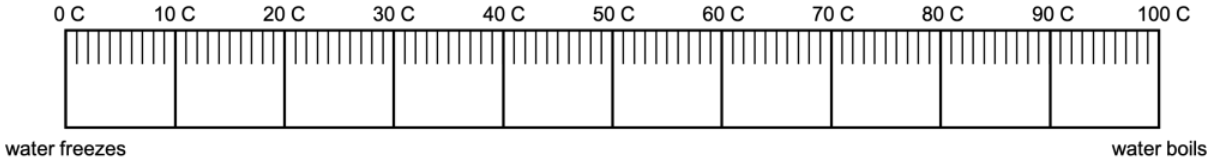


Figure 6.5.4 – The Celsius scale was developed by setting 0 as the freezing point of water at 1 atm and setting 100 as the boiling point of water at 1 atm. This created a total number of 100 degrees between hot and cold. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.

Celsius is a scientific scale because it's repeatable. As long as two (or more) scientists use pure water, and freeze and melt that water at one atmosphere of pressure, they will develop identical temperature scales. Because of this, Celsius is the scale that we will use, almost exclusively, to discuss temperature in this textbook.

Although we will not be using the Fahrenheit scale in this textbook, it is still useful to understand how to convert between the Fahrenheit and Celsius scales. To convert between scales, we need to know where the two scales overlap with each other, and how much of a change in one scale relates to a change in the other scale. On the first point: 0 ^{o}C is equal to 32 ^{o}F. On the second point: a change in 1 ^{o}C is equal to a change in 1.8 ^{o}F. (Note the use of the symbol ^{o}C to denote a Celsius degree, which is used to distinguish a change in temperature from a temperature value.) Therefore, to convert from degrees Celsius to degrees Fahrenheit, take the temperature in Celsius, multiply by 1.8, and add 32:

$$T_F = 1.8T_C + 32 \tag{6.5.1}$$

To convert from degrees Fahrenheit to degrees Celsius, take the temperature in Fahrenheit and subtract 32 from it. Multiply the result of that subtraction by five-ninths. The result is the temperature in degrees Celsius:

$$T_C = (T_F - 32) \times \frac{5}{9} \tag{6.5.2}$$

6.5.1.2: Thermometers

To measure temperature, a thermometer is used. How do thermometers work, and how are they designed?

In general, a thermometer exploits a thermometric property of a substance. A thermometric property is simply a property of the substance that varies with temperature. To achieve the best sensitivity for a thermometer, you want to choose a property that has a very large variation for small changes in temperature. Most analog thermometers (see, for example, Figure 6.5.5) contain a substance that will remain a liquid at all temperatures that the thermometer can reasonably be expected to experience. For example, in geographic regions with hot summers and cold winters, a thermometer would need to remain liquid between temperatures of roughly -20 ^{o}C and +40 ^{o}C. Modern thermometers are generally filled with dyed ethyl alcohol, which remains liquid between temperatures of -114 ^{o}C and +78 ^{o}C. (Previously, thermometers were filled with mercury, which remains liquid to much higher temperatures, but which is a hazardous toxic element.)



Figure 6.5.5 – An analog thermometer uses a liquid that will remain in liquid form throughout a wide temperature range. This thermometer uses red dyed alcohol. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.

Materials such as liquids will generally expand as they heat and contract as they cool. That is, the thermometric property used is the volume of the substance. This means that as the thermometer is placed in cooler temperatures, the level of liquid will fall. As the thermometer is placed in hotter temperatures, the level of liquid will rise. To calibrate the thermometer, it can be placed in freezing water to establish the 0 ^{o}C point, placed in boiling water to determine the 100 ^{o}C point, and then 99 gradations placed in between. To determine the temperature at any given time, the level of liquid inside the thermometer can be read, as after a time it will have risen or fallen to the level corresponding to the current temperature.

A digital thermometer (shown in Figure 6.5.6 , for example) has a device inside whose electrical properties are changed as a function of temperature. The thermometric property in this case of the resistivity of a semiconductor. The relationship between temperature and resistivity is well known. Therefore, by measuring the resistivity, the temperature can be determined. A microcontroller then converts that temperature into numbers and displays them on an LCD screen.



Figure 6.5.6 – *A digital thermometer uses the relationship between temperature and electrical properties to determine the temperature. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.*

6.5.2: **Heat**

Heat is energy that is transferred from one object to another in response to a difference in temperature. The symbol for heat is the uppercase letter Q. Calories (cal) are the unit for heat. Because heat is a form of energy, joules is another unit that can be used to express heat.

Heat only spontaneously flows from hot to cold, and never spontaneously flows in the opposite direction. To relate this to something more familiar, consider it to be similar to gravity. If a ball is placed at the top of a ramp, gravity will pull the ball downward, causing it to roll down the ramp. Once the ball reaches the bottom of the ramp, gravity will not pull it back up to the top again. The only way for the ball to reach the top of the ramp is for a person, animal, or machine to expend energy in physically moving it back to the top again. Going against gravity requires work.

In much the same way, working against the established flow of heat takes work. Maybe you use a refrigerator or air conditioner. These seem to work against the flow of heat from hot to cold. And they do, but it requires energy to do this. If you've paid an electrical bill during a hot summer month when running the air conditioner, you know it's not cheap to keep things cool. In other words, your refrigerator and air conditioner will not cool the regions you want unless you plug them in and turn them on!

The mechanisms through which heat can flow from one place to another will be the subject of the next chapter of this textbook.

6.5.3: **Specific heat capacity**

Specific heat capacity defines how difficult it is to change the temperature of a substance. (It can be thought of as "thermal inertia.") The symbol for specific heat capacity is the lowercase letter c. The unit is calories per gram degree Celsius (cal/(g°C)). Specific heat capacity describes how many calories of heat are required to increase (or decrease) the temperature of a certain mass of material by a certain amount.

The equation that relates heat, specific heat capacity, mass, and change in temperature is

$$Q = mc\Delta T \tag{6.5.3}$$

where Q is the heat (measured in calories), m is the mass (measured in grams), c is the specific heat capacity, and ΔT is the temperature change (measured in degrees Celsius).

It is important to note that this equation only works when the temperature of a substance changes, and cannot be used when an item changes phase, for example to calculate the heat required to boil water.

The specific heat capacity of water is 1 cal/(g°C). This means that 1 calorie of heat is required to raise the temperature of a single gram of water by one Celsius degree. (The calorie unit was actually defined on this basis; one calorie was equal to the amount of heat required to increase the temperature of one gram of water by one Celsius degree.) This may not seem like a lot, but water actually has one of the highest specific heat capacities of common substances. It makes water a very good candidate for use in cooling systems, because it can absorb a lot of heat without changing its temperature very much.

Definition: Large Calories and Small Calories

The unit of calorie may be familiar if you have looked at the nutrition label for food (such as the one shown in Figure 6.5.7). The unit of calorie used in food products does relate to the amount of heat required to raise the temperature of water by one Celsius degree, however, in this case, the amount of water is one kilogram, not one gram! These calories are known as "large calories," "food calories," or "kilogram calories" and are sometimes specifically spelled out as Calories with a capital C to distinguish them from the so-called small calorie described above.

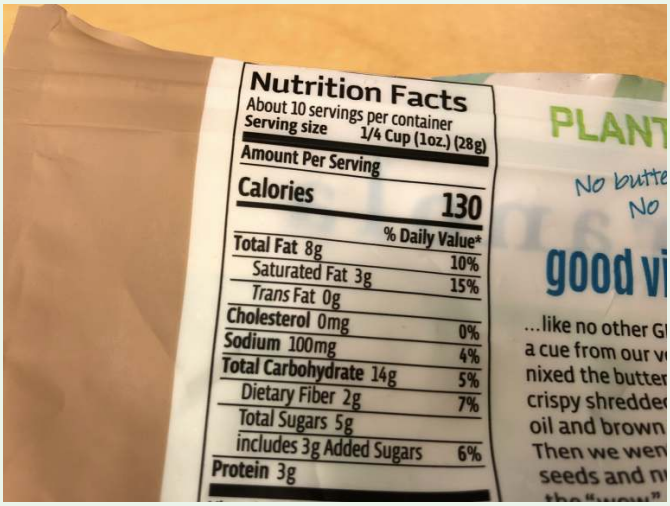


Figure 6.5.7 – A nutrition label indicates the calorie content of the food, which describes the amount of heat required to raise the temperature of one kilogram of water by one Celsius degree. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.

This fact also explains why the climate tends to be milder if you live near a large body of water. This could be an ocean, or even a large lake such as Lake Michigan. Because the water in an ocean or lake doesn't change its temperature easily, it means that the water will act as a moderating influence as the seasons change. This also explains why daily temperature fluctuations are much larger in the desert than they are in wetter climates. Humidity in the air acts as a moderating influence to keep temperatures from swinging to extremes between night and day. For example, Figure 6.5.8 shows the hourly temperature in Phoenix, AZ and Miami, FL on September 14, 2021. (Download this data [XLSX, 9 kB]) In Phoenix, a desert, the temperature demonstrates a much greater variation than in Miami, a much wetter climate.

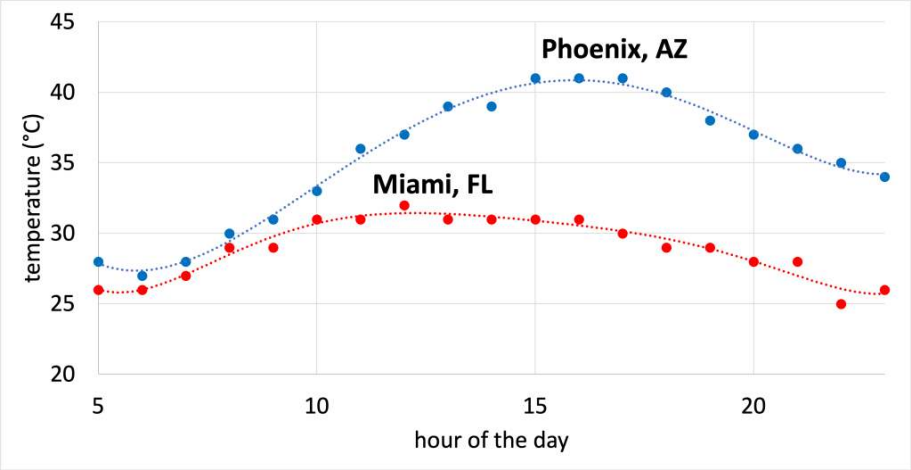


Figure 6.5.8 – *The temperature in Phoenix, AZ (a desert) demonstrates a much wider range of temperatures than the temperature in Miami, FL (a humid climate). This data was taken on September 14, 2021. This figure, created by Alyssa J. Pasquale, Ph.D., is licensed under CC BY-NC-SA 4.0.*

6.5.3.1: Temperature mixtures

When two substances at different initial temperatures are combined together, the hot substance will cool down and the cool substance will heat up until the two substances arrive at thermal equilibrium. At this point the temperature will remain constant. According to the law of conservation of energy, the energy that is lost by the hot substance will be completely transferred to the cool substance. (This assumes that no heat is lost to the surroundings.) In equation form,

$$-Q_{hot} = Q_{cold} \tag{6.5.4}$$

$$Q_{hot} + Q_{cold} = 0 \tag{6.5.5}$$

Unless the two substances are composed of the same material with identical specific heat capacities and have the same mass, while both substances will experience a temperature change, the magnitude of change in temperature of each substance may not be the same. (For example, if the hot substance cools down by 10 C^o, the cool object may not warm up by that same amount.) All other things being equal, a substance with a higher specific heat capacity will experience a smaller temperature change than a substance with a lower specific heat capacity.

To determine the final temperature of a mixture of two substances, the conservation of energy equation defined above can be substituted with $Q = mc\Delta T$ to calculate T_{final}. This equation is

$$T_{final} = \frac{m_h c_h T_{i,h} + m_c c_c T_{i,c}}{m_h c_h + m_c c_c} \tag{6.5.6}$$

In this equation, subscript i indicates initial conditions, h is for the initially hot substance, and c is for the initially cold substance. The final temperature should be somewhere in between the two initial starting temperatures. (This is a good "smell test" to use to determine if your final temperature calculation makes sense.)

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CHAPTER OVERVIEW

7: Non-Renewable Energy

7.1: Fossil Fuels
7.2: Coal
7.3: Oil
7.4: Natural Gas
7.5: Fossil Fuels and Greenhouse Gases
7.6: Nuclear Energy
7.7: Electric Power Generation
7.8: Appendix

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7.1: Fossil Fuels

Learning Objectives

- List specific examples of non-renewable energy sources
- Explain what makes an energy source non-renewable
- Describe the main types of fossil fuels and how they formed
- Explain the environmental impacts associated with exploration, extraction and use of the different types of fossil fuels
- Explain nuclear energy, how it works, its benefits and risks

Fossil fuels is the term given to energy sources with a high **hydrocarbon** content (see Chapter 1 for a review of hydrocarbon molecules) found in the Earth's crust that formed in the geologic past and can be burned to release their energy. They were formed from prehistoric plants and animals that lived hundreds of millions of years ago (100 – 500 million years ago). When these ancient living organisms died they were quickly buried and subjected to immense pressure from overlying earth materials including layers of mud, rock, sand, and sometimes surface water bodies such as oceans and lakes.

During the millions of years that passed, the dead plants and animals slowly decomposed in **anaerobic** (very low to no oxygen) conditions and their chemical energy became concentrated. The organic compounds that once made up tissues of these organisms were chemically changed under high pressures and temperatures. While some fossil fuels may be in the process of formation today, the amount of time required for usable quantities to form is measured in millions of years, so these fuels will never be available for us. Thus for all practical purposes we consider fossil fuels to be finite and **non-renewable**.

7.1.1: Fossil Fuel Types and Formation

There are three main types of fossil fuels – natural gas, oil, and coal – and the specific type formed depends on the combination of organic matter that was present, how long it was buried and what temperature and pressure conditions existed when they were decomposing. **Oil** and **natural gas** were created from organisms that lived in water and were buried under ocean or river sediments. Long after the great prehistoric seas and rivers vanished, heat, pressure, and bacteria combined to compress and transform the organic material under layers of silt or shale rock (Figure 7.1.1). In most areas, a thick liquid called oil formed first, but in deeper, hot regions underground, the transformation process continued until natural gas was formed. Over time, some of this oil and natural gas began working its way upward through the earth's crust until they ran into rock formations called "**caprocks**" that are dense enough to prevent them from seeping to the surface. It is from under these caprocks that most oil and natural gas is retrieved today.

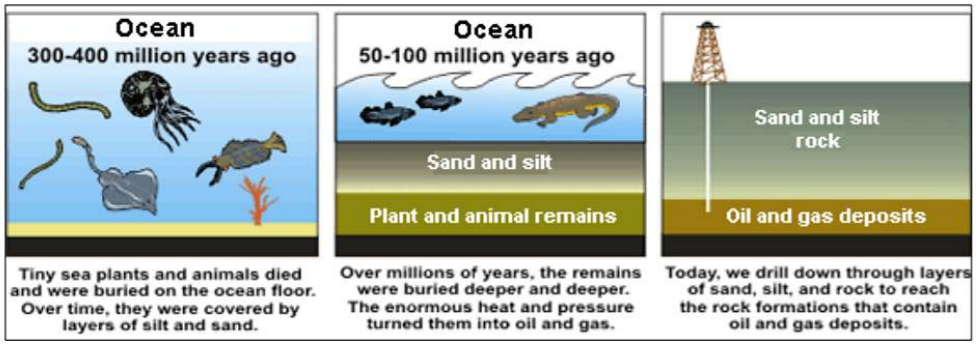


Figure 7.1.1: Oil and natural gas (petroleum) formation. Source: U.S. Energy Information Administration. http://www.eia.gov/energyexplained/i...tural_gas_home

Coal is a fossil fuel that formed from the remains of trees, ferns, and other plants that lived 300 to 400 million years ago (Figure 7.1.2). In some areas, such as portions of what is now the eastern United States, coal was formed from swamps covered by sea water. The sea water contained a large amount of sulfur, and as the seas dried up, the sulfur was left behind in the coal. Scientists are working on ways to take the sulfur out of coal because when coal burns, the sulfur is released in to the atmosphere as an air pollutant (see Chapter 6). Some coal deposits, however, were formed from freshwater swamps which had very little sulfur in them. These coal deposits, located largely in the western part of the United States, have much less sulfur in them.

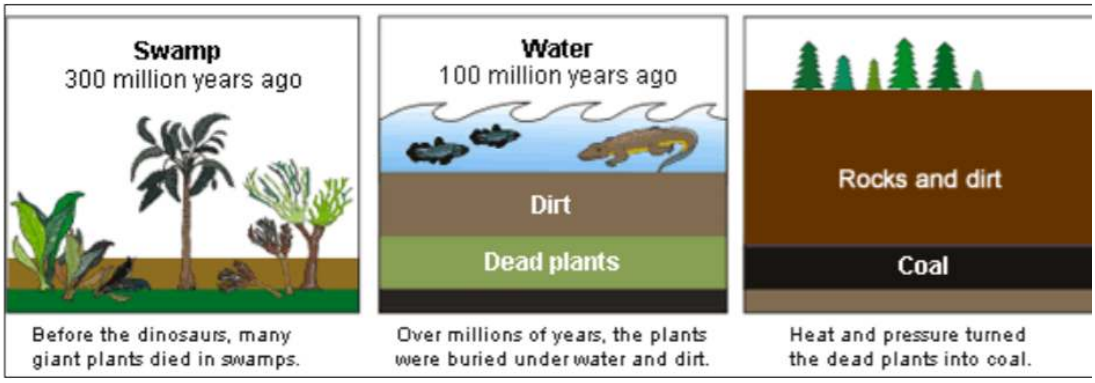


Figure 7.1.2: The process of coal formation. Source: U.S. Energy Information Administration.

7.1.2: Consumption

Historically, human prosperity has been directly correlated with energy use. The health and vitality of world societies critically depends on energy, most of which comes from fossil fuels (Figure 7.1.3). Energy resources, however, are unevenly distributed throughout the world, and so are the consumption rates. Developed regions generally consume far more energy than the developing regions. For example, the United States has only about 5% of the world's population but constitutes over 20% of the world's energy consumption. Additionally, developing countries devote a larger proportion of energy consumption to subsistence activities such as growing and preparing food, and heating homes. Industrialized nations rely more on mechanized equipment and technology and, therefore, a greater proportion of their energy consumption goes to transportation and industry.

Fossil fuels can be utilized without being converted or transformed to another form of energy, this is referred to as **primary energy** consumption. In their primary form, fossil fuels can be used for transportation, heating and cooking, or used to generate electricity. The use of **electricity** is a form of **secondary energy** consumption. Transforming fossil fuel energy into electricity allows for easier transportation over long distances and application to a variety of uses. Additionally, there are four major sectors that consume energy: 1) The industrial sector which includes facilities and equipment used for manufacturing, agriculture, mining, and construction; 2) The transportation sector includes vehicles that transport people or goods including cars, trucks, buses, motorcycles, trains, aircraft, boats, barges, and ships; 3) The residential sector consists of homes and apartments; 4) The commercial sector includes offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, places of worship, and more. Each of these sectors also consumes electricity produced by the electric power sector.

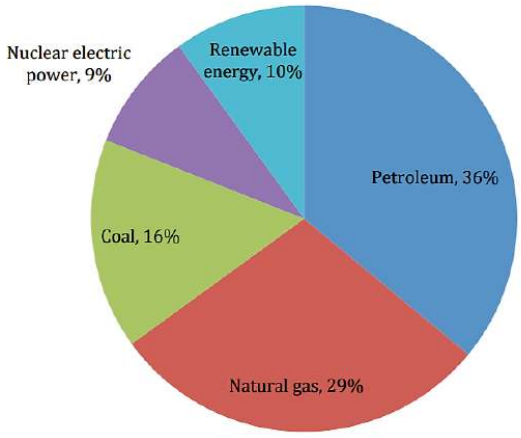


Figure 7.1.3: U.S. primary energy consumption by source (all sectors), 2015, showing that about 80 % of our energy consumption comes from fossil fuels. Data from U.S. Energy Information Administration, April 2016.

Another perspective is to look at how energy consumption has changed over time. In Figure 7.1.4 the world's energy use is shown from 1800 to present. Pre-1900 era was powered by biomass (wood burning, for example). It is clear that early in the 20th century fossil fuels became the dominant primary energy sources. Alternative energy sources such as nuclear and hydro began their climb after 1950. Not until around the year 2000 do we see renewables such as wind and solar emerge.

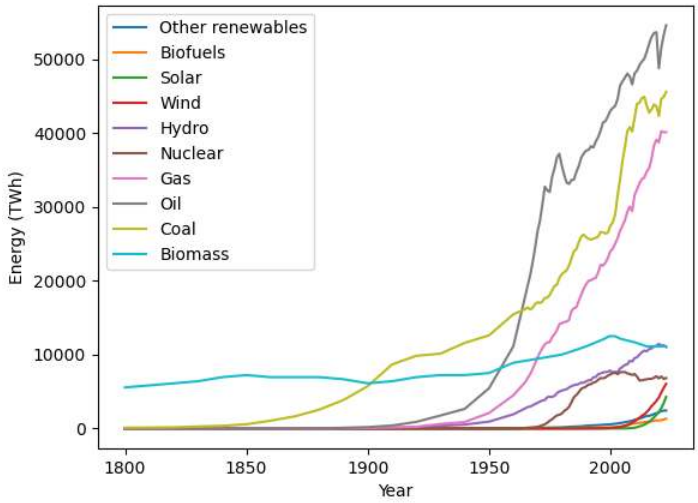


Figure 7.1.4: World primary energy consumption by source since 1800, showing the rise in fossil fuels beginning in the early 20th century. Data from U.S. Energy Information Administration, 2023.

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7.2: Coal

Coal is a combustible black or brownish-black sedimentary rock with a high amount of carbon and hydrocarbons. Coal is classified into four main types, or ranks depending on the types and amounts of carbon present and on the amount of heat energy the coal can produce, including anthracite, bituminous, subbituminous, and lignite (highest to lowest ranked, pictured in Figure 7.2.1). For us to use the potential energy stored in coal, it first must be mined from the ground. This process in itself uses a great deal of resources and has its own environmental impacts. Coal then typically undergoes processing to make it suitable for use in **coal-fire power plants**. Finally, the processed coal is burned in these power plants, and the kinetic energy released from its combustion is harnessed for electricity generation or other purposes. We will investigate each of these steps individually below.

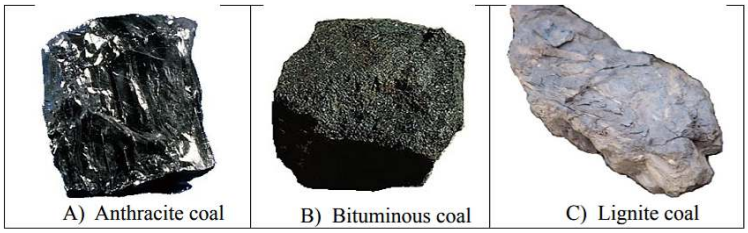


Figure 7.2.1: Different types of coal. Images obtained from Wikimedia Commons.

7.2.1: Coal Mining and Processing, and Electricity Generation

There are two primary methods of coal mining: **strip mining** and **underground mining**. Strip-, or surface-, mining uses large machines to remove the soil and layers of rock known as **overburden** to expose coal seams. It is typically used when the coal is less than 200 feet underground. **Mountaintop removal** is a form of surface mining where the tops of mountains are blasted with dynamite and removed to access coal seams. After the mining is finished, the disturbed area can be re-covered with topsoil, and the area is replanted. However, the topography of the mountain is permanently altered.

Underground mining, sometimes called deep mining, is used when the coal is several hundred feet below the surface. Some underground mines are thousands of feet deep, and extend for miles. Miners ride elevators down deep mine shafts and travel on small trains in long tunnels to get to the coal. The miners use large machines that dig out the coal.

Once mined, coal may go to a preparation plant located near the mining site where it is cleaned and processed to remove impurities such as rocks and dirt, ash, sulfur, and other unwanted materials. This process increases the amount of energy that can be obtained from a unit of coal, known as its **heating value**.

Finally, the mined and processed coal must be transported. Transportation can be more expensive than mining the coal. Nearly 70% of coal delivered in the United States is transported, for at least part of its trip, by train. Coal can also be transported by barge, ship, or truck. Coal can also be crushed, mixed with water, and sent through a slurry **pipeline**. Sometimes, coal-fired electric power plants are built near coal mines to lower transportation costs.

Once at the power plant, coal is first pulverized into a fine powder then mixed with hot air and blown into a **furnace**, allowing for the most complete combustion and maximum heat possible. Purified water, pumped through pipes inside a **boiler**, is turned into steam by the heat from the combustion of coal. The high pressure of the steam pushing against a series of giant **turbine** blades turns the turbine shaft. The turbine shaft is connected to the shaft of the **generator**, where magnets spin within wire coils to produce electricity. After doing its work in the turbine, the steam is drawn into a **condenser**, a large chamber in the basement of the power plant. In this important step, millions of gallons of cool water from a nearby source (such as a river or lake) are pumped through a network of tubes running through the condenser. The cool water in the tubes converts the steam back into water that can be used over and over again in the plant. The cooling water is returned to its source without any contamination except at a higher temperature than when first extracted from the river or lake. Figure 7.2.2 below is a schematic diagram showing a typical layout of a coal-fire power plant. You can also watch a short video of a virtual tour of a coal power plant at the URL provided below.

Coal Power Plant Virtual Tour Video https://www.youtube.com/watch?v=2IKECt4Y3RI

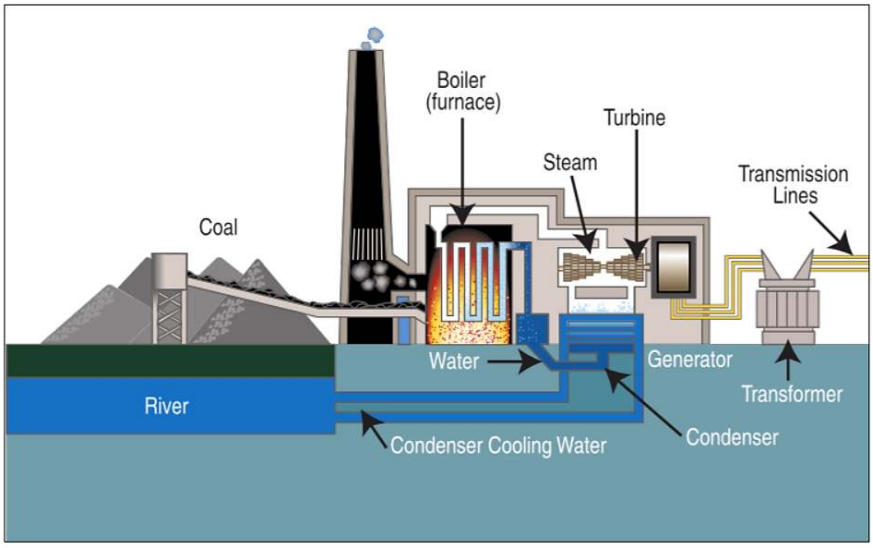


Figure 7.2.2: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Image by US Tennessee Valley Authority – Public domain. www.tva.com

7.2.2: Impacts of coal mining and burning

7.2.2.1: Impacts of coal mining on the environment

A majority of the coal mined in the United States (about 66%) is from surface, or strip mines which leave highly visible impacts at the surface. Strip mining operations generally involve removing soils, rock, and other material to access shallow deposits of coal and therefore leave permanent scars on the landscape. It also involves the destruction of substantial amounts of forests and other ecosystems, destroying natural habitats and threatening biodiversity.

Mountaintop removal, the extreme form of strip mining, has affected large areas of the Appalachian Mountains in West Virginia and Kentucky. The tops of mountains are removed using a combination of explosives and mining equipment and the material is deposited into nearby valleys. This technique not only alters the landscape (Figure 7.2.3) but affects the health and quality of nearby streams by depositing rocks, dirt, and pollutants that can harm aquatic wildlife. While mountaintop removal mining has existed since the 1970s, its use became more widespread and controversial beginning in the 1990s. U.S. laws require that dust and water runoff from areas affected by coal mining operations be controlled, and that the area be **reclaimed**, and returned to close to its original condition.



Figure 7.2.3: A) Strip mine for lignite coal at Garzweiler near Koln, Germany. Image from Wikimedia commons https://commons.wikimedia.org/wiki/F...strip.mine.jpg B) Mountaintop removal in Eunice WV, photo by Roston, obtained from https://commons.wikimedia.org/wiki/F...niceblast3.JPG

One of the largest environmental impacts of underground mining may be the **methane** gas that must be vented out of mines to make the mines a safe place to work. Methane is a **greenhouse gas**, meaning that it enhances the greenhouse effect naturally occurring in our atmosphere, and contributes to global warming and global climate change. Its global warming potential, or relative capacity to produce the greenhouse effect, is higher than that of carbon dioxide (see chapter 7). Other impacts of underground

mining include ground collapse above mine tunnels and draining of acidic water from abandoned mines into nearby streams. Acidic water lowers the pH (resulting in increased **acidity**), which is detrimental to aquatic organisms. This **acid mine drainage** is an environmental impact associated with both underground mining and strip mining.

7.2.2.2: Impacts of coal burning on the environment and human health

In the United States and most of the world, most of the coal consumed is used as a fuel to generate electricity. Burning coal produces emissions such as **sulfur dioxide** (SO_2) and **nitrogen oxides** (NO_x) that are associated with acid rain (more on this in chapter 6). **Carbon dioxide** (CO_2), another emission resulting from burning coal, is a major greenhouse gas that is associated with global warming (see chapter 7).

Ash (including fly ash and bottom ash) is a residue created when coal is burned at power plants. In the past, fly ash was released into the air through the smokestack, where it would contribute to **particulate matter** air pollution (see chapter 6). Laws now require that much of the fly ash now must be be captured by pollution control devices, like scrubbers. In the United States, fly ash is generally stored at coal power plants or placed in landfills. Pollution leaching from ash storage and landfills into groundwater and the rupture of several large impoundments of ash are environmental concerns.

Burning coal produces emissions that also impact human health. Emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulates contribute to respiratory illnesses. Particulates also contribute to a condition among coal miners and other coal workers known as coal workers' pneumoconiosis (CWP) or black lung disease, which results from long exposure to coal dust. Inhaled coal dust progressively builds up in the lungs and is unable to be removed by the body; this leads to inflammation, fibrosis, and in worse cases, tissue death (necrosis).

Coal is the largest source of **mercury** and also a source of other **heavy metals**, many of which have been linked to both neurological and developmental problems in humans and other animals. Mercury concentrations in the air usually are low and of little direct concern. However, when mercury enters water, either directly or through deposition from the air, biological processes transform it into **methylmercury**, a highly toxic chemical that accumulates in fish and the animals (including humans) that eat fish.

7.2.3: Reducing the environmental impacts of coal use

Regulations such as the **Clean Air Act** and the **Clean Water Act** require industries to reduce pollutants released into the air and water. Below are some actions that have been taken to reduce the negative impacts of coal on human and environmental health:

- **Clean coal technology**: Industry has found several ways to reduce sulfur, NO_x, and other impurities from coal before burning.
- Coal consumers have shifted toward greater use of low sulfur coal.
- Power plants use **scrubbers**, to clean SO_2, NO_x, particulate matter, and mercury from the smoke before it leaves their smokestacks. In addition, industry and the U.S. government have cooperated to develop technologies that make coal more energy-efficient so less needs to be burned.
- Research is underway to address emissions of carbon dioxide from coal combustion. **Carbon capture & sequestration** separates CO_2 from emissions sources and recovers it in a concentrated stream. The CO_2 can then be sequestered, which puts CO_2 into storage, possibly underground, where it will remain permanently (see chapter 7)
- Reuse and recycling can also reduce coal's environmental impact. Land that was previously used for coal mining can be reclaimed and used for airports, landfills, and golf courses. Waste products captured by scrubbers can be used to produce products like cement and synthetic gypsum for wallboard.

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7.3: Oil

Petroleum Oil is currently the most widely used fossil fuel and accounts for about one third of global energy consumption. Unlike coal, which is primarily used as a fuel for electricity generation, oil is primarily used as a fuel for **transportation**. Oil is also used to manufacture plastics and other synthetic compounds ubiquitous to our everyday life. **Crude** (unprocessed) oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the oil.

Oil is made up of hydrocarbons which are molecules that contain hydrogen and carbon in various lengths and structures, from straight chains to branching chains to rings. Hydrocarbons contain a lot of energy and many of the things derived from crude oil like gasoline, diesel fuel, paraffin wax and so on take advantage of this energy.

4.4.1: Extraction

Oil is mainly obtained by drilling either on land (**onshore**) or in the ocean (**offshore**). Early offshore drilling was generally limited to areas where the water was less than 300 feet deep. Oil and natural gas drilling rigs now operate in water as deep as two miles. Floating platforms are used for drilling in deeper waters. These self-propelled vessels are attached to the ocean floor using large cables and anchors. Wells are drilled from these platforms which are also used to lower production equipment to the ocean floor. Some drilling platforms stand on stilt-like legs that are embedded in the ocean floor. These platforms hold all required drilling equipment as well as housing and storage areas for the work crews.

Offshore oil producers are required to take precautions to prevent pollution, spills, and significant changes to the ocean environment. Offshore rigs are designed to withstand hurricanes. Offshore production is much more expensive than land-based production. When offshore oil wells are no longer productive enough to be economical, they are sealed and abandoned according to applicable regulations.

4.4.2: Processing and Refining

When extracted, crude oil consists of many types of hydrocarbons as well as some unwanted substances such as sulfur, nitrogen, oxygen, dissolved metals, and water all mixed together. Unprocessed crude oil is therefore, not generally useful in industrial applications and must first be separated into different useable products at a **refinery** (Figure 7.3.1). All refineries perform three basic steps: separation, conversion, and treatment in the processing and refining of crude oil.



Figure 7.3.1: Tesoro Corporation Oil Refinery in Anacortes, Washington. Photo by Walter Siegmund. https://commons.wikimedia.org/wiki/O...nery_31904.JPG

During **separation**, the various products (hydrocarbons) are separated in to different components (called *fractions*), by taking advantage of the differences in boiling temperature of the components. This process is called *fractional distillation* and involves heating up the crude, letting it vaporize and then condensing the vapor. The lightest components have the lowest boiling temperature and rise to the top while the heaviest which also have the highest boiling temperature remain at the bottom.

Conversion is the chemical processing in which some of the fractions are transformed in to other products, for example, a refinery can turn diesel fuel into gasoline depending on the demand for gasoline. Conversion can involve breaking larger hydrocarbon chains into smaller ones (cracking), combining smaller chains into larger ones (unification) or rearranging the molecules to created desired products (alteration).

Treatment is done to the fractions to remove impurities such as sulfur, nitrogen and water among others. Refineries also combine the various fractions (processed and unprocessed) into mixtures to make desired products. For example, different mixtures of hydrocarbon chains can create gasolines with different octane ratings, with and without additives, lubricating oils of various weights and grades (e.g., WD-40, 10W-40, 5W-30, etc.), heating oil and many others. The products are stored on-site until they can be delivered to various markets such as gas stations, airports and chemical plants.

A 42 U.S. gallon barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. This increase in volume is similar to what happens to popcorn when it is popped. Gasoline makes up the largest fraction of all petroleum products obtained (Figure 7.3.2). Other products include diesel fuel and heating oil, jet fuel, petrochemical feedstocks, waxes, lubricating oils, and asphalt.

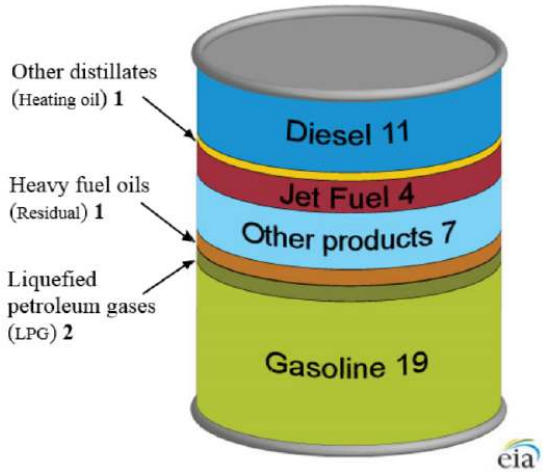


Figure 7.3.2: Main products (measured in gallons) made from a barrel of crude oil, 2013. Source: U.S. Energy information administration http://www.eia.gov/energyexplained/i...?page=oil_home

4.4.3: Fracking for oil

Hydraulic fracturing, informally referred to as "fracking," is an oil well development process that typically involves injecting water, sand, and chemicals under high pressure into a bedrock formation via the well. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. Hydraulic fracturing is a well-stimulation technique used commonly in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil flow to a well from petroleum-bearing rock formations (Figure 7.3.3).

Energy development often requires substantial amounts of water, and hydraulic fracturing is no exception. Water is needed not only for the traditional drilling process, but also for the actual fracturing as well. Water is first mixed with chemicals and fine sands, then pumped at extremely high pressure into the shale rock to fracture it, forming pathways for the oil and gas to reach the well. The water is then recovered, along with the oil and gas.

There are concerns regarding the potential contamination of fresh groundwater resources from oil and gas extraction wells that use hydraulic fracturing; either from the petroleum resource being produced or from the chemicals introduced in the fracturing process. Fracking fluid flowback – the fluid pumped out of the well and separated from oil and gas – not only contains the chemical additives used in the drilling process but also contains heavy metals, radioactive materials, **volatile organic compounds** (VOCs) and hazardous air pollutants such as benzene, toluene, ethylbenzene and xylene. In some cases, this contaminated water is sent to water treatment plants that are not equipped to deal with some of these classes of contamination.

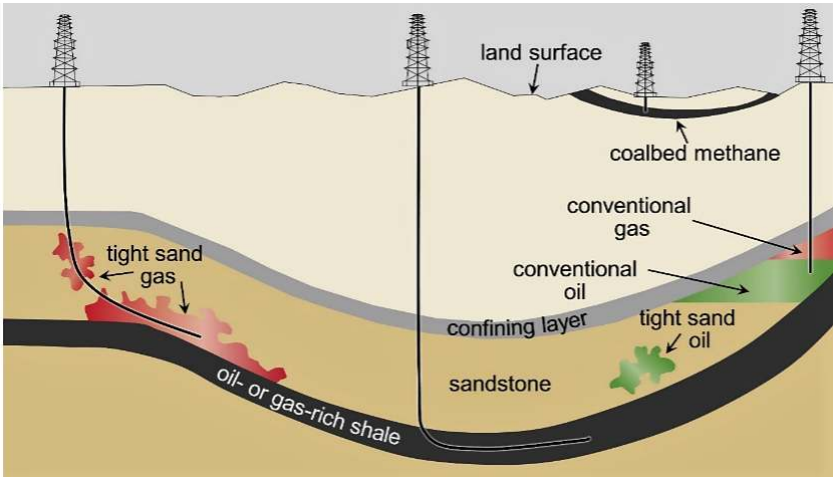


Figure 7.3.3: Schematic cross-section of general types of oil and gas resources and the orientations of production wells used in hydraulic fracturing. Source: US EPA (Public Domain)

4.4.4: Environmental Impacts of Oil

Burning petroleum oil products releases emission such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate material all of which are air pollutants that impact the environment as well as human health (see more on air pollution in Chapter 6). Petroleum also emits carbon dioxide which is a greenhouse gas Exploring and drilling for oil may disturb land and ocean habitats. On land, extensive infrastructure such as road networks, transport pipelines and housing for workers are needed to support a full-scale drilling operation. These can pollute soil and water, fragment habitats, and disturb wildlife.

Human-caused **oil spills** in rivers and oceans harm ecosystems. Natural oil seepages do occur and may be a significant source of oil that enters the environment globally, but they are slow, small, and spread out over large areas, and the ecosystem has adapted to them. Spills from tankers or well spills have more catastrophic impacts. The quantity of oil spilled during accidents has ranged from a few hundred tons to several hundred thousand tons but even small spills have been shown to have a great impact on ecosystems.

Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin oil slick which can cover beaches with a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill site before most of the oil escapes, and land animals can avoid the oil more easily. The amount of oil spilled from ships dropped significantly during the 1990s partly because new ships were required to have a double-hull lining to protect against spills.

Leaks also happen when we use petroleum products on land. For example, gasoline sometimes drips onto the ground when people are filling their gas tanks, when motor oil gets thrown away after an oil change, or when fuel escapes from a leaky storage tank. When it rains, the spilled products get washed into the gutter and eventually flow to rivers and into the ocean. Another way that oil sometimes gets into water is when fuel is leaked from motorboats and jet skis.

When a leak in a storage tank or pipeline occurs, petroleum products can also get into the ground, and the ground must be cleaned up. To prevent leaks from underground storage tanks, all buried tanks are supposed to be replaced by tanks with a double lining.

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7.4: Natural Gas

4.5.1: Introduction

Crude oil is frequently found in reservoirs along with natural gas. In the past, natural gas was either burned or allowed to escape into the atmosphere. Now, technology has been developed to capture the natural gas and either reinject it into the well or compress it into **liquid natural gas** (LNG).

Natural gas is predominately composed of methane (CH_4). Some of the gases that are produced along with methane, such as butane and propane (by-products), are separated and cleaned at a gas processing plant. The by-products, once removed, are used in a number of ways. For example, propane can be used for cooking on gas grills. Natural gas withdrawn from a well may contain liquid hydrocarbons and nonhydrocarbon gases. This is called "wet" natural gas. The natural gas is separated from these components near the site of the well or at a processing plant. The gas is then considered "dry" and is sent through pipelines to a local distribution company, and, ultimately, to the consumer.

Most of the natural gas consumed in the United States is produced in the United States. Some is imported from Canada and shipped to the United States in pipelines. A small amount of natural gas is shipped to the United States as LNG. We can also use machines called **digesters** that turn today's organic material (plants, animal wastes, etc.) into natural gas through the process of anaerobic decomposition. This process replaces waiting for millions of years for the gas to form naturally. The natural gas produced by these digesters is not a fossil fuel, but is rather a renewable source of bioenergy (see chapter 5).

4.5.2: Fracking for Gas

Conventional natural gas is found in permeable reservoirs, typically composed of sandstone or limestone, where extraction is relatively straightforward because the gas generally flows freely. Unconventional gas is found in rocks with extremely low permeability, which makes extracting it much more difficult. Such gas is extracted by employing so-called “unconventional” techniques such as hydraulic fracturing (fracking), which has been in use since the late 1940s. In recent decades, fracking technology has greatly improved, and its use has been expanded. The process of fracking for gas is very similar to that of fracking for oil, and the environmental impacts are similar also.

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7.5: Fossil Fuels and Greenhouse Gases

Fossil fuels are made up mainly of hydrogen and carbon. When burned, the carbon combines with oxygen to create carbon dioxide (CO_2). The amount of CO_2 produced depends on the carbon content of the fuel. For example, for the same amount of energy produced, natural gas produces about half and petroleum produces about three-fourths of the amount of CO_2 produced by coal. Energy-related CO_2 emissions, resulting from the combustion of coal, petroleum, and natural gas, account for about 80% of total U.S. human-caused (anthropogenic) greenhouse gas (GHG) emissions. There are many sources of non-energy CO_2 emissions, but those emissions account for a relatively small share of total GHG emissions. See chapter 7 for a discussion of the results of GHG emissions.

Energy use is largely driven by economic growth and by weather patterns that affect heating and cooling needs. The fuels used in electricity generation also have an impact on the amount of GHG emissions. In the United States, most of the electricity generated comes from coal power plants and consequently, the majority of the carbon dioxide emission resulting from electricity generation is from coal combustion (Figure 7.5.1). Although the industrial sector is the largest consumer of energy (including direct fuel use and purchased electricity), the transportation sector emits more carbon dioxide because of its near complete dependence on petroleum fuels. The residential and commercial sectors have lower emission levels (most of which comes from fossil energy combustion to produce electricity) than the transportation and industry sectors.

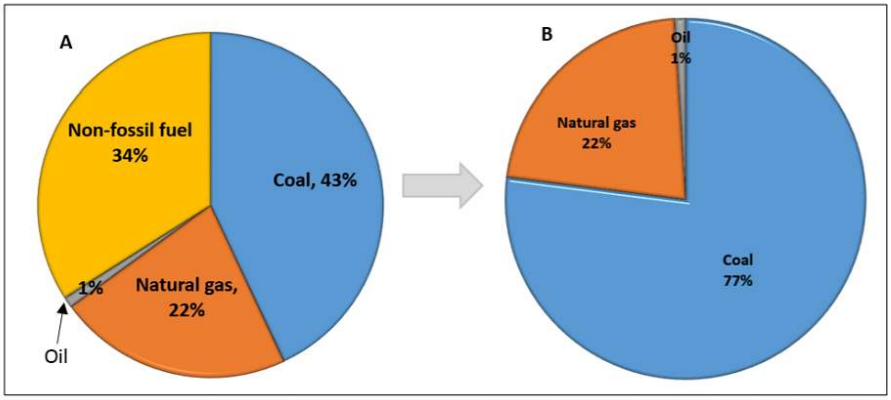


Figure 7.5.1: *A) Major fuel/energy sources for U.S. electricity generation, 2013. B) Resulting carbon dioxide emissions from electricity generation by fuel type, 2013. Based on data from U.S. Energy Information Administration*

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7.6: Nuclear Energy

Nuclear energy is energy in the **nucleus** (core) of an atom (see chapter 1 for a review of atomic structure). There is enormous energy in the forces that hold protons and neutrons in the nucleus together. Energy is released when those forces are broken. Nuclear energy can be released from atoms by splitting apart the nucleus of an atom to form smaller atoms, a process known as **nuclear fission**. During nuclear fission, a small atomic particle called a **neutron** hits the uranium atom and splits it, releasing a great amount of energy in the form of heat and **radiation**. More neutrons are also released when the uranium atom splits. These neutrons go on to bombard other uranium atoms, and the process repeats itself over and over again. This is called a **chain reaction** (Figure 7.6.1). Nuclear power plants use the energy from nuclear fission to produce electricity.

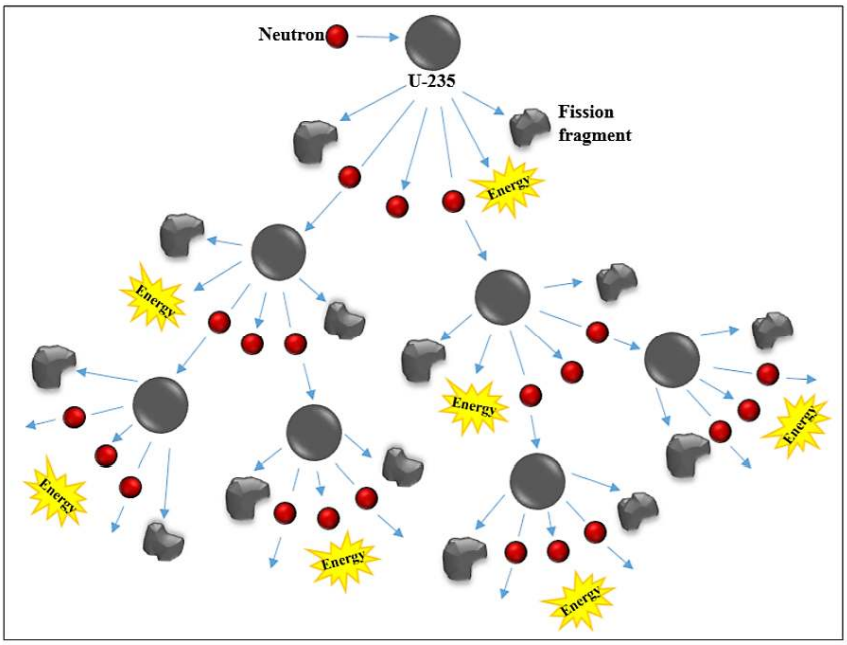


Figure 7.6.1**:** *Fission chain reaction – begins when a neutron bombards a U-235 atom, splitting it into two fission fragments, along with more neutrons and energy. The neutrons bombard other uranium atoms releasing more energy and more neutrons and the reaction continues.*

7.6.1: Nuclear fuel processing

Uranium is a naturally occurring radioactive element that decays into daughter isotopes (see chapter 1 for a review of isotopes), releasing radiation energy in the process. There are three naturally occurring isotopes of uranium almost all (99.27 %) of which is uranium-238 (U238); the remainder consists of U-235 (0.72 %) and U-234 (0.006 %). **U-235** is the preferred nuclear fuel because when its atoms are split (fissioned), they not only emit heat and high energy radiation but also enough neutrons to maintain a chain reaction and provide energy to power a nuclear power plant. Uranium is found in rocks all over the world but is relatively rare and the supply is finite making it a nonrenewable energy source.

Uranium usually occurs in combination with small amounts of other elements and once it is mined, the U-235 must be extracted and processed before it can be used as a fuel in a nuclear power plant to generate electricity. The process begins with **exploration** for uranium and the development of mines to extract the discovered **ore** (ore refers to rock that contains minerals of economic importance). Mining is either conventional (underground or open pit) or unconventional, such as in-place solution mining or heap leaching, which use liquid solvents to dissolve and extract the ore. Mined uranium ore (Figure 7.6.2A) typically yields one to four pounds of uranium concentrate per ton of uranium ore (0.05% to 0.20%).

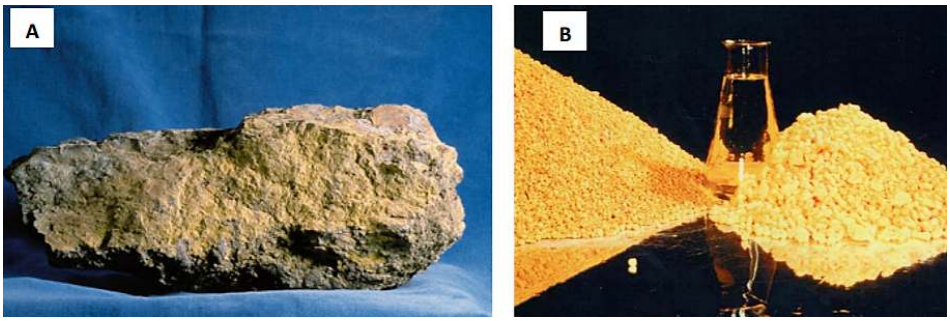


Figure 7.6.2*: A) Uranium ore B) Yellowcake (U_3O_8). Images obtained from United States Geological Survey (A) and United States Department of Energy (B).*

Uranium ore from a conventional mine is usually refined into uranium concentrate in a process referred to as **milling**. The ore is crushed and ground into fine powder that is then reacted with chemicals to separate the uranium from other minerals. The concentrated uranium product is typically a bright yellow or orange powder called yellowcake (U_3O_8) (Figure 7.6.2B), and the waste stream from these operations is called mill tailings. Uranium ore in solution is also milled into yellowcake by retrieving the uranium out of the solution and concentrating it.

The yellowcake then undergoes **conversion** into uranium hexafluoride (UF_6) gas. This step enables the atomic segregation of the three naturally occurring uranium isotopes in to individual components. In the UF6 gas, the original concentrations of uranium isotopes are still unchanged. This gas is then sent to an **enrichment** plant where the isotope separation takes place and the concentration of U-235 is increased to about a 4% to 5% (compared to 0.72 % original concentration). The product, called *enriched* UF_6 is sealed in canisters and allowed to cool and solidify before it is transported to a fuel assembly plant.

The next step in the production of nuclear fuel takes place at fuel **fabrication** facilities. Here, the enriched UF_6 gas is reacted to form a black uranium dioxide (UO_2) powder. The powder is then compressed and formed into the shape of small ceramic fuel pellets (Figure 7.6.3A). Each ceramic pellet produces roughly the same amount of energy as 150 gallons of oil. The pellets are stacked and sealed into long metal tubes that are about 1 centimeter in diameter to form **fuel rods**. (Figure 7.6.3B) fuel rods are then bundled together to make up a fuel assembly (Figure 7.6.3C). Depending on the reactor type, there are about 179 to 264 fuel rods in each fuel assembly. A typical reactor core holds 121 to 193 fuel assemblies.

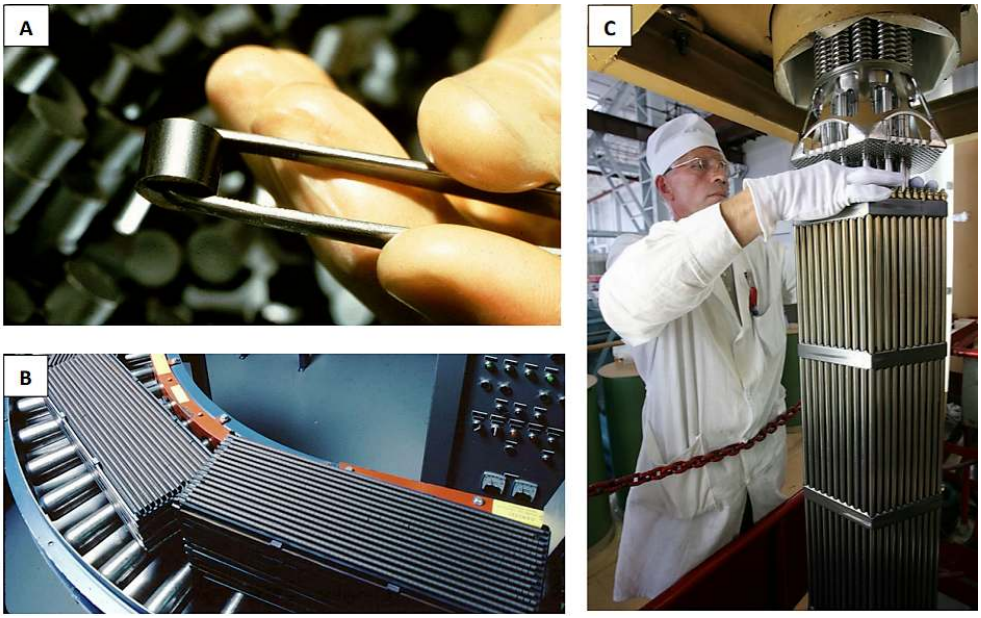


Figure 7.6.3*: Fuel fabrication process. A) Uranium dioxide powder compressed into fuel pellets. B) Fuel pellets stacked and sealed in metal tubes forming fuel rods. C) Fuel rods are bundled into a fuel assembly. Images A and B from NRC (public domain); C from RIA Novosti archive, image #132602 / Ruslan Krivobok / CC-BY-SA 3.0*

7.6.2: Nuclear Power Plant

After fabrication, fuel assemblies are transported to nuclear power plants where they are used as a source of energy for generating electricity. They are stored onsite until they are needed by the reactor operators. At this stage, the uranium is only mildly radioactive, and essentially all radiation is contained within the metal tubes. When needed, the fuel is loaded into a reactor core (Figure 7.6.4). Typically, about one third of the reactor core (40 to 90 fuel assemblies) is changed out every 12 to 24 months.

The most common type of reactors are the **pressurized water reactors** (PWR) (Figure 7.6.4) in which water is pumped through the reactor core and heated by the fission process. The water is kept under high pressure inside the reactor so it does not boil. The heated water from the reactor passes through tubes inside the steam generator where the heat is transferred to water flowing around the tubes in the steam generator. The water in the steam generator boils and turns to steam. The steam is piped to the turbines. The force of the expanding steam drives the turbines, which spin a magnet in coil of wire – the generator– to produce electricity.

After passing through the turbines, the steam is converted back to water by circulating it around tubes carrying cooling water in the condenser. The condensed steam – now water – is returned to the steam generators to repeat the cycle.

The three water systems (condenser, steam generator, and reactor) are separate from each other and are not permitted to mix. Water in the reactor is radioactive and is contained within the containment structure whereas water in the steam generator and condenser is nonradioactive.

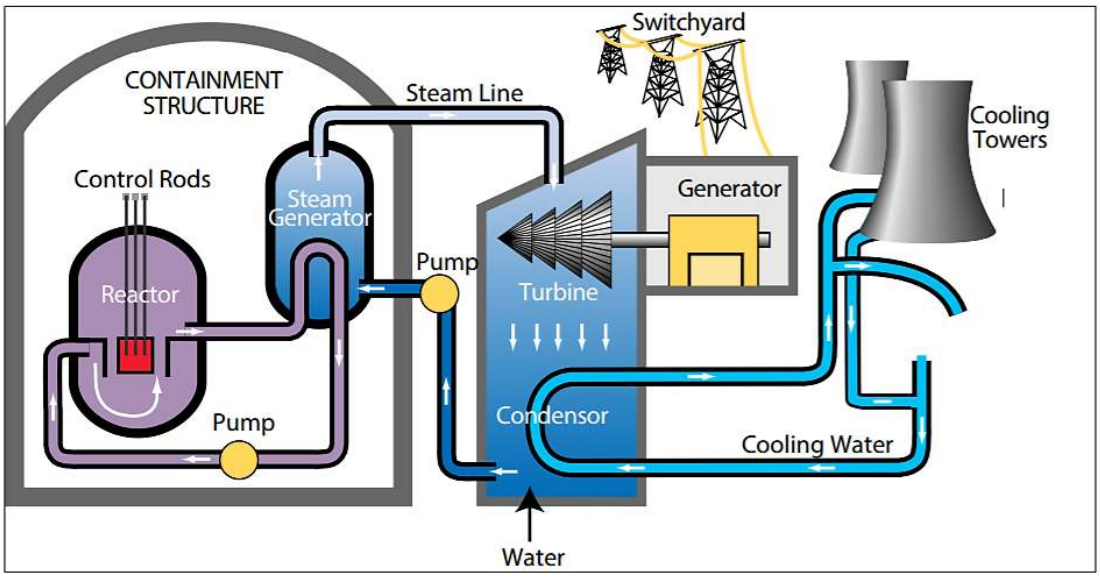


Figure 7.6.4: *A schematic diagram of a pressurized water reactor (PWR), the most common type of nuclear reactor. Diagram from Tennessee Valley Authority (public domain). www.tva.com*

7.6.3: Benefits of Nuclear Energy

By using fission, nuclear power plants generate electricity without emitting air pollutants like those emitted by fossil fuel-fired power plants. This means that financial costs related to chronic health problems caused by air pollutants such as particulate material, carbon monoxide, nitrogen oxides and ozone among others are significantly reduced. In addition nuclear reactors do not produce carbon dioxide while operating which means that nuclear energy does not contribute to the global warming problem.

Another benefit of nuclear energy over fossil fuels especially coal is that uranium generates far more power per unit weight or volume. This means that less of it needs to be mined and consequently the damage to the landscapes is less especially when compared to the damage that results from coal mining such as mountaintop removal.

7.6.4: The Drawbacks of Nuclear Energy

The main environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent (used) reactor fuel, and other radioactive wastes. These materials can remain radioactive and dangerous to human health for thousands of years. Radioactive wastes are classified as low-level and high-level. By volume, most of the waste related to the

nuclear power industry has a relatively low-level of radioactivity. Uranium mill tailings contain the radioactive element radium, which decays to produce **radon**, a radioactive gas. Most uranium mill tailings are placed near the processing facility or mill where they come from. Uranium mill tailings are covered with a barrier of material such as clay to prevent radon from escaping into the atmosphere, and they are then covered by a layer of soil, rocks, or other materials to prevent erosion of the sealing barrier.

The other types of low-level radioactive waste are the tools, protective clothing, wiping cloths, and other disposable items that get contaminated with small amounts of radioactive dust or particles at nuclear fuel processing facilities and power plants. These materials are subject to special regulations that govern their handling, storage, and disposal so they will not come in contact with the outside environment.

High-level radioactive waste consists of spent nuclear reactor fuel (i.e., fuel that is no longer useful for producing electricity). The spent reactor fuel is in a solid form consisting of small fuel pellets in long metal tubes called rods. Spent reactor fuel assemblies are initially stored in specially designed pools of water, where the water cools the fuel and acts as a radiation shield. Spent reactor fuel assemblies can also be stored in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling. There is currently no permanent disposal facility in the United States for high-level nuclear waste.

When a nuclear reactor stops operating, it must be **decommissioned**. This involves safely removing the reactor and all equipment that has become radioactive from service and reducing radioactivity to a level that permits other uses of the property. The U.S. Nuclear Regulatory Commission has strict rules governing nuclear power plant decommissioning that involve cleanup of radioactively contaminated plant systems and structures, and removal of the radioactive fuel.

A **nuclear meltdown**, or uncontrolled nuclear reaction in a nuclear reactor, can potentially result in widespread contamination of air and water. Some serious nuclear and radiation accidents have occurred worldwide. The most severe accident was the Chernobyl accident of 1986 in the then Soviet Union (now Ukraine) which killed 31 people directly and sickened or caused cancer in thousands more. The Fukushima Daiichi nuclear disaster (2011) in Japan was caused by a 9.0 magnitude earthquake that shut down power supply and a tsunami that flooded the plant's emergency power supply. This resulted in the release of radioactivity although it did not directly result in any deaths at the time of the disaster. Another nuclear accident was the Three Mile Island accident (1979) in Pennsylvania, USA. This accident resulted in a near disastrous core meltdown that was due to a combination of human error and mechanical failure but did not result in any deaths and no cancers or otherwise have been found in follow up studies of this accident. While there are potentially devastating consequences to a nuclear meltdown, the likelihood of one occurring is extremely small. After every meltdown, including the 2011 Fukushima Daiichi disaster, new international regulations were put in place to prevent such an event from occurring again.

The processes for mining and refining uranium ore and making reactor fuel require large amounts of energy. Nuclear power plants have large amounts of metal and concrete, which also require large amounts of energy to manufacture. If fossil fuels are used for mining and refining uranium ore or in constructing the nuclear plant, then the emissions from burning those fuels could be associated with the electricity that nuclear power plants generate.

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7.7: Electric Power Generation

Fossil fuels may be used directly for their energy content. For example, gasoline is used directly in automobiles; natural gas is used for heating, cooking, transportation, etc. However, in many cases, the primary energy source is not in a usable form for the end-use energy consumer. Approximately one-third of the U.S. energy consumed is in the form of electricity. Except for photovoltaic energy produced from the solar energy, electrical energy is produced indirectly from primary sources such as fossil fuels. The amount of electrical energy produced from various primary sources is shown in Table 7.7.1. Fossil fuels made up 60% of the primary energy sources for producing electricity in the U.S. in 2023.

Energy source	Billion kWh	Share of total
Total - all sources	4,178	
Fossil fuels (total)	2,505	60.0%
Natural gas	1,802	43.1%
Coal	675	16.2%
Petroleum (total)	16	0.4%
Petroleum liquids	12	0.3%
Petroleum coke	5	0.1%
Other gases[3]	11	0.3%
Nuclear	775	18.6%
Renewables (total)	894	21.4%
Wind	425	10.2%
Hydropower	240	5.7%
Solar (total)	165	3.9%
Photovoltaic	162	3.9%
Solar thermal	3	0.1%
Biomass (total)	47	1.1%
Wood	31	0.8%
Landfill gas	8	0.2%
Municipal solid waste (biogenic)	6	0.1%
Other biomass waste	2	0.1%
Geothermal	16	0.4%
Pumped storage hydropower[4]	-6	-0.1%
Other sources[5]	10	0.2%

Table 7.7.1: U.S. utility-scale electricity generation by source, amount, and share of total in 2023. Source US Energy Information Administration.

7.7.1: Electromagnetic Induction

In order to produce electricity, one must employ the laws of electromagnetism. Recall the steam-cycle power plant from Section 7.2.1. The primary energy source could be any fossil fuel that produces heat to create steam. The objective is to rotate a turbine connected to an electrical generator.

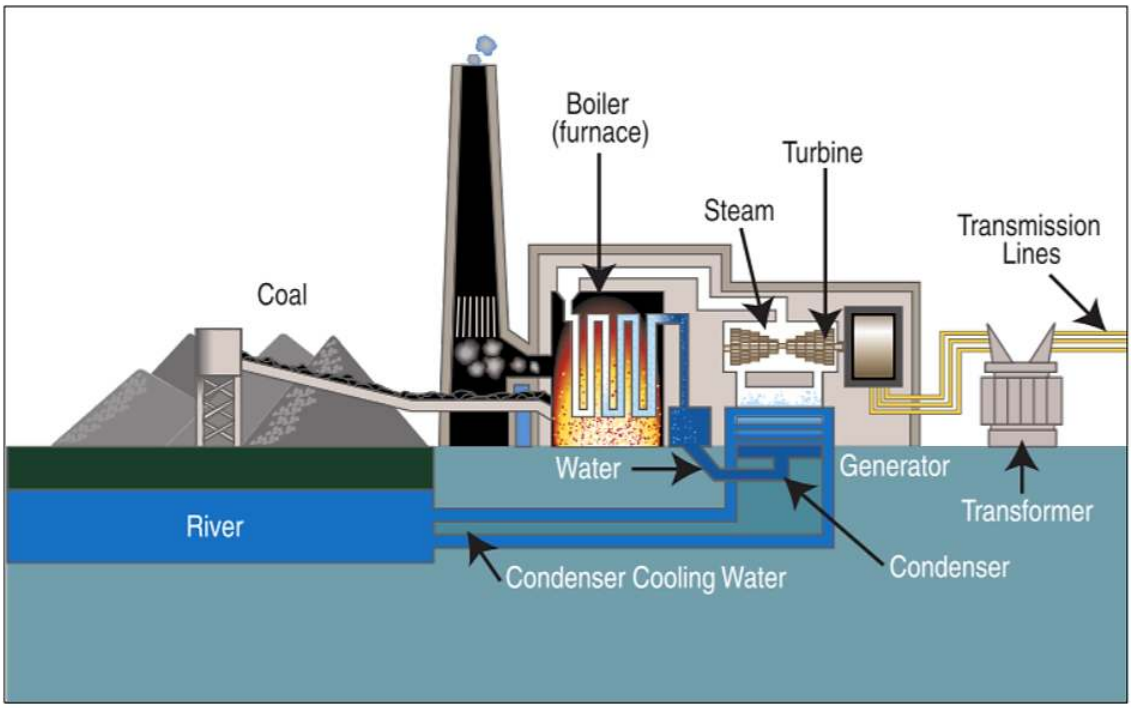


Figure 7.7.2: Diagram of a typical steam-cycle coal power plant (proceeding from left to right). Image by US Tennessee Valley Authority – Public domain. www.tva.com

When the generator is turned, electricity is produced due to Faraday's Law of Induction. A diagram of an electric generator is shown in Figure 7.7.3.

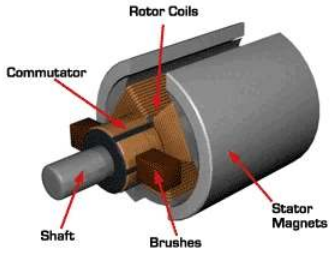


Figure 7.7.3: An electric generator with rotating coils of wire and static magnets. The relative motion of the coils and magnets produces electricty due to Faraday's Law of Induction. Source https://www.quora.com/What-is-the-use-of-a-magnet-in-an-electric-motor.

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7.8: Appendix

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U.S Energy Information Administration www.eia.gov/

U.S. Environmental Protection Agency www.epa.gov

Terms list

Acid mine drainage

Enrichment

Non-renewable

Anaerobic

Exploration

Nuclear fission

Ash

Fabrication

Nuclear meltdown

Boiler

Fossil fuel

Nucleus

Caprocks

Fuel rods

Offshore

Carbon capture & sequestration

Furnace

Oil

Generator

Oil spill

Carbon dioxide

Greenhouse gas

Onshore

Carbon monoxide

Heating value

Ore

Chain reaction

Heavy metals

Overburden

Chemical energy

Hydraulic fracturing

Particulate matter

Clean Air Act

Hydrocarbon

Petroleum

Clean coal technology

Isotope

Pipeline

Clean Water Act

Kinetic energy

Plastic

Coal

Liquid natural gas

Potential energy

Coal-fire power plant

Mercury

Pressurized water reactors

Condenser

Methane

Primary energy

Conversion

Methylmercury

Radiation

Crude

Milling

Radon

Decommissioned

Mountaintop removal

Reclaimed

Digesters

Natural gas

Refinery

Electricity

Neutron

Scrubber

Energy

Nitrogen oxides

Secondary energy

Separation

Strip mining

Sulfur dioxide

Transporation

Treatment

Turbine

U-235

Underground mining

Uranium

Volatile organic compounds

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CHAPTER OVERVIEW

8: Alternative Energy

8.1: Introduction
8.2: Solar Energy
8.3: Biomass Energy
8.4: Wind Power
8.5: Geothermal Power
8.6: Hydroelectric Power (Hydropower)
8.7: Other Alternative Renewable Energy Sources
8.8: Policy and Conservation
8.9: Appendix

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8.1: Introduction

Learning Objectives

By the end of this chapter, students should be able to.

- Describe arguments for alternative energy
- Explain the following aspects of solar energy:
  - How passive solar energy works and provide examples of its use.
  - How solar panels (photovoltaic cells) work.
  - The limitations and environmental costs associated with solar energy.
- Explain the following aspects of biofuels / biomass energy:
  - Describe what is meant by the term “carbon neutral” and explain how biomass energy can and cannot be carbon neutral.
  - Describe current achievements in biofuels and potential of this area for growth.
- Describe wind energy and explain the advantages and disadvantages.
- Describe geothermal energy and explain the advantages and disadvantages
- Describe hydroelectric energy, advantages and disadvantages

Energy sources that are more or less continuously made available in a time frame useful to people are called **renewable energy.** Renewable energy sources are often considered alternative sources because, in general, most industrialized countries do not rely on them as their main energy source. Instead, they tend to rely on the conventional energy sources such as fossil fuels or nuclear power that are non-renewable. Because of the energy crisis in the United States during the 1970s, dwindling supplies of fossil fuels and hazards associated with nuclear power, use of renewable energy sources such as solar energy, hydroelectric, wind, biomass, and geothermal has grown. Renewable energy comes from the sun (considered an "unlimited" supply) or other sources that can theoretically be renewed at least as quickly as they are consumed. If used at a sustainable rate, these sources will be available for consumption for thousands of years or longer. Renewable alternatives derive from wind, water, solar or biomass (Figure 8.1.1). Note that wind, water and biomass energy sources are indirect sources of solar energy. One limitation currently associated with most forms of renewable energy is that the energy is not concentrated and not easily portable.



Figure 8.1.1: A variety of voltage sources (clockwise from top left): the Brazos Wind Farm in Fluvanna, Texas (credit: Leaflet, Wikimedia Commons); the Krasnoyarsk Dam in Russia (credit: Alex Polezhaev); a solar farm (credit: U.S. Department of Energy); and a group of nickel metal hydride batteries (credit: Tiaa Monto). The voltage output of each depends on its construction and load, and equals emf only if there is no load.

Energy is an important ingredient in all phases of society. We live in a very interdependent world, and access to adequate and reliable energy resources is crucial for economic growth and for maintaining the quality of our lives. However, current levels of energy consumption and production are not sustainable because of the heavy reliance on non-renewable energy sources. The principal energy resources used in the world are shown in Figure 8.1.2. The fuel mix has changed over the years but now is dominated by oil, although natural gas and solar contributions are increasing. About 80 % of our energy comes from nonrenewable

fossil fuels and nuclear. The link between global warming and fossil fuel use, with its production of carbon dioxide through combustion, has made, in the eyes of many scientists, a shift to non-fossil fuels of utmost importance – but it will not be easy. About 40 % of the world's energy comes from oil, and much of that goes to transportation uses.

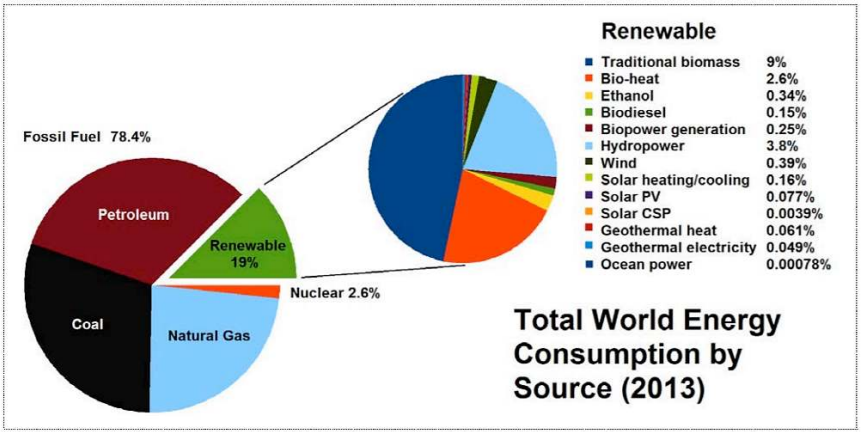


Figure 8.1.2: World energy consumption by source, 2013, in percent. Notice that when all forms of biomass energy are combined, biomass makes up the largest proportion of renewable energy used worldwide. Source: Wikimedia commons - By Delphi234 - Own work, CC0, https://commons.wikimedia.org/w/inde...curid=33567170

5.1.1: The World's Growing Energy Needs

World energy consumption continues to rise especially in countries like China where the economy is improving. Global demand for energy has tripled in the past 50 years and might triple again in the next 30 years (Figure 5.1.3). While much of this growth will come from the rapidly booming economies of China and India, many of the industrialized countries, especially those in Europe, are hoping to meet their energy needs by expanding the use of renewable sources. Although presently only a small percentage, renewable energy is growing very fast, especially wind energy. For example, Germany plans to meet 20% of its electricity and 10% of its overall energy needs with renewable resources by the year 2020. Energy is a key constraint in the rapid economic growth of China and India. In 2003, China surpassed Japan as the world's second largest consumer of oil. However, over 1/3 of this oil is imported. Unlike most Western countries, coal dominates the commercial energy resources of China, accounting for 2/3 of its energy consumption. In 2009 China surpassed the United States as the largest emitter of CO_2. In India, the main energy resources are biomass (wood and dung) and coal. Half of India's oil is imported. About 70% of India's electricity is generated by highly polluting coal. Yet there are sizeable strides being made in renewable energy. India has a rapidly growing wind energy base, and it has the largest solar cooking program in the world. While non-renewable sources dominate, some countries get a sizeable percentage of their electricity from renewable resources. For example, about 67% of New Zealand's electricity demand is met by hydroelectric. Renewable resources, primarily hydroelectric, generate only 10% of the U.S. electricity.

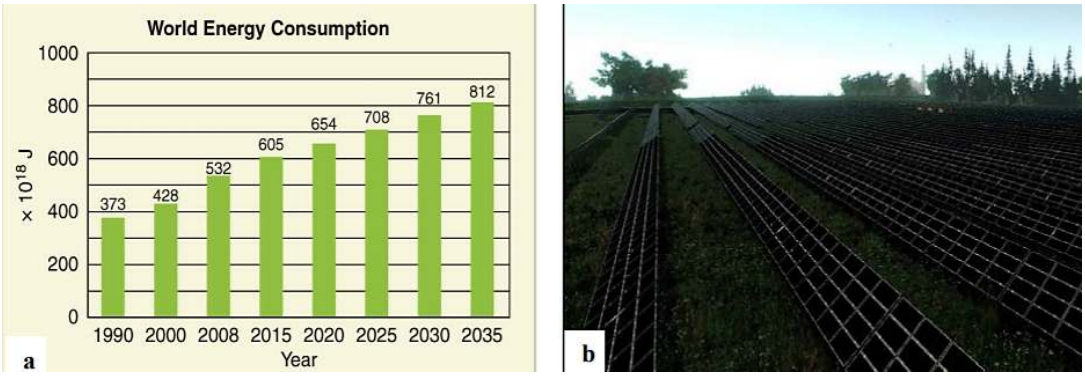


Figure 8.1.3: *(a) Past and projected world energy use (source: Based on data from U.S. Energy Information Administration, 2011). (b) Solar cell arrays at a power plant in Steindorf, Germany (credit: Michael Betke, Flickr).*

5.1.2: Why Use Renewable Energy Sources?

Majority of renewable energy sources including solar, wind, water, and biomass can be directly or indirectly attributed to the sun. The fact that the sun will continue burning for another 4-5 billion years makes it inexhaustible as an energy source for human civilization. With appropriate technology, renewable energy sources allow for local, decentralized control over power. Homes, businesses, and isolated communities can use sources such as solar to produce electricity without being near a power plant or being connected to a grid. This eliminates problems such as spills associated with extraction and transportation of fossil fuels that is needed in order to supply these fossil fuels to those areas that are lacking. Most renewable energy sources do not pollute the air with greenhouse gas emissions and other air pollutants associated with fossil fuels. This is especially important in combating climate change.

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8.2: Solar Energy

Solar energy is the ultimate energy source driving life on earth and many human activities. Though only one billionth of the energy that leaves the sun (Figure 8.2.1) actually reaches the earth's surface, this is more than enough to meet the world's energy requirement. In fact, all other sources of energy, renewable and non-renewable, are actually stored forms of solar energy. The process of directly converting solar energy to heat or electricity is considered a renewable energy source. Solar energy represents an essentially unlimited supply of energy as the sun will long outlast human civilization on earth. The difficulties lie in harnessing the energy. Solar energy has been used for centuries to heat homes and water, and modern technology (photovoltaic cells) has provided a way to produce electricity from sunlight. There are two basic forms of solar energy collectors are passive and active.

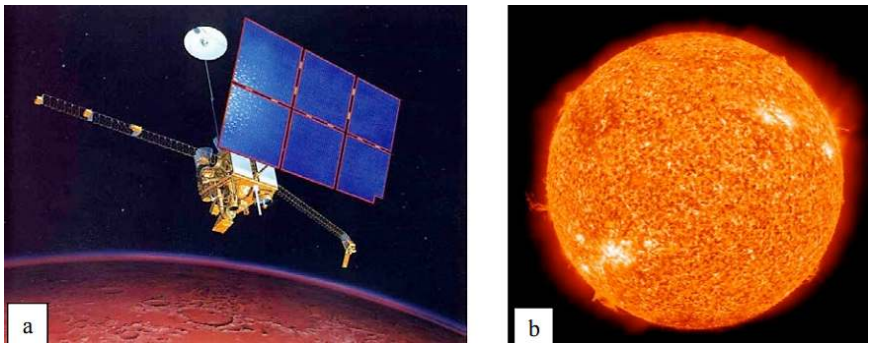


Figure 8.2.1: a) Mars Observer in Mars Orbit showing the solar panel. (Picture: Wikimedia Commons www.jpl.nasa.gov/images/space...t1-browse.jpg,). b) The Sun photographed at 304 angstroms by the Atmospheric Imaging Assembly (AIA 304) of NASA's Solar Dynamics Observatory (SDO). This is a false-color image of the Sun observed in the extreme ultraviolet region of the spectrum. sdo.gsfc.nasa.gov/assets/img/..._4096_0304.jpg, NASA/SDO (AIA)

5.2.1: Passive and Active Solar Energy

Passive solar energy uses heating and cooling strategies that have been used historically such as natural ventilation, solar heat gain, solar shading and efficient insulation. Passive solar space heating happens when the sun shines through the windows of a building and warms the interior (Figure 8.2.2). Building designs that optimize passive solar heating usually have south facing windows that allow the sun to shine on solar heat-absorbing walls or floors during the winter. The solar energy heats the building by natural radiation and convection and the heat is trapped, absorbed and stored by materials with high thermal mass (usually bricks or concrete) inside the house. The heat is released at night when needed to warm up the building as it loses heat to the cooler outdoors. Window overhangs or shades block the sun from entering the windows during the summer to keep the building cool.

Active solar energy systems require the input of some energy to pump a heat-absorbing fluid medium through a collector to store and distribute the energy. Fans or pumps circulate air or heat-absorbing liquids through collectors and then transfer the heated fluid directly to a room or to a heat storage system. The solar collectors are either concentrating or non-concentrating. In the **non-concentrating collectors**, the surface area that intercepts the solar radiation is the same as the area absorbing the radiation. Flat-plate collectors are the most common type of nonconcentrating collectors and are used when temperatures lower than 200°F are sufficient. The collectors absorb and transfer heat to a fluid (water or air) which is then circulated to provide heating to a building. In **concentrating collectors** the surface area intercepting the solar radiation is greater, sometimes hundreds of times greater, than the absorber area. The collector focuses or concentrates solar energy onto an absorber. The collector usually moves so that it maintains a high degree of concentration on the absorber.



Figure 8.2.2: Passive solar building near Crestone, Colorado (image from Wiki Commons)

Photovoltaic (PV) Cells

Solar photovoltaic (PV) devices, or solar cells, change sunlight directly into electricity. PV uses semiconducting materials such as silicon to produce electricity from sunlight: when light hits the cells, the material produces free electrons that migrate across the cell, creating an electric current. Small PV cells can power calculators, watches, and other small electronic devices. Arrangements of many solar cells in PV panels and arrangements of multiple PV panels in PV arrays can produce electricity for an entire house (Figure 8.2.3a). Some PV power plants have large arrays that cover many acres to produce electricity for thousands of homes.

Hundreds of thousands of houses and buildings around the world have PV systems on their roofs. Many multi-megawatt PV power plants have also been built. Covering 4% of the world's desert areas with photovoltaics could supply the equivalent of all of the world's electricity. The Gobi Desert alone could supply almost all of the world's total electricity demand.

Solar Thermal Power Plants

Solar thermal power plants, like the one in Figure 8.2.3b use concentrating solar collector systems to collect and concentrate sunlight to produce the high temperature heat needed to generate electricity. All solar thermal power systems have solar energy collectors with two main components: reflectors (mirrors) that capture and focus sunlight onto a receiver. In most types of systems, a heat-transfer fluid is heated and circulated in the receiver and used to produce steam. The steam is converted into mechanical energy in a turbine, which powers a generator to produce electricity. Solar thermal power systems have tracking systems that keep sunlight focused onto the receiver throughout the day as the sun changes position in the sky.

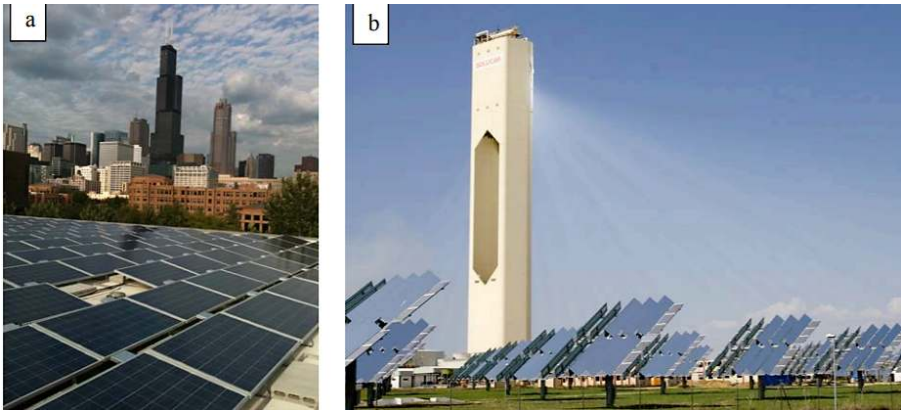


Figure 8.2.3: a) Rooftop Solar Installations on Douglas Hall at the University of Illinois at Chicago has no effect on land resources, while producing electricity with zero emissions. Source: Office of Sustainability. b) Solucar PS10 solar power tower in Andalusia, Spain, is a solar thermal power plant that generates electricity commercially. (Photo by Afloresm Solucar PS10 CC BY 2.0)

5.2.3: Environmental Impacts of solar energy

Solar power has minimal impact on the environment, depending on where it is placed. In 2009, one percent of the renewable energy generated in the United States was from solar power (1646 MW) out of the eight percent of the total electricity generation that was from renewable sources. The manufacturing of photovoltaic (PV) cells generates some hazardous waste from the chemicals and solvents used in processing. Often solar arrays are placed on roofs of buildings or over parking lots or integrated into

construction in other ways. However, large systems may be placed on land and particularly in deserts where those fragile ecosystems could be damaged if care is not taken. Some solar thermal systems use potentially hazardous fluids (to transfer heat) that require proper handling and disposal. Concentrated solar systems may need to be cleaned regularly with water, which is also needed for cooling the turbine-generator. Using water from underground wells may affect the ecosystem in some arid locations.

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8.3: Biomass Energy

Biomass energy is from the energy stored in materials of biological origin such as plants and animals. Biomass energy is the oldest energy source used by humans. Until the Industrial Revolution prompted a shift to fossil fuels in the mid-18th century, biomass energy was the world's dominant fuel source. It includes *direct combustion* of solid biomass to provide energy for heating, cooking, and even generating electricity. The most common source for direct combustion is wood, but energy can also be generated by burning animal manure (dung), herbaceous plant material (non-wood), peat (partially decomposed plant and animal tissues), or converted biomass such as charcoal (wood that has been partially burned to produce a coal-like substance). Biomass can also be converted into a liquid biofuels used to power vehicles such as ethanol from corn, sugarcane residue and soybeans or even used cooking oil for biodiesel. Biomass energy can also be in gaseous form such as methane. Currently, about 12 percent of the world's energy comes from biomass (Figure 8.3.2). Biomass is most frequently used as a fuel source in many developing nations, but with the decline of fossil fuel availability and the increase in fossil fuel prices, biomass is increasingly being used as a fuel source even in developed nations.

5.3.1: Direct combustion of solid biomass

Using wood and charcoal made from wood, for heating and cooking can replace fossil fuels and may result in lower CO_2 emissions. If wood is harvested from forests or woodlots that have to be thinned or from urban trees that fall down or needed be cut down anyway, then using it for biomass does not impact those ecosystems. However, wood smoke contains harmful pollutants like carbon monoxide and particulate matter. For home heating, it is most efficient and least polluting when using a modern wood stove or replace insert that are designed to release small amounts of particulates. However, in places where wood and charcoal are major cooking and heating fuels such as in industrializing countries, the wood may be harvested faster than trees can grow resulting in deforestation.

9Biomass is also being used on a larger scale, where small power plants are powered by biomass such as woodchips (Figure 8.3.1). For instance, Central State Hospital, Milledgeville, GA has a woodchip burning plant that was the most advanced system available for its time and operating today. Colgate University in Hamilton, New York, has had a wood-burning boiler since the mid-1980's that processes about 20,000 tons of locally and sustainably harvested wood chips, the equivalent of 1.17 million gallons (4.43 million liters) of fuel oil, avoiding 13,757 tons of emissions, and saving the university over $1.8 million in heating costs. The University's steam-generating wood-burning facility now satisfies more than 75 percent of the campus's heat and domestic hot water needs. For more information about this, click here Colgate University.



Figure 8.3.1: A biomass (woodchip) power plant in Germany. Image from Wikimedia Public Domain.

Waste products of various industries and processes such as lumber mill sawdust, paper mill sludge, yard waste, oat hulls from an oatmeal processing plant, woody debris from logging, organic waste from feedlots, and residue from crops can also be used for energy. Waste to energy processes are gaining renewed interest as they can solve two problems at once: 1) disposal of waste as landfill capacity decreases, and 2) production of energy from a renewable resource. In the United States, several plants have been constructed to burn urban biomass waste and use the energy to generate electricity. Many of the environmental impacts are similar to those of a coal plant like air pollution, ash generation, etc. Since the fuel source is less standardized than coal and hazardous materials may be present in municipal solid waste (MSW), or garbage, incinerators and waste-to-energy power plants need to clean

the stack gases of harmful materials. The U.S. EPA regulates these plants very strictly and requires anti-pollution devices to be installed. If not contained, waste is distributed in many ecosystems. The ash from these plants may contain high concentrations of various metals that were present in the original waste. If ash is clean enough it can be recycled as a MSW landfill cover or to build roads, cement block and artificial reefs. Also, while incinerating at high temperature many of the toxic chemicals may break down into less harmful compounds.

5.3.2: Gaseous Biomass

Organic material can be converted to methane, the main component of natural gas, by anaerobic decomposition or fermentation, a process that utilizes anaerobic bacteria. Methane is a relatively clean fuel that burns efficiently. It can be generated from any kind of organic waste such as municipal sewage and garbage, livestock manure, kitchen, and garden scraps. In fact, municipal landfills are active sites of methane production contributing annually to methane in the atmosphere and to global warming. This gas can and is currently being captured by numerous landfills around the United States that burn it to generate electricity at power plants or supply it to homes for heating. The electricity may replace electricity produced by burning fossil fuels and result in a net reduction in CO_2 emissions. Burning methane produced from manure provides more heat than burning the dung itself, and the sludge left over from bacterial digestion is a rich fertilizer, containing healthy bacteria as well as most of the nutrients originally in the dung. The main environmental impacts are from the construction of the plant itself. Burning methane releases CO_2 and although CO_2 is a greenhouse gas, its global warming potential is much lower than that of methane (see chapter 7). Also, since this methane if from organic waste resulting from ongoing photosynthetic processes, it is considered carbon-neutral, unlike CO_2 from fossil fuels.

5.3.3: Liquid Biofuels

Biofuels are transportation fuels produced from plant sources and used to power vehicles. The most common ones are ethanol and biodiesel. **Ethanol**, also known as ethyl alcohol or grain alcohol, is produced by fermenting crops such as corn, sugarcane, and other crops and then mixed with conventional gasoline. As an additive, ethanol lowers reliance on conventional oil and increases the combustion efficiency of gasoline, reducing pollutant emissions. In Brazil, which has a sizeable ethanol industry based on sugarcane, all gasoline sold contains 25 percent alcohol, and over 70 percent of the cars sold each year can run on either ethanol or gasoline. Ethanol-gasoline mixtures burn cleaner than pure gasoline but are more volatile and thus have higher "evaporative emissions" from fuel tanks and dispensing equipment. These emissions contribute to the formation of harmful, ground level ozone and smog. Gasoline requires extra processing to reduce evaporative emissions before it is blended with ethanol.

Biodiesel which is essentially vegetable oil, can also be derived from a wide range of plant sources, including rapeseed, sunflowers, and soybeans, and can be used in most conventional diesel engines. Biodiesel can also be made from used vegetable oil and has been produced on a very local basis. Because it burns more cleanly than its petroleum-based counterpart, biodiesel can reduce pollution from heavy-duty vehicles such as trucks and buses. Compared to petroleum diesel, biodiesel combustion produces less sulfur oxides, particulate matter, carbon monoxide, and unburned and other hydrocarbons, but more nitrogen oxide.

Calculating the net energy or CO_2 generated or reduced in the process of producing the biofuel is crucial to determining its environmental impact. Biofuels may be derived from parts of plants not used for food (cellulosic biomass) thus reducing that impact. Cellulosic ethanol feedstock includes native prairie grasses, fast growing trees, sawdust, and even waste paper. Also, in some parts of the world, large areas of natural vegetation and forests have been cut down to grow sugarcane for ethanol and soybeans and palm-oil trees to make biodiesel. This is not sustainable land use.

Biomass energy may be considered to be **carbon-neutral** because the plants that are used to make them (such as corn and sugarcane for ethanol, or soy beans and palm oil trees for biodiesel) take up CO_2 from the atmosphere through photosynthesis as they grow and may offset the CO_2 produced when burned. If the biomass is not burned for energy generation, the carbon contained in the biomass would still be returned to the atmosphere as CO_2 when the organisms die and decompose to complete the cycle. Burning biomass, therefore, does not result in new additional CO_2 in the atmosphere but rather returns carbon that came from the atmosphere and used to produce the biomass in the first place. On the other hand, burning fossil fuels introduces new carbon into the atmosphere that was previously stored deep in the Earth's crust and would have stayed there if we (humans) did not extract it.

5.3.4: Environmental Impacts of Biomass Energy

A major challenge of biomass is determining if it is really a more sustainable option. The energy content of some biomass energy sources may not be as high as fossil fuels so more must be burned to generate the same energy. It often takes energy to make energy and biomass is one example where the processing to make it may not be offset by the energy it produces. If traditional monoculture crops like corn or soybeans are used, they require major quantities of fossil fuel to manufacture fertilizer, run farm machines, and ship the fuel to markets, so these biofuels do not always offer significant net energy savings over gasoline and diesel fuel. In such instances, biofuels may not be carbon-neutral because the process of producing the biofuels results in more CO_2 added to the atmosphere than that removed by the growing crops. Even if the environmental impact is net positive, for example if renewable energy sources are used to make the biofuels, the economic and social effects of growing plants for fuels need to be considered. The land, fertilizers, water, and energy used to grow biofuel crops could be used to grow food crops instead. The competition of land for fuel vs. food can increase the price of food, which has a negative effect on society. It could also decrease the food supply and increase malnutrition and starvation globally.

Trees that are cut for firewood are frequently not replanted. In order to be used sustainably, one tree must be planted for every one cut down. If too much biomass is taken it can reduce forest and grassland contributions to ecosystem services. Forests and grasslands help take CO_2 out of the atmosphere through photosynthesis and the loss of photosynthetic activity results in increased amounts of CO_2 in the atmosphere and contribute to global warming since CO_2 is a greenhouse gas. Burning biomass directly (wood, manure, etc.) produces high particulate material pollution (see chapter 6 on Air Pollution), produces CO_2 and deprives the soil of nutrients it normally would have received from the decomposition of the organic matter. Each type of biomass energy source, therefore, must be evaluated for its full life-cycle impact in order to determine if it is really advancing sustainability and reducing environmental impacts.

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8.4: Wind Power

Wind is a renewable energy source that uses the power of moving air to generate electricity. Wind turbines use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift (similar to the effect on airplane wings), which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces electricity (Figure 8.4.1). Wind turbines are becoming a more prominent sight across the United States, even in regions that are considered to have less wind potential. Wind turbines (often called windmills) do not release emissions that pollute the air or water (with rare exceptions), and they do not require water for cooling. The U.S. wind industry had 40,181 MW of wind power capacity installed at the end of 2010, with 5,116 MW installed in 2010 alone, providing more than 20 % of installed wind power around the globe. According to the American Wind Energy Association, over 35 % of all new electrical generating capacity in the United States since 2006 was due to wind, surpassed only by natural gas.

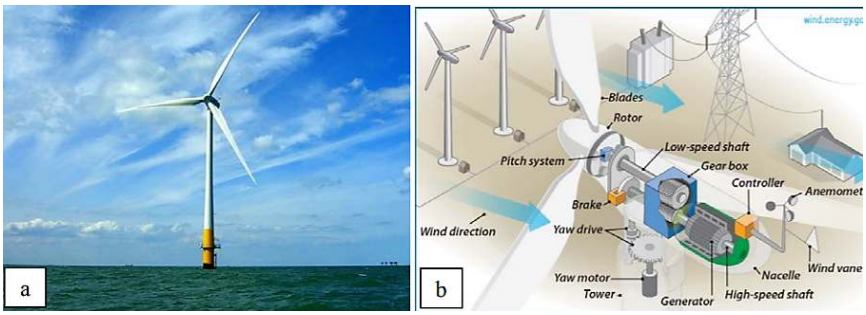


Figure 8.4.1: a) This wind turbine in the Thames Estuary in the UK is an example of induction at work, (credit: Phault, Flickr). Wind pushes the blades of the turbine, spinning a shaft attached to magnets, see image b for parts. The magnets spin around a conductive coil, inducing an electric current in the coil, and eventually feeding the electrical grid. Follow this link for an Animation.

Most windmills generate about 1kW of electricity, which is only practical for decentralized power generation. California has about 17,000 windmills with a capacity of about 1,400 MW. This is about 80% of all windmills in the U.S. In West Europe windmill generators are quite common. Since a wind turbine (Figure 8.4.1) has a small physical footprint relative to the amount of electricity it produces, many wind farms are located on crop, pasture, forest land, or coastal areas. They contribute to economic sustainability by providing extra income to farmers and ranchers, allowing them to stay in business and keep their property from being developed for other uses. For example, energy can be produced by installing wind turbines in the Appalachian Mountains of the United States instead of engaging in mountain top removal for coal mining.

5.4.1: Environmental Impacts of Wind Energy

Offshore wind turbines on lakes or the ocean may have smaller environmental impacts than turbines on land. Wind turbines do have a few environmental challenges. There are aesthetic concerns to some people when they see them on the landscape. A few wind turbines have caught on fire, and some have leaked lubricating fluids, though this is relatively rare. Some people do not like the sound that wind turbine blades make. Turbines have been found to cause bird and bat deaths particularly if they are located along their migratory path. This is of particular concern if these are threatened or endangered species. There are ways to mitigate that impact and it is currently being researched. There are some small impacts from the construction of wind projects or farms, such as the construction of service roads, the production of the turbines themselves, and the concrete for the foundations. However, overall life cycle analysis has found that turbines make much more energy than the amount used to make and install them.

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8.5: Geothermal Power

Geothermal energy uses heat from the Earth's internal geologic processes in order to produce electricity or provide heating. The subsurface temperature of the Earth provides an endless energy resource. One source of geothermal energy is steam. Groundwater percolates down through cracks in the subsurface rocks until it reaches rocks heated by underlying magma, and the heat converts the water to steam. Sometimes this steam makes its way back to the surface in the form of a geyser or hot spring. Wells can be dug to tap the steam reservoir and bring it to the surface, to drive generating turbines and produce electricity (Figure 8.5.1a). Hot water can be circulated to heat buildings. Regions near tectonic plate boundaries have the best potential for geothermal activity.

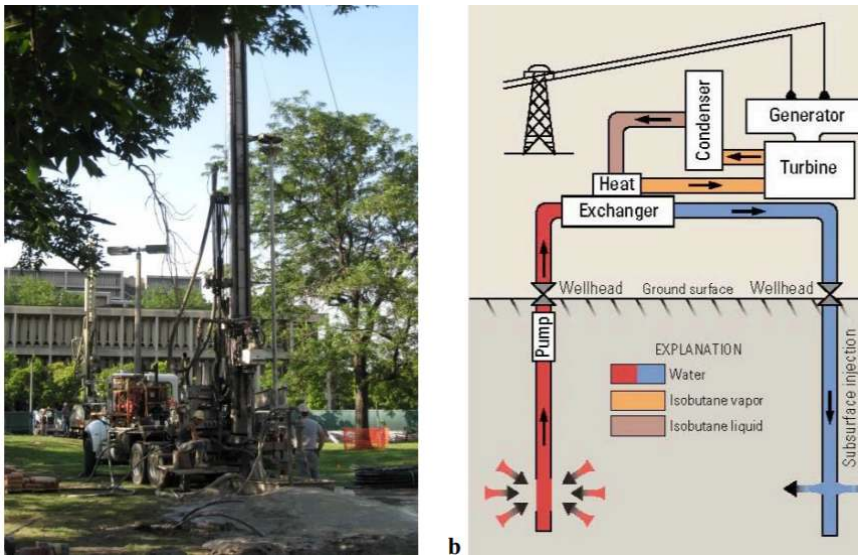


Figure 8.5.1: a) Installing a Geothermal Pipe System Drilling to install geothermal ground source pipe system. Source: Office of Sustainability. b) Electricity generation at a moderate-temperature hydrothermal system. The geothermal water is used to boil a second fluid (isobutane in this example) whose vapor then drives a turbine generator. The wastewater is injected back into the subsurface. Source: USGS.

5.5.1: Environmental Impacts of Geothermal Energy

The environmental impact of geothermal energy depends on how it is being used. Direct use and heating applications have almost no negative impact on the environment. Geothermally heated water can release dissolved gases, including carbon dioxide, methane, ammonia and hydrogen sulfide, although these are usually in very small quantities when compared to those released from fossil fuel plants. In addition, geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water. They emit 97 % less acid rain-causing sulfur compounds than are emitted by fossil fuel plants.

Even though geothermal energy is renewable, not every plant built to capture this energy will be able to operate indefinitely because the energy relies on groundwater recharge. If the heated water is used faster than the recharge rate of groundwater, the plant will eventually run out of water. The Geysers in California started experiencing this and operators responded by injecting municipal wastewater into the ground to replenish the supply. Also, patterns of geothermal activity in the Earth’s crust naturally shift over time and an area that produces hot groundwater now may not always so do. The water of many hot springs is laced with salts and minerals that corrode equipment, shorten the lifetime of plants and increase maintenance costs.

Electrical power is restricted to regions where energy can be tapped from naturally heated groundwater but most areas of the world are not rich in naturally heated groundwater. Engineers are trying to overcome this by drilling deeply into dry rock, fracture the rock and pump in cold water which becomes heated and drawn up through an outlet well and used to generate power. However, this approach is said to trigger minor earthquakes.

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8.6: Hydroelectric Power (Hydropower)

This is the second largest source of renewable energy used, next to biomass energy. The majority of hydropower currently comes from dams built across a river to block the flow of river water. The water stored behind the dam contains potential energy (see chapter 4) and when released, the potential energy is converted to kinetic energy as the water rushes down. This energy is used to turn blades of turbines and causing a generator to generate electricity. Electricity generated in the powerhouse of a dam is transmitted to the electric grid by transmission lines while the water flows into the riverbed below the dam and continues down river. An alternative approach considered less disruptive involves diverting a portion of the river's water through a pipe or channel and passed through a powerhouse to generate electricity and returned to the river. Another approach involves pumping water from a lower reservoir to a higher reservoir and then allowed to flow downhill through a turbine, generating electricity. This approach, however, requires energy input to pump the water.

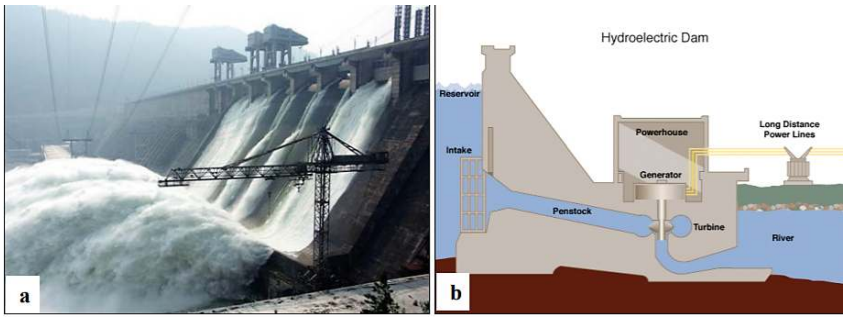


Figure 8.6.1: a) Hydroelectric facility (credit: Denis Belevich, Wikimedia Commons); b) An illustration showing how water is funneled through a portion of the dam to rotate turbines and generate electricity. (Image from Wikimedia, public domain).

Figure 8.6.2 shows the Hoover Power Plant located on the Colorado River. In the U.S., hydroelectric plants account for about 10% of total production and account for about 35 % of the United States' renewable energy consumption. In 2003 capacity was at 96,000 MW and it was estimated that 30,000 MW capacity is undeveloped. Energy produced can be calculated and modeled as shown in Figure 8.6.3.



Figure 8.6.2: a) A view of the Hoover dam from above (credit Adam Kliczek). b) Hydroelectric generators at the Hoover dam (credit: Jon Sullivan).

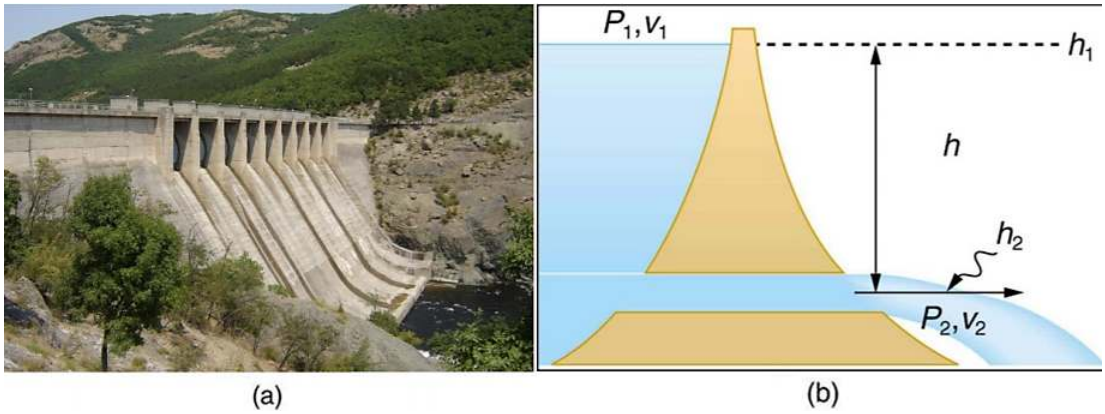


Figure 8.6.3: (a) Water gushes from the base of the Studen Kladenetz dam in Bulgaria. (credit: Kiril Kapustin; http://www.ImagesFromBulgaria.com) (b) In the absence of significant resistance, water flows from the reservoir with the same speed it would have if it fell the distance h without friction.

8.6.1: Environmental Impacts of Hydroelectric Power

Hydropower (hydro-electric) is considered a clean and renewable source of energy since it does not directly produce emissions of air pollutants and the source of power is regenerated. However, hydropower dams, reservoirs, and the operation of generators can have serious environmental impacts. A dam that is used to create a reservoir or to divert water to a run-ofriver hydropower plant can obstruct migration of fish to their upstream spawning areas in areas where salmon must travel upstream to spawn, such as along the Columbia River in Washington and Oregon. Hydro turbines kill and injure some of the fish that pass through the turbine although there are ways to reduce that effect. This problem can be partially alleviated by using 'fish ladders' that help the salmon get up the dams.

A reservoir and operation of the dam can affect the natural water habitat due to changes in water temperatures, chemistry, flow characteristics, and silt loads, all of which can lead to significant changes in the ecology and physical characteristics of the river upstream and downstream. Construction of reservoirs may cause natural areas, farms, and archeological sites to be covered and force populations to relocate and result in the loss of scenic rivers.

Carbon dioxide and methane may also form in reservoirs where water is more stagnant and be emitted to the atmosphere. The exact amount of greenhouse gases produced from hydropower plant reservoirs is uncertain. If the reservoirs are located in tropical and temperate regions, including the United States, those emissions may be equal to or greater than the greenhouse effect of the carbon dioxide emissions from an equivalent amount of electricity generated with fossil fuels (EIA, 2011 p. 333).

8.6.2: Potential of Tidal Power

Tidal power involves placing turbines in zones of the ocean with significant tides and currents, and using the power of flowing water to turn the blades of a turbine to generate electricity. Ocean power systems are still being researched and currently still experimental. For example, the Bay of Fundy, which has a 15 m tide, a dam constructed across the estuary would let water enter on the incoming tide, then release the water through turbines at low tide. The energy potential is great http://www.ialtenergy.com/tidal-power-news.html , and so is the environmental cost. Tapping tidal energy resources involves building major dams on inlets and estuaries that are prized for other purposes, so few tidal energy facilities have been developed. Harnessing waves and currents on a significant scale will involve designing turbine structures that are large, inexpensive, and can operate for long periods under the physical stresses and corrosive forces of ocean environments. Though proposed, a tidal power plant has not been constructed at Fundy. There is a 240,000 kW tidal plant at La Rance, France. Figure 8.6.4 shows a diagram of a tidal power plant. During high tide, water flows into the tidal basin (a). During low tide, water flows out of the water basin back to the main body of water (b). These produce power by spinning the generator in opposite directions. This is shown in the graph of Figure $PageIndex4$ (c). More details can be found at Alternative Energy Tutorials.

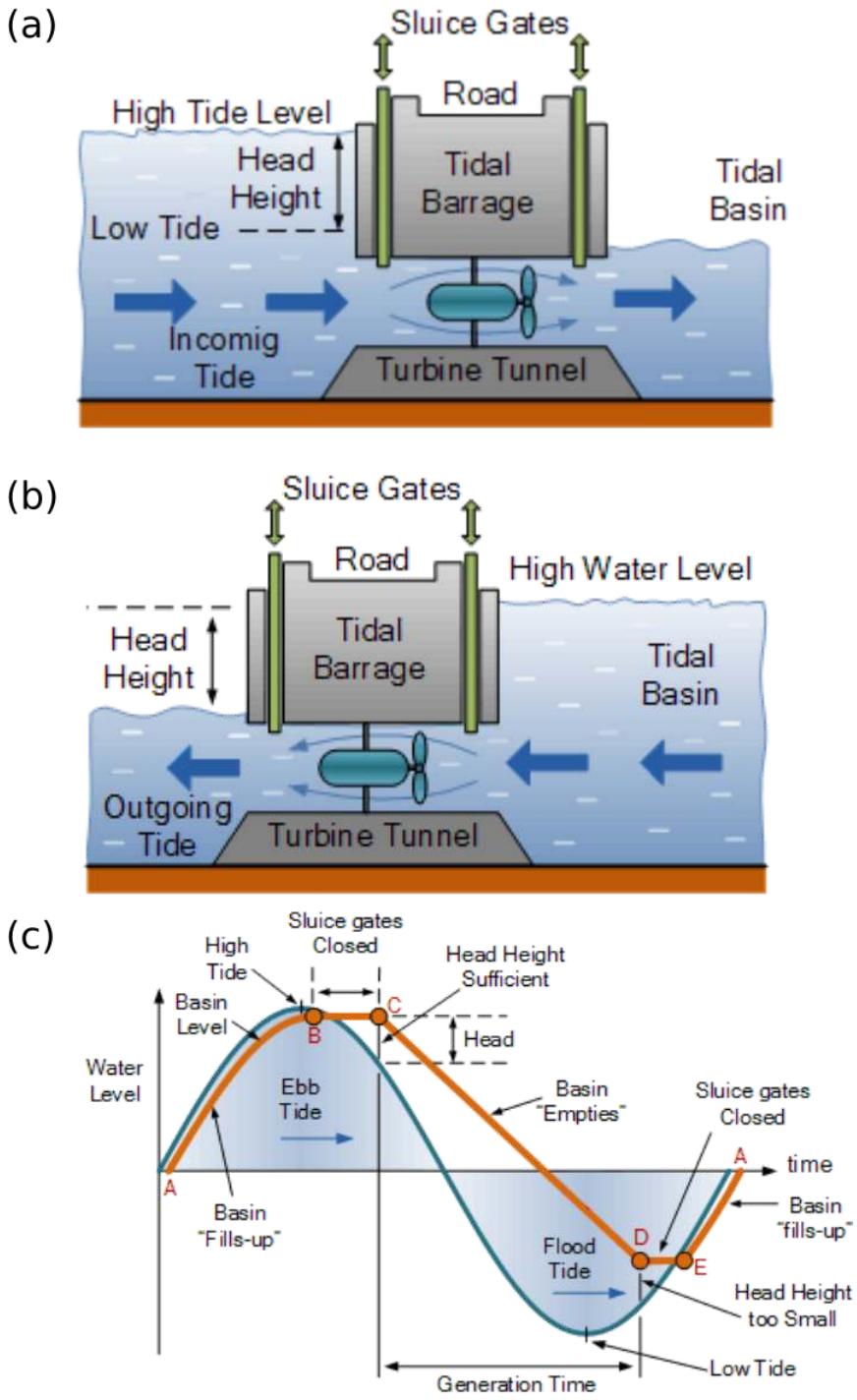


Figure $PageIndex4$: (a) Diagram of a tidal power plant at high tide. The water is able to flow into the tidal basin This generates the ebb tide power shown in (c). (b) The tidal power plant at low tide when the outgoing flows back into the primary body of water. This generates the flood tide power shown in (c). Source: https://www.alternative-energy-tutorials.com/tidal-energy/tidal-barrage.html

8.6.3: Wave Power

Ocean waves represent a significant, yet largely untapped, source of renewable energy. Capturing the energy of these traveling waves involves various technologies that convert the wave's motion into usable electricity. These technologies include point

absorbers, attenuators, overtopping devices, and oscillating water columns, each with unique designs and working principles. See Figure 8.6.5 for examples of these devices.

8.6.3.1: How it works

- **Point Absorbers:**

  These devices, often buoy-like, move up and down with the waves, driving a generator to produce electricity **according to EKT Interactive**.

- **Attenuators:**

  These devices are designed to move with the waves, using the resulting mechanical energy to drive a generator.

- **Overtopping Devices:**

  These capture water as waves break over a structure, then channel the water through a turbine.

- **Oscillating Water Columns:**

  These devices trap air pockets within a chamber. Wave action compresses and decompresses the air, driving a turbine to generate power.

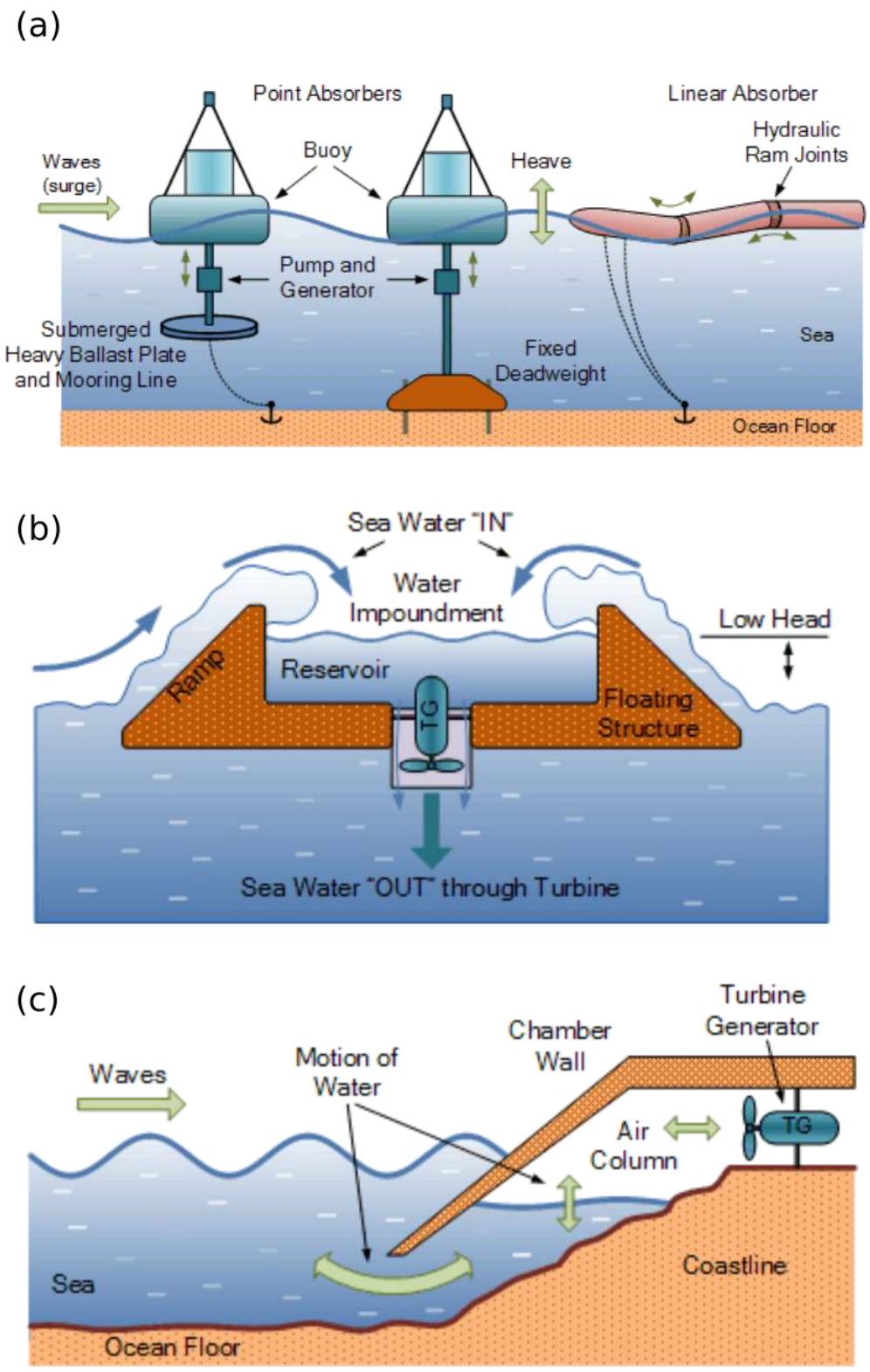


Figure 8.6.5: Types of wave energy extraction. (a) Point absorbers have a buoy that moves relative to a fixed weight and attenuators bend with waves generating energy from the mechanical bends. (b) Overtopping devices "catch" waves and use the gravitational potential energy to turn a turbine. (c) Oscillating water columns use trapped air columns to drive turbines.

8.6.3.2: Challenges

- **High Production and Installation Costs:** Developing and deploying wave energy converters can be expensive.
- **Maintenance Complexity:** The harsh marine environment can lead to maintenance challenges and costly repairs.
- **Potential Environmental Impacts:** There are concerns about the impact on marine life from both the devices themselves and the noise they generate.

8.6.3.3: Potential

Wave energy could play a significant role in the future energy mix, particularly in densely populated coastal regions and remote locations. It offers a more consistent and predictable power source compared to wind and solar, making it a valuable addition to the renewable energy portfolio.

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8.7: Other Alternative Renewable Energy Sources

5.7.1: Hydrogen

Hydrogen gas may be an important clean fuel of the future. Hydrogen is considered an energy carrier, like electricity and batteries, it carries energy that can be converted for use later. Hydrogen gas does not tend to exist freely but rather hydrogen atoms bind to other atoms and molecules becoming incorporated in everything from water to organic compounds. Therefore, to obtain hydrogen gas for fuel, energy is needed to force these substances to release their hydrogen atoms. One such procedure is known as **electrolysis** in which an electric current is passed through water to decompose the water molecule into oxygen and hydrogen (Figure 8.7.1). Hydrogen can also be produced from hydrocarbons such as natural gas and coal, fermentation of plant waste material, and using algae.

The nation of Iceland is attempting to become the first hydrogen-based energy economy using its abundant geothermal energy resources. Some energy experts believe that combining hydrogen fuel and electricity could serve as a basis for a clean, safe, and energy efficient energy system. Electricity generated from intermittent renewable sources such as wind and solar can be used to produce hydrogen fuel for fuel cells that would then generate electricity to power vehicles, computers, heat homes and many other uses. An energy system based on hydrogen would alleviate dependence on foreign fuels and help fight climate change. Hydrogen is the most abundant element in the universe and we will never run out of it.

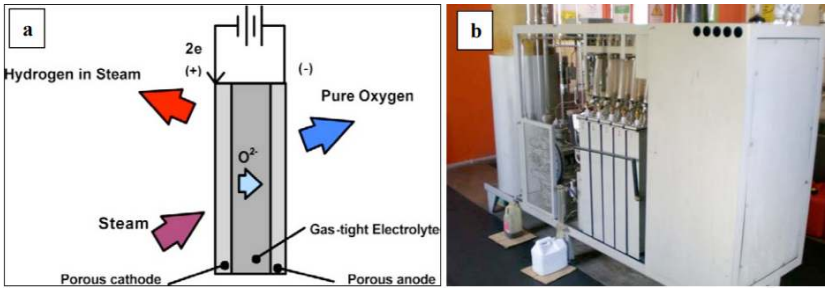


Figure 8.7.1: a) An electric current passed through water resulting in the separation of hydrogen atoms from oxygen to produce the hydrogen fuel. b) An electrolyser used in the production of hydrogen by CambridgeBayWeather. After production the hydrogen is used to inflate weather balloons to which a radiosonde is attached. The oxygen produced is vented to the outside.

Fuel Cells

Fuel cells are highly efficient power plants that produce electricity using hydrogen fuel in a chemical reaction that is a reverse of the electrolysis process that produced the hydrogen fuel (Figure 8.7.2). Energy is released by an exothermic electrochemical reaction that combines hydrogen and oxygen ions through an electrolyte material to generate electricity and heat. Experimental fuel cells that can power automobiles have been developed (Figure 8.7.2).



Figure 8.7.2: The electrochemical processes showing how hydrogen fuel is combined with oxygen generating heat energy along with water as a waste product. Some vehicles that use the fuel cell include buses (photo is a hydrogen fuel bus on Tower Bridge London, photo by Sludge G.), cars (The Toyota Fine N car based on fuel cell technology, photo by Chris 73, CC BY-SA 3.0) and motorcycles (Suzuki Burgman Fuel Cell cutaway model shown here, Photo by Mario CC BY-SA 3.0).

Challenges of Hydrogen

Currently, the infrastructure for using hydrogen fuel is lacking and converting a nation such as the United States to hydrogen would require massive and costly development of facilities to produce, store, transport, and provide the fuel. The environmental impact of hydrogen production itself depends on the source of material used to supply the hydrogen. For example, biomass and fossil fuel sources result in carbon-based emissions. Some research suggests that leakage of hydrogen from its production, transport, and use could potentially deplete stratospheric ozone. Research into this is still ongoing.

5.7.2: Electric cars

Electric cars are vehicles that solely depend on electricity to work. They are charged using fossil fuel energy sources (Figure 8.7.3 a), but they are very efficient. Although it might seem like science fiction the electric car is already here, and has been here for the last hundred years. The main problem with the electric car is that it cannot go very far before it needs to be recharged, something that takes between three to six hours. Different models have been explored (Figure 8.7.3b), but for now most cars are equipped as a hybrid with a back up reservoir using fossil fuel.

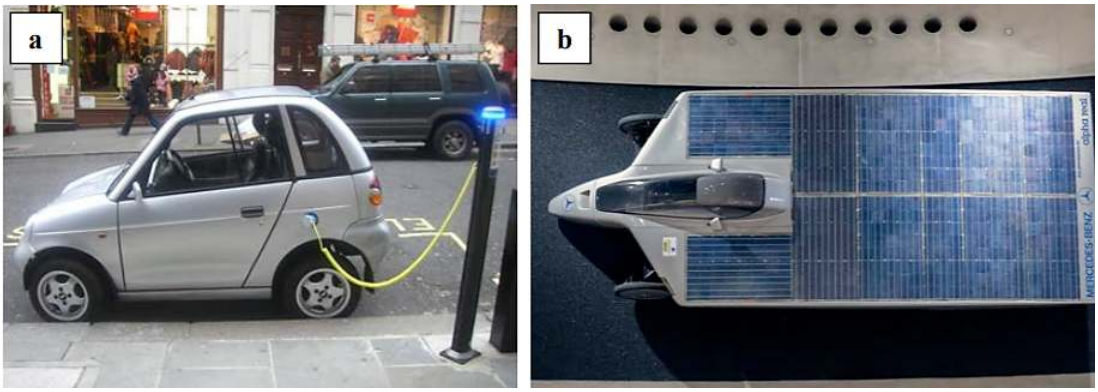


Figure 5.7.3: a) This REVAi, an electric car, gets recharged on a street in London. (credit: Frank Hebbert). b) 1985 Mercedes-Benz/Alpha Real "Tour de Sol" Solarmobile; built for the 1985 Tour de Sol Centennial Rally, solar car race from Lake Constance to Lake Geneva.

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8.8: Policy and Conservation

As we finish this chapter on energy and work, it is relevant to draw some distinctions between two sometimes misunderstood terms in the area of energy use. As has been mentioned elsewhere, the "*law of the conservation of energy*" is a very useful principle in analyzing physical processes. It is a statement that cannot be proven from basic principles, but is a very good bookkeeping device, and no exceptions have ever been found. It states that the total amount of energy in an isolated system will always remain constant. Related to this principle, but remarkably different from it, is the important philosophy of energy conservation. Conservation has to do with seeking to decrease the amount of energy used by an individual or a group through (1) reduced consumption (e.g., turning down thermostats, driving fewer kilometers) and/or (2) increasing conversion efficiencies in the performance of a particular task—such as developing and using more efficient room heaters, cars that have greater miles-per-gallon ratings, energy efficient compact fluorescent lights, energy efficient appliances, etc. Since energy in an isolated system is not destroyed or created, one might wonder why we need to be concerned about our energy resources, since energy is a conserved quantity. The problem is that the final result of most energy transformations is waste heat transfer to the environment and conversion to energy forms no longer useful for doing work. To state it in another way, the potential for energy to produce useful work has been "degraded" in the energy transformation.

A rational energy policy should encourage research by private industry and should provide funding for basic research, ensure fair access to alternative energy sources, encourage the internalization of external cost of fossil fuel energy, and promote the dissemination of information about the costs and benefits of alternative energy sources.

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8.9: Appendix

Questions:

1. Describe three major environmental challenges for fossil fuels in general or one in particular.

2. Rate the following electricity sources for their contribution to climate change from most to least: biomass, coal, solar, wind, nuclear, natural gas, oil, geothermal, hydroelectric, MSW. Is there any compelling reason not to use any of the carbon neutral (no net carbon emissions) sources?

3. Describe the environmental and social concerns associated with biofuels.

In class activities: Design a sustainable city of the future

Websites for more information and further discussion

News: algae car: http://inhabitat.com/first-algae-pow...ross-us-on-25- gallons/

For a video presentation on the different ways to use geothermal energy, visit http://geothermal.marin.org/video/vid_pt5.html

Are Electric Vehicles Better for the Environment than Gas-Powered Ones? www.technologyreview.com/view...-powered-ones/

See excel file with terminology introduced in this chapter.

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CHAPTER OVERVIEW

9: Air Pollution

9.1: Composition and Structure of the Atmosphere
9.2: Ozone
9.3: Outdoor Air Pollution
9.4: Indoor Air Pollution
9.5: Effects of Air Pollution on Human Health
9.6: Acid Rain
9.7: Air Pollution Legislation
9.8: Appendix

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9.1: Composition and Structure of the Atmosphere

Learning Objectives

By the end of this chapter, students will be able to

- Describe the composition and structure of the atmosphere.
- Explain the importance of the ozone layer, its depletion, and specific steps taken to address it.
- Distinguish between indoor and outdoor air pollution and how these compare among industrialized and less industrialized countries
- Identify natural and anthropogenic sources of air pollution
- Explain the effects of air pollution on human and ecosystem health
- Explain how the Clean Air Act legislation works and describe its outcomes

Atmosphere refers to the layer of gases that surrounds Earth and is held in place by Earth's gravitational attraction (gravity). The mix of gases in the atmosphere forms a complex system organized into layers that together support life on Earth. Although there are numerous gases, as shown in Table 9.1.1, the top four gases make up 99.998 % of the volume of *clean dry air* (unpolluted air that does not contain water vapor). Of this dry composition of the atmosphere **nitrogen**, by far, is the most common (78%).



Figure 9.1.1: Emissions from this power plant in New Mexico contained excessive amounts of sulfur dioxide. Image from National Parks Service (Public Domain).

Nitrogen dilutes oxygen and prevents rapid or instantaneous burning at the Earth's surface, as oxygen gas is a necessary reactant of the combustion process. Nitrogen is also needed and used by living things to make proteins, though as nitrogen gas, N_2, it is unavailable to most living things. **Oxygen** is used by all living things to make molecules that are essential for life. It is also essential for aerobic respiration as well as combustion or burning. **Argon** is a non-reactive gas and we use it in light bulbs, in double-pane windows, and to preserve priceless documents such as the original Declaration of Independence and the Constitution. **Carbon dioxide** is an essential gas used by plants and other organisms to make sugar (food) through photosynthesis. This process is essential for other life as well because during photosynthesis, water molecules are split apart and their oxygen is released back to the atmosphere. Carbon dioxide also acts as a blanket that prevents the escape of heat into outer space (see more on this in Chapter 7). The atmosphere is rarely, if ever, completely dry. **Water vapor** (water in a 'gas' state) is usually present up to about 4% of the total volume depending on location. In the Earth's desert regions (30° N/S) when dry winds are blowing, the water vapor contribution to the composition of the atmosphere will be near zero.

Table 9.1.1: Average composition of clean dry air in the lower atmosphere

Gas	Symbol	Content
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Argon	Ar	0.93%
Carbon	CO_2	0.03% (this and the above three add to 99.998%)
Neon	Ne	18.20 parts per million
Helium	He	5.20 ppm
Krypton	Kr	1.10 ppm
Sulfur Dioxide	SO_2	1.00 ppm
Methane	CH_4	2.00 ppm
Hydrogen	H_2	0.50 ppm
Nitrous Oxide	N_2O	0.50 ppm
Xenon	Xe	0.09 ppm
Ozone	O_3	0.07 ppm
Nitrogen Dioxide	NO_2	0.02 ppm
Iodine	I_2	0.01 ppm
Carbon Monoxide	CO	Trace
Ammonia	NH_3	Trace

Source: National Weather Service www.srh.noaa.gov/jetstream/at...tmos_intro.htm

Earth's atmosphere is divided into four distinct layers based on thermal characteristics (temperature changes), chemical composition, movement, and density (Figure 9.1.2). The **troposphere** is the lowest layer extending from the surface up to roughly 18 km above the surface depending on location (varies from as low as 6 km to as high as 20 km). There is continuous flow and swirling of air constantly through convection currents redistributing heat and moisture around the globe. This results in the short-lived and local patterns of temperature and moisture that we call **weather**. Because gravity holds most air molecules close to the Earth's surface, the troposphere is the densest of all layers, containing about 75% of the total mass of the atmosphere. The density of the gases in this layer decrease with height so the air becomes thinner. In response, the temperature in the troposphere also decreases with height. As one climbs higher, the temperature drops from an average around 17°C (62°F) at sea level to about -51°C (-60°F) at the tropopause, a sharp boundary at the top of the troposphere that limits mixing between the troposphere and the upper layers.

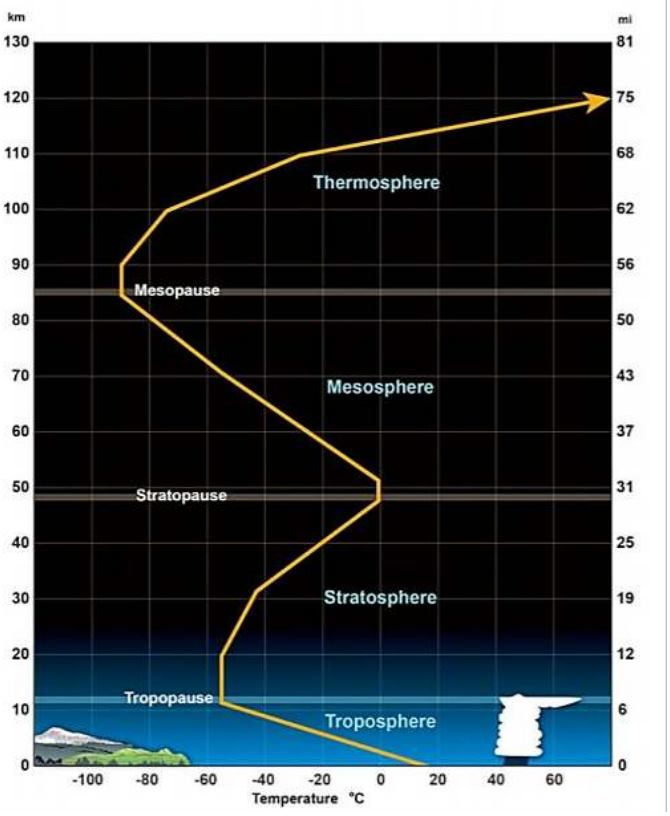


Figure 9.1.2: An average temperature profile through the lower layers of the atmosphere. Height (in miles and kilometers) is indicated along each side. Source: National Weather Service *www.srh.noaa.gov/jetstream/at...atmprofile.htm*

The **stratosphere** is the layer that extends from the tropopause up to about 50 km to 53 km above the Earth's surface depending on location. The proportions of most gases in this layer is similar to that of the troposphere with two main exceptions: 1) there is almost no water vapor in the stratosphere and 2) the stratosphere has nearly 1,000 times more ozone (O_3) than the troposphere. With only about 19% of the total mass of the atmosphere, the density of the stratosphere is significantly lower than the troposphere. However, temperature in this region increases with height as a result of heat that is produced during the formation of ozone (more on ozone in section 6.2). This heat is responsible for temperature increases from an average -51 °C (-60°F) at tropopause to a maximum of about -15°C (5°F) at the top of the stratosphere. This increase in temperature with height means warmer air is located above cooler air. This prevents "convection" as there is no upward vertical movement of the gases. The consequence of this little to no mixing of gases in the stratosphere makes it relatively calm but also means that once substances such as pollutants enter this zone, they can remain suspended for many years. The top of the stratosphere is bound by a boundary known as the **stratopause**.

Above the stratosphere is the **mesosphere** which extends to about 85 km above the Earth's surface. The mesosphere has no ozone molecules and the other gases such as oxygen and nitrogen continue to become less dense with height. As a result, not much ultraviolet and x-ray radiation from the sun is absorbed by molecules in this layer so temperature decreases with altitude. Both the stratosphere and the mesosphere are considered the middle atmosphere.

Between about 85 km and 600 km lies the **thermosphere**. This layer is known as the upper atmosphere. Unlike the mesosphere, the gases in this layer readily absorb incoming high energy ultraviolet and x-ray radiation from the sun. Because of this absorption, the temperature in the thermosphere increases with height and can reach as high as 2,000°C (3,600°F) near the top depending on solar activity. However, despite the high temperature, this layer of the atmosphere would still feel very cold to our skin due to the very thin atmosphere. The high temperature indicates the amount of energy absorbed by molecules but with so few in this layer, the total number of molecules is not enough to heat our skin. There's no sharp boundary that marks the end of the atmosphere. Pressure and density simply continue to decrease with distance until they become indistinguishable from the near-vacuum of outer space.

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9.2: Ozone

Ozone (O_3) is a molecule in which three atoms of oxygen are bonded together. The oxygen gas in the air we breathe has two oxygen atoms bonded together (O_2). Ozone is relatively unstable and releases its third oxygen atom readily so it oxidizes and burns things more readily than oxygen gas. This characteristic makes ozone in the troposphere (ground-level ozone) an air pollutant (see section 6.3) but in the stratosphere, ozone is essential for protecting life on Earth. Ozone in the stratosphere is formed when an oxygen molecule (O_2) is broken apart into two separate oxygen atoms (O) by high-energy ultra violet (UV) solar radiation. Each of the resulting oxygen atoms (O) in turn reacts with an oxygen molecule (O_2) creating ozone (O_3) (Figure 6.2.1). Once produced, ozone can absorb UV radiation breaking the molecule to regenerate an oxygen molecule and a single oxygen atom. So, while ozone is continually being replenished, it is also continually being destroyed. If the rate of ozone creation is equal to the rate of destruction, the total amount will remain the same. Because there is so much oxygen in our atmosphere, this "ozone-oxygen cycle" is continuously absorbing UV radiation.

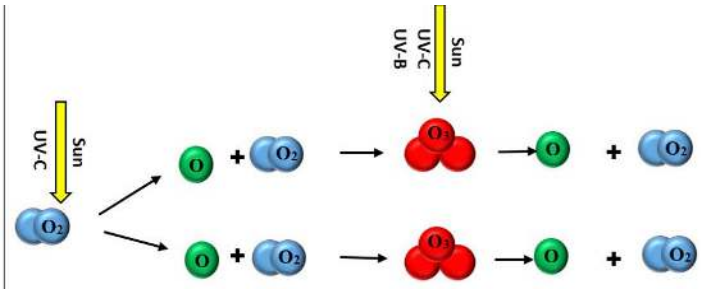


Figure 9.2.1: The "ozone-oxygen cycle" showing the natural formation and breaking of ozone (O3) in the stratosphere

9.2.1: The Ozone Layer

Ozone makes up a very small proportion of the gases in our atmosphere and most of it is concentrated in a portion of the stratosphere roughly 17–30 km above the surface. This region, called the **ozone layer**, acts as a protective shield that protects life on the surface of the Earth by absorbing most of the harmful portions of the high-energy UV radiation coming from the sun. UV is subdivided into three types namely UV-A, UV-B, and UV-C (Figure 6.2.2). Of these three types, UV-A is the least energetic and least harmful but can cause some damage to living cells, resulting in sunburns and skin damage. UV-A is also not absorbed by ozone in the stratosphere and is therefore transmitted through the atmosphere to the surface of the Earth. UV-C is the most harmful and most energetic of all UV, but is strongly absorbed in both the thermosphere and the stratosphere and does not make it to the Earth's surface. UV-C is the one responsible for the splitting of oxygen molecules in the stratosphere that leads to the formation of ozone. When ozone absorbs UV it regenerates oxygen atoms and releases heat which warms the upper part of the stratosphere. Since UV-C does not make it to the Earth's surface, the most harmful form of UV radiation that reaches the surface is UV-B. However, the amount of UV-B that reaches Earth's surface is significantly reduced because most of it is absorbed by ozone in the stratosphere. Ozone is the only known gas that absorbs UV-B.

Natural conditions in the stratosphere sustain a dynamic balance between the creation and destruction of ozone which helps to ensure the continued existence of the ozone layer. Any disruption of this balance that results in a higher rate of ozone destruction than ozone creation would result in depletion of ozone. Ozone depletion, consequently, leads to significant increase in the amount of harmful UV-B radiation that reaches the Earth's surface and this what we are talking about when we discuss the **ozone problem**.

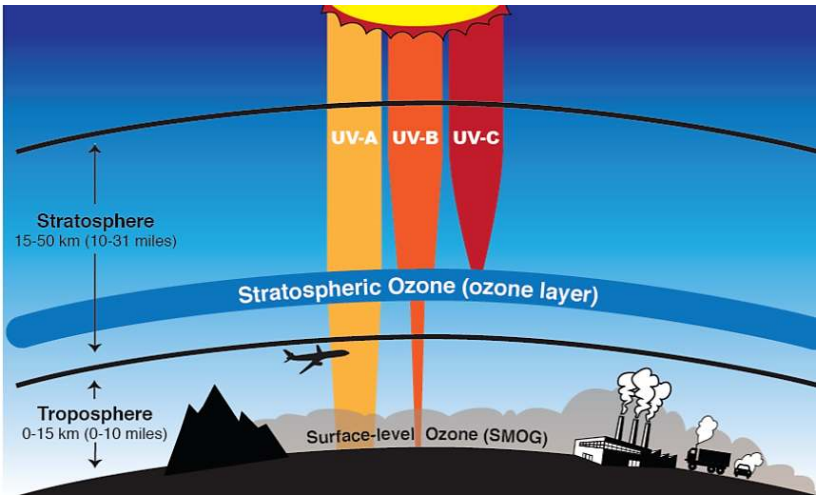


Figure 9.2.2: Ozone is "good" in the stratosphere because it absorbs most ultraviolet radiation. Ozone is "bad" in the troposphere because it is harmful to breathe and is the primary component of smog in summer. Source: www.nasa.gov

9.2.2: The Ozone Hole

The **Ozone Hole** is not really a "hole" but rather an area where the thickness of the ozone layer is greatly reduced. This hole is a result of ozone depletion that occurs every year during the Antarctic spring (Figure 9.2.3) and was first reported to the public by the British Antarctic Survey in 1985. The thickness of the ozone layer above the Antarctic continued to decline while the geographic area covered by the ozone hole continued to increase, reaching its lowest concentration (thickness) in 1994 and largest geographic area in 2000. Recent data shows that ozone concentration globally and in the Arctic and Antarctic is no longer declining.

During the long winter months of darkness over the Antarctic, atmospheric temperatures drop, creating unique conditions for chemical reactions that are not found anywhere else in the atmosphere. During this time, the Antarctic air mass is isolated from the rest of the atmosphere and circulates around the pole in what is known as the *polar vortex*. This isolation allows temperatures to drop low enough to create ice crystals at high altitudes. Ozone, nitric acid, sulfuric acid and other chlorine-containing molecules are absorbed on the surfaces of these ice particles. When the sun rises over the Antarctic in the southern spring (October), light rapidly releases free chlorine atoms into the stratosphere. The chlorine atoms react with ozone breaking it down to molecular oxygen and an oxygen atom. The polar vortex keeps the ozone-depleted air inside the vortex from mixing with the undepleted air outside the vortex, hence the formation of an ozone hole.

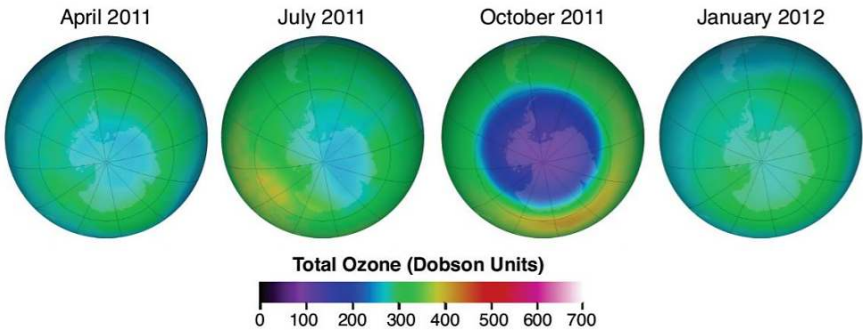


Figure 9.2.3: Ozone concentrations over the Antarctic region for four months representing the four seasons. Ozone concentration drops significantly during the Antarctic spring (October). Source: www.nasa.gov

9.2.3: Ozone Depletion

Global ozone concentrations change periodically with regular natural cycles such as changing seasons, winds, and long time scale sun variations. Concentrations of ozone in the atmosphere are measured in parts per billion (ppb). Scientists have been measuring ozone since the 1920's using ground-based instruments that look skyward. Satellite measurements of concentrations of atmospheric ozone began in 1970 and continue today.

Ozone depletion occurs when the rate at which ozone is broken down is greater than the rate of its creation, interfering with the dynamic balance between creation and destruction that maintains the ozone layer. When this happens, the amount of harmful UV-B radiation that reaches the Earth's surface increases. Ozone depletion was first identified over the Antarctic. Scientists suggested that reactions involving man-made chlorine-containing compounds were responsible for depleting ozone in the stratosphere. This hypothesis was based mostly on the physical and chemical properties of these compounds and knowledge about atmospheric conditions.

Chlorofluorocarbons (CFCs) are man-made compounds made up of chlorine, fluorine and carbon. These compounds were commonly used as propellants in everyday products such as shaving cream, hair spray, deodorants, paints and insecticides and as coolants in refrigerators and air conditioners. CFCs are extremely stable molecules and do not react with other chemicals in the lower atmosphere, part of the reason why they were considered a safe choice. Their stability means that they tend to remain in the atmosphere for a very long time. With the constant movement of air in the lower atmosphere, CFCs eventually make their way into the stratosphere. Exposure to ultraviolet radiation in the stratosphere breaks them apart, releasing chlorine atoms. Free chlorine (Cl) atoms then react with ozone molecules, taking one oxygen atom to form chlorine monoxide (ClO) and leaving an oxygen molecule (O_2) (Figure 9.2.4). The ClO reacts with other atoms freeing up the Cl making it available to react with another ozone molecule, repeating the cycle over and over resulting in ozone depletion.

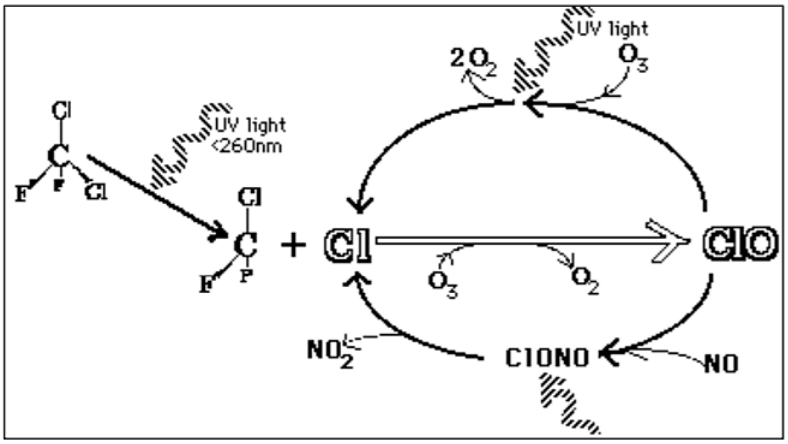


Figure 9.2.4: Ozone destruction. UV radiation frees a chlorine (Cl) atom from a CFC molecule, this atom reacts with ozone and produces an oxygen gas molecule and chlorine monoxide (ClO). ClO reacts with another oxygen atom, it frees up the Cl atom which then proceeds to destroy another ozone molecule. Source: Wiki commons https://commons.wikimedia.org/wiki/C..._catalysis.GIF

If each chlorine atom released from a CFC molecule destroyed only one ozone molecule, CFCs would pose very little threat to the ozone layer. However, when a chlorine monoxide molecule encounters a free atom of oxygen, the oxygen atom breaks up the chlorine monoxide, stealing the oxygen atom and releasing the chlorine atom back into the stratosphere to destroy another ozone molecule. These two reactions happen over and over again, so that a single atom of chlorine, acting as a catalyst, destroys many molecules (about 100,000) of ozone. The consequence of stratospheric ozone depletion is increased levels of UV-B radiation reaching the Earth's surface, posing a threat to human health and the environment. Figure Runaway argument for \eatSpaces? shows a lower than average amount of stratospheric ozone over North America in 1997 when it was abnormally cold compared to 1984, which was warmer than average, showing that ozone depletion does not exclusively affect just the South Pole (Antarctic).

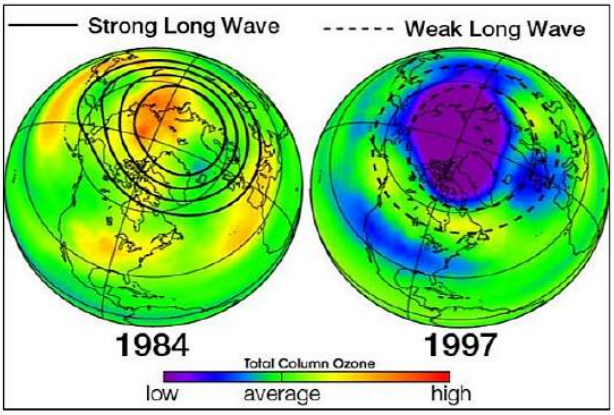


Figure 9.2.5: Seasonal ozone depletion over North America was lower in 1984 and greater in 1997. Source: NASA http://earthobservatory.nasa.gov/IOT...ew.php?id=1771

9.2.4: The Montreal Protocol

International policy efforts to restrict production of ozone depleting CFCs culminated in the 1987 treaty known as the **Montreal Protocol** in which signing nations agreed to cut CFC production in half by 1998. At least five follow-up agreements since then helped to deepen the cuts, advanced timetables for compliance, and addressed additional ozone-depleting substances such as halons, methyl chloroform, carbon tetrachloride, and hydrochlorofluorocarbons (HCFCs). Most countries around the world have phased out production of the substances covered by the agreements and industry has been able to shift to safer alternative chemicals. As a result, there's evidence that the Antarctic ozone hole has stopped growing worse, although recovery is not expected anytime soon. Phasing out CFCs and HCFCs is also beneficial in protecting the earth's climate, as these substances are also very damaging greenhouse gases.

As part of the United States' commitment to implementing the Montreal Protocol, the U.S. Congress amended the Clean Air Act (section 6.7), adding provisions for protection of the ozone layer. Most importantly, the amended Act required the gradual end to the production of chemicals that deplete the ozone layer. The Clean Air Act amendments passed by Congress requires the Environmental Protection Agency (EPA) to develop and implement regulations for the responsible management of ozone-depleting substances in the United States. Under the Clean Air Act, EPA has created several regulatory programs to address numerous issues, including:

- ending the production of ozone-depleting substances,
- ensuring that refrigerants and halon fire extinguishing agents are recycled properly,
- identifying safe and effective alternatives to ozone-depleting substances,
- banning the release of ozone-depleting refrigerants during the service, maintenance, and disposal of air conditioners and other refrigeration equipment,
- requiring that manufacturers label products either containing or made with the most harmful ozone depleting substances.

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9.3: Outdoor Air Pollution

Air pollution refers to the introduction, into the atmosphere, of substances that have harmful effects on humans, other living organisms, and the environment either as solid particles, liquid droplets or gases. Air pollution can result from natural processes such as dust storms, forest fires, and volcanic eruptions, or from human activities such as biomass burning, vehicular emissions, mining, agriculture, and industrial processes. Improved technology and government policies have helped reduce most types of outdoor air pollution in many industrialized countries including the United States, in recent decades. However, outdoor air quality is still a problem in less industrialized nations, especially in megacities of rapidly industrializing nations such as China and India.

Outdoor pollutants can come from **stationary (point)** sources or **mobile (nonpoint)** sources (Figure 9.3.1). Stationary sources have a fixed location, for example power plant smokestacks, burning, construction sites, farmlands and surface mines among others. Mobile sources of air pollutants move from place to place while emitting pollutants. Examples of mobile sources include vehicles, aircrafts, ships, and trains.

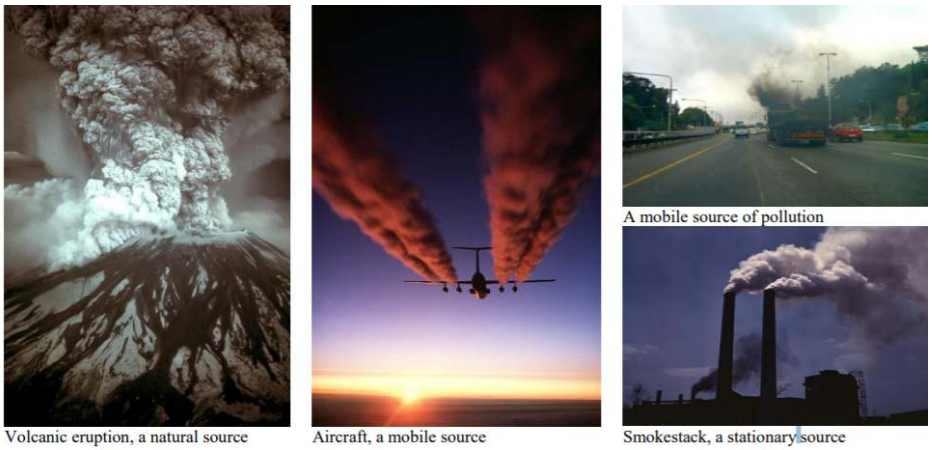


Figure 9.3.1: Images showing various sources of air pollution, including natural and anthropogenic, stationary and mobile. Source: All images obtained from Wiki Commons commons.wikimedia.org/wiki/Air_pollution

Pollutants are categorized into two major types based on how they originated namely primary and secondary pollutants. **Primary pollutants** are those released directly from the source into the air in a harmful form. The primary pollutants that account for nearly all air pollution problems are carbon monoxide (58%), volatile organic compounds (VOCs, 11%), nitrogen oxides (15%), sulfur dioxides (13%), and particulate material (3%). **Secondary pollutants** are produced through reactions between primary pollutants and normal atmospheric compounds. For example, ground-level ozone forms over urban areas through reactions, powered by sunlight, between primary pollutants (oxides of nitrogen) and other atmospheric gases such as VOCs.

9.3.1: 6.3.1: Criteria pollutants

Under the Clean Air Act (section 6.7.1), the Environmental Protection Agency (EPA) establishes air quality standards to protect public health and the environment. EPA has set national air quality standards for six common air pollutants namely: 1) carbon monoxide; 2) ground-level ozone; 3) nitrogen dioxide; 4) Sulfur dioxide; 5) lead; and 6) particulate matter (also known as particle pollution). Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA calls these pollutants "criteria" air pollutants because it regulates them by developing human health-based and/or environmentally-based criteria (science-based guidelines) for setting permissible levels. The set of limits based on human health is called primary standards. Another set of limits intended to prevent environmental and property damage is called secondary standards.

1. **Carbon Monoxide (CO)**: is a colorless, odorless gas emitted from combustion processes, specifically, the incomplete combustion of fuel. Nationally and, particularly in urban areas, the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. At extremely high levels, CO can cause death.
2. **Ground-level ozone (O_3)**: is a colorless gas with a slightly sweet odor that is not emitted directly into the air, but is created by the interaction of sunlight, heat, oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). Ozone is likely to reach

unhealthy levels on hot sunny days in urban environments. Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of NO_x and VOCs.

3. **Nitrogen dioxide (NO_2)**: is one of a group of highly reactive gasses known as "oxides of nitrogen," or "nitrogen oxides (NO_x)." Other nitrogen oxides include nitrous acid and nitric acid. NO_2 is a yellowish-brown to reddish-brown foul-smelling gas that is a major contributor to smog and acid rain. Nitrogen oxides result when atmospheric nitrogen and oxygen react at the high temperatures created by combustion engines. Most emissions in the U.S. result from combustion in vehicle engines, electrical utility, and industrial combustion.
4. **Sulfur dioxide (SO_2)**: Sulfur dioxide is one of a group of highly reactive gasses known as “oxides of sulfur.” The largest sources of SO_2 emissions are from fossil fuel combustion at power plants (73%) and other industrial facilities (20%). Smaller sources of SO_2 emissions include industrial processes such as extracting metals from their ores, and the burning of high sulfur containing fuels by locomotives, large ships, and non-road equipment.
5. **Lead (Pb)**: is a metal found naturally in the environment as well as in manufactured products. The major sources of lead emissions have historically been from fuels in motor vehicles (such as cars and trucks) and industrial sources. As a result of EPA's regulatory efforts to remove lead from gasoline, emissions of lead from the transportation sector dramatically declined by 95 percent between 1980 and 1999, and levels of lead in the air decreased by 94 percent during that time period. The major sources of lead emissions today are ore and metal processing and piston-engine aircraft operating on leaded aviation gasoline. Today, the highest levels of lead in air are usually found near lead smelters.
6. **Particulate material (PM)**, sometimes known simply as “**particulates**” refers to solid particles and liquid droplets suspended in the air we breathe. Particulate pollution is made up of a variety of components, including acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (pollen and mold spores). The size of the particles in directly linked to their potential for causing health problems. Particles that are 10 micrometers in diameter or smaller generally pass through the throat and nose and enter the lungs. EPA groups these into two types: "**inhalable coarse particles**," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "**fine particles**," with diameters that are 2.5 micrometers and smaller. How small is 2.5 micrometers? Think about a single hair from your head. The average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle (Figure 9.3.2). Our respiratory systems are equipped to filter larger particles out of the air once it is inhaled. However, the lungs are vulnerable to both coarse particles (PM_{10}), and fine particles ($PM_{2.5}$). These can slip past the respiratory system's natural defenses and get deep into the lungs and some may even get into the bloodstream. Coarse particles come from road dust while fine particles come from combustion processes.

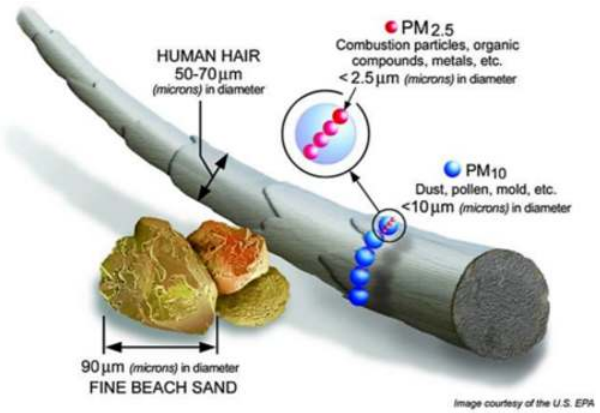


Figure 9.3.2: Graphic showing size comparison of particulate material (PM_{10} and $PM_{2.5}$) compared to fine beach sand and human hair. Source: US EPA www.epa.gov/air/particlepollution/basic.html

9.3.2: 6.3.2: Volatile Organic Compounds

Volatile organic compounds (VOCs) are carbon-containing chemicals emitted as gases from natural and human-made sources. Natural sources of VOCs include plants, the largest source, and bacteria in the guts of termites and ruminant animals. These compounds are generally oxidized to carbon monoxide and carbon dioxide in the atmosphere. VOCs are of great concern because they are precursors for the formation of ozone, a secondary air pollutant.

A large number of synthetic organic chemicals such as benzene, toluene, formaldehyde, vinyl chloride, chloroform, and phenols are widely used as ingredients in countless household products. Paints, paint strippers, varnishes, many cleaning, disinfecting,

cosmetic, degreasing, and hobby products all contain VOCs. Fuels are also made up of organic chemicals. All of these products can release organic compounds while you are using them, and, to some degree, when they are stored. The “new car smell” characteristic of new cars is from a complex mix of dozens of VOC. Also, concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. They are often held responsible for sick building syndrome, an illness resulting from indoor pollution in which the specific cause is not identified.

9.3.3: 6.3.3: Smog

Smog is a mixture of air pollutants (sulfur dioxide, nitrogen oxides, ozone, and particulates) that often form over urban areas as a result of fossil fuel combustion. The term was coined from the terms “smoke” and “fog” referring to a brownish haze that pollutes the air, greatly reducing visibility and making it difficult for some people to breathe (Figure 9.3.3 and 9.3.4). There are two main types of smog: industrial and photochemical smog. **Industrial smog** is produced primarily by the burning of fossil fuels which produces carbon dioxide (from complete combustion), carbon monoxides (from partial combustion), sulfur, and mercury. The sulfur reacts with other chemicals in the atmosphere producing several sulfur compounds including sulfur dioxide. These compounds along with particulate material make up industrial smog. **Photochemical smog** is formed when sunlight drives chemical reactions between primary pollutants from automobiles and normal atmospheric compounds. The product is a mix of over 100 different chemicals with the most abundant being ground-level ozone.



Figure 9.3.3: Smog over Almaty city, Kazakhstan. Photo by Igors Jefimovs. Source: Wikicommons commons.wikimedia.org/wiki/C...dia/File:Smog_ over_Almaty.jpg



Figure 9.3.4: Smog over Santiago in Chile. Source: German Wikipedia commons.wikimedia.org/wiki/C...#/media/File:Santiago30std.jpg

9.3.4: 6.3.4: Toxic pollutants

Toxic air pollutants, also known as hazardous air pollutants, are those pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples of toxic air pollutants include benzene, which is found in gasoline; perchloroethylene, which is emitted from some dry cleaning facilities; methylene chloride, which is used as a solvent and paint stripper by a number of industries; and others such as dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as volcanic eruptions and forest fires. Exposure to air toxics is mainly through breathing but some toxic air pollutants such as mercury can deposit onto soils or surface waters, where they are taken up by plants and ingested by animals and are eventually magnified up through the food chain. Like humans, animals may experience health problems if exposed to sufficiently high quantities of air toxics over time.

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9.4: Indoor Air Pollution

In both developed and developing nations, indoor air pollution poses a greater health risk than outdoor air pollution. According to the World Health Organization (WHO) and other agencies such as the Environmental Protection Agency (EPA), indoor air generally contains higher concentrations of toxic pollutants than outdoor air. Additionally, people generally spend more time indoors than outdoors, hence, the health effects from indoor air pollution in workplaces, schools, and homes are far greater than outdoor. Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems in homes. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home.

Outdoor air enters and leaves a building by infiltration, natural ventilation, and mechanical ventilation. In infiltration, outdoor air flows into the house through openings, joints, and cracks in walls, floors, and ceilings, and around windows and doors. In natural ventilation, air moves through opened windows and doors. Air movement associated with infiltration and natural ventilation is caused by air temperature differences between indoors and outdoors and by wind. Finally, there are a number of mechanical ventilation devices, from outdoor-vented fans that intermittently remove air from a single room, such as bathrooms and kitchen, to air handling systems that use fans and duct work to continuously remove indoor air and distribute filtered and conditioned outdoor air to strategic points throughout the house. The rate at which outdoor air replaces indoor air is described as the air exchange rate. When there is little infiltration, natural ventilation, or mechanical ventilation, the air exchange rate is low and pollutant levels can increase. High temperature and humidity levels can also increase concentrations of some pollutants.

There are many sources of indoor air pollution in any home (Figure 9.4.1). These include combustion sources such as oil, gas, kerosene, coal, wood, and tobacco products; building materials and furnishings as diverse as deteriorated, asbestos-containing insulation, wet or damp carpet, and cabinetry or furniture made of certain pressed wood products; products for household cleaning and maintenance, personal care, or hobbies; central heating and cooling systems and humidification devices. Pollutants causing indoor air pollution can also originate from outside sources such as radon, pesticides, and outdoor air pollution. Radon is a naturally occurring radioactive gas produced from the decay of uranium in rock. If a building/home is constructed in an area with uranium containing rock, the gas can seep through the foundations and accumulate in basements. Exposure to radon can cause lung cancer.

The relative importance of any single source depends on how much of a given pollutant it emits and how hazardous those emissions are. In some cases, factors such as how old the source is and whether it is properly maintained are significant. For example, an improperly adjusted gas stove can emit significantly more carbon monoxide than one that is properly adjusted. Some sources, such as building materials, furnishings, and household products like air fresheners, release pollutants more or less continuously. Other sources, related to activities carried out in the home, release pollutants intermittently. These include smoking, the use of unvented or malfunctioning stoves, furnaces, or space heaters, the use of solvents in cleaning and hobby activities, the use of paint strippers in redecorating activities, and the use of cleaning products and pesticides in house-keeping. High pollutant concentrations can remain in the air for long periods after some of these activities.

Risks from indoor air pollution differ between less industrialized and industrialized nations. Indoor pollution has a greater impact in less industrialized nations where many people use cheaper sources of fuel such as wood, charcoal, and crop waste among others for cooking and heating, often with little or no ventilation. The most significant indoor pollutant, therefore, is soot and carbon monoxide. In industrialized nations, the primary indoor air health risks are cigarette smoke and radon.

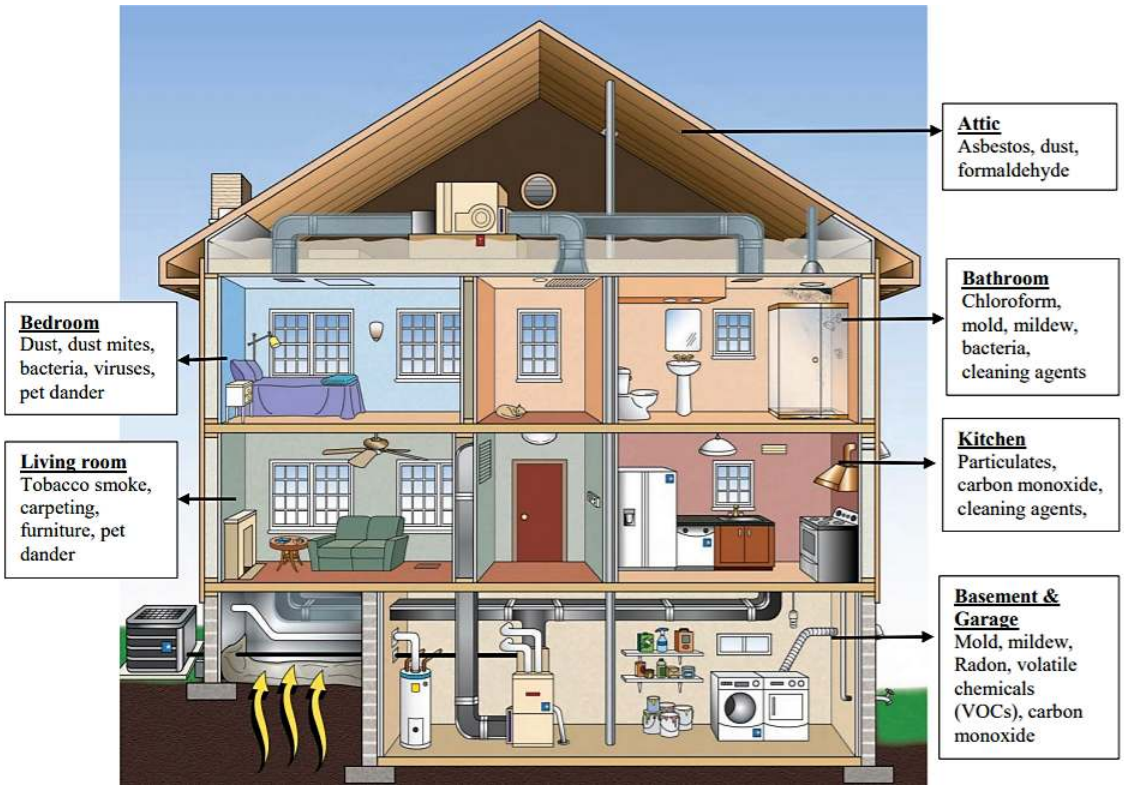


Figure 9.4.1: Sources of indoor air pollution. Image source: EPA http://www.epa.gov/iaq/pdfs/careforyourair.pdf

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9.5: Effects of Air Pollution on Human Health

The World Health Organization (WHO) and other international agencies recognize air pollution as a major threat to human health. Numerous scientific studies have linked air pollution to a variety of health problems (Table 9.5.1) including: aggravation of respiratory and cardiovascular diseases; decreased lung function; increased frequency and severity of respiratory symptoms such as difficulty breathing and coughing; increased susceptibility to respiratory infections; effects on the nervous system, including the brain, such as IQ loss and impacts on learning, memory, and behavior; cancer; and premature death. Immediate effects of air pollution may show up after a single exposure or repeated exposures. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure.

Immediate effects of air pollution include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Sometimes the treatment is simply eliminating the person's exposure to the source of the pollution, if it can be identified. Symptoms of some diseases, including asthma, hypersensitivity pneumonitis, and humidifier fever , may also show up soon after exposure to some indoor air pollutants.

Table 9.5.1: Sources and health effects of criteria pollutants

Pollutant	Sources	Health Effects
Ground-level Ozone (O_3)	Secondary pollutant typically formed by chemical reaction of volatile organic compounds (VOCs) and NO_x in the presence of sunlight.	Decreases lung function and causes respiratory symptoms, such as coughing and shortness of breath; aggravates asthma and other lung diseases leading to increased medication use, hospital admissions, emergency department (ED) visits, and premature mortality.
Particulate Matter (PM)	Emitted or formed through chemical reactions; fuel combustion (e.g., burning coal, wood, diesel); industrial processes; agriculture (plowing, field burning); and unpaved roads.	Short-term exposures can aggravate heart or lung diseases leading to respiratory symptoms, increased medication use, hospital admissions, ED visits, and premature mortality; long-term exposures can lead to the development of heart or lung disease and premature mortality.
Lead	Smelters (metal refineries) and other metal industries; combustion of leaded gasoline in piston engine aircraft; waste incinerators; and battery manufacturing.	Damages the developing nervous system, resulting in IQ loss and impacts on learning, memory, and behavior in children. Cardiovascular and renal effects in adults and early effects related to anemia.
Oxides of Nitrogen (NO_x)	Fuel combustion (e.g., electric utilities, industrial boilers, and vehicles) and wood burning.	Aggravate lung diseases leading to respiratory symptoms, hospital admissions, and ED visits; increased susceptibility to respiratory infection.
Carbon Monoxide (CO)	Fuel combustion (especially vehicles), industrial processes, fires, waste combustion, and residential wood burning.	Reduces the amount of oxygen reaching the body’s organs and tissues; aggravates heart disease, resulting in chest pain and other symptoms leading to hospital admissions and ED visits.
Sulfur Dioxide (SO_2)	Fuel combustion (especially high-sulfur coal); electric utilities and industrial processes; and natural sources such as volcanoes.	Aggravates asthma and increased respiratory symptoms. Contributes to particle formation with associated health effects.

Source: www.epa.gov

The likelihood of immediate reactions to air pollutants depends on several factors. Age and preexisting medical conditions are two important influences. Some sensitive individuals appear to be at greater risk for air pollution-related health effects, for example, those with pre-existing heart and lung diseases (e.g., heart failure/ischemic heart disease, asthma, emphysema, and chronic bronchitis), diabetics, older adults, and children. In other cases, whether a person reacts to a pollutant depends on individual sensitivity, which varies tremendously from person to person. Some people can become sensitized to biological pollutants after repeated exposures, and it appears that some people can become sensitized to chemical pollutants as well.

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9.6: Acid Rain

Pure rainfall is slightly acidic, pH 5.6, because water reacts with atmospheric carbon dioxide to produce weak carbonic acid. When higher than normal amounts of nitric and sulfuric acid occur in the atmosphere, the result is precipitation with a pH below 5.6 which is referred to as **acid rain**. Acid rain includes both wet deposition (rainfall, snow, fog) and dry deposition (particulates). Acid rain formation results from both natural sources, such as volcanoes and decaying vegetation, and man-made sources, primarily emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) resulting from fossil fuel combustion. In the United States, roughly 2/3 of all SO_2 and ¼ of all NO_x come from electric power generation that relies on burning fossil fuels, like coal. Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds (Figure 9.6.1). The result is a mild solution of sulfuric acid and nitric acid. When sulfur dioxide and nitrogen oxides are released from power plants and other sources, prevailing winds blow these compounds across state and national borders, sometimes over hundreds of miles. Regions of greatest acidification tend to be downwind from heavily industrialized source areas of pollution.

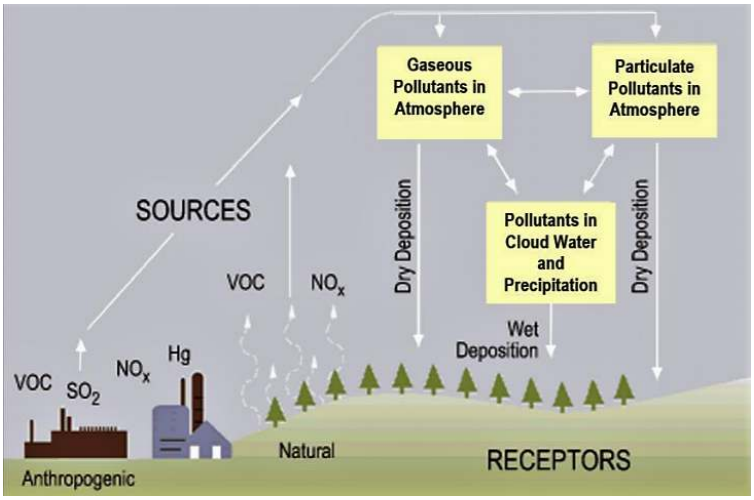


Figure 9.6.1: Formation of acid rain from both natural and anthropogenic pollutants Source: US EPA www.epa.gov/acidrain/images/origins.gif

- Acid rain is a serious environmental problem that is particularly damaging to lakes, streams, and forests and the plants and animals that live in these ecosystems, as well as to infrastructure. Some of the impacts include:
- Leaching of soil nutrients such as calcium, magnesium, and potassium out of the topsoil, altering soil chemistry and harming plants and soil organisms.
- Acid rain causes the release of substances that are toxic to trees and other plants, such as aluminum, into the soil. Scientists hypothesize that this combination of loss of soil nutrients and increase of toxic aluminum may be one way that acid rain harms trees (Figure 6.6.2). Such substances also wash away in the runoff and are carried into streams, rivers, and lakes.
- Damage to automotive paints and other coatings. The reported damage typically occurs on horizontal surfaces and appears as irregularly shaped, permanently etched areas.
- Acidic particles contribute to the corrosion of metals (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects significantly reduce the societal value of buildings, bridges, cultural objects (such as statues, monuments, and tombstones) (Figure 6.6.3).
- Sulfates and nitrates that form in the atmosphere contribute to visibility impairment, meaning we cannot see as far or as clearly through the air. Sulfate particles account for 50 to 70 percent of the visibility reduction in the eastern part of the U.S., affecting our enjoyment of national parks, such as the Shenandoah and the Great Smoky Mountains



Figure 9.6.2: Effects of acid rain on trees, Jizera Mountains, Czech Republic. Image from Wikimedia commons, Public Domain. commons.wikimedia.org/wiki/C...:Acid_rain#/media/File:Acid_rain_woods1.JPG



Figure 9.6.3: Effects of acid rain on a monument in Greenwood cemetery, Brooklyn New York. Photo by James P. Fischer. commons.wikimedia.org/wiki/C...rain#/media/File:Charlotte_Canda_Memorial_(Angel).jpg

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9.7: Air Pollution Legislation

In 1930, 63 people died and 1000 were sickened in Belgium when a phenomenon referred to as temperature inversion caused pollutants to be trapped near the surface, leading to a sudden spike in atmospheric sulfur levels. In October 1948, a thick cloud of air pollution formed above the industrial town of Donora, Pennsylvania. The cloud which lingered for five days, killed 20 people and caused sickness in 6,000 of the town's 14,000 people. In 1952, the infamous London fog in which acid aerosols trapped in the lower atmosphere killed 4000 people. Events like these alerted us to the dangers that air pollution poses to public health.

9.7.1: 6.7.1: Clean Air Act

In the United States, several federal and state laws were passed, including the original Clean Air Act of 1963, which established funding for the study and cleanup of air pollution. But there was no comprehensive federal response to address air pollution until Congress passed a much stronger Clean Air Act in 1970. That same year Congress created the Environmental Protection Agency (EPA) and gave it the primary role in carrying out the law. Since 1970, EPA has been responsible for a variety of Clean Air Act programs to reduce air pollution nationwide. The Clean Air Act is a federal law covering the entire country. However, states, tribes and local governments do a lot of the work to meet the Act's requirements. For example, representatives from these agencies work with companies to reduce air pollution. They also review and approve permit applications for industries or chemical processes.

9.7.2: 6.7.2: EPA's Role

EPA's mission is basic health and environmental protection from air pollution for all Americans. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that focus on:

- reducing outdoor, or ambient, concentrations of air pollutants that cause smog, haze, acid rain, and other problems;
- reducing emissions of toxic air pollutants that are known to, or are suspected of, causing cancer or other serious health effects; and
- phasing out production and use of chemicals that destroy stratospheric ozone.

Under the Clean Air Act, EPA sets limits on certain air pollutants, including setting limits on how much can be in the air anywhere in the United States. The Clean Air Act also gives EPA the authority to limit emissions of air pollutants coming from sources like chemical plants, utilities, and steel mills. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits than those set by EPA. EPA must approve state, tribal, and local agency plans for reducing air pollution. If a plan does not meet the necessary requirements, EPA can issue sanctions against the state and, if necessary, take over enforcing the Clean Air Act in that area. EPA assists state, tribal, and local agencies by providing research, expert studies, engineering designs, and funding to support clean air progress. Since 1970, Congress and the EPA have provided several billion dollars to the states, local agencies, and tribal nations to accomplish this.

9.7.3: 6.7.3: State and Local Governments' Role

It makes sense for state and local air pollution agencies to take the lead in carrying out the Clean Air Act. They are able to develop solutions for pollution problems that require special understanding of local industries, geography, housing, and travel patterns, as well as other factors. State, local, and tribal governments also monitor air quality, inspect facilities under their jurisdictions and enforce Clean Air Act regulations. States have to develop State Implementation Plans (SIPs) that outline how each state will control air pollution under the Clean Air Act. A SIP is a collection of the regulations, programs and policies that a state will use to clean up polluted areas. The states must involve the public and industries through hearings and opportunities to comment on the development of each state plan.

9.7.4: 6.7.4: Outcomes of the Clean Air Act

For more than forty years, the Clean Air Act has cut pollution as the U.S. economy has grown. The combined emissions of the six criteria pollutants has continued to decrease while population, gross domestic product, energy consumption, and vehicle miles travelled have all continued to increase (Figure 6.7.1). The following is a summary of some of the accomplishments of the Clean Air Act:

- Clean Air Act programs have lowered levels of the six criteria pollutants - particulates, ozone, lead, carbon monoxide, nitrogen dioxide and sulfur dioxide - as well as numerous toxic pollutants.

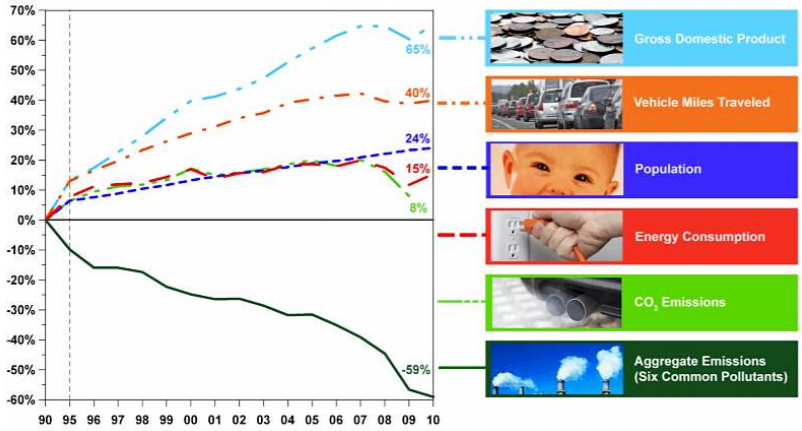


Figure 9.7.1: Showing a decrease in the combined emissions for the six criterial pollutants in the past two decades. Meanwhile, population, energy consumption, vehicle miles travelled, and gross domestic product have all increased. Source: US EPA

- From 1970 to 2012, aggregate national emissions of the six common pollutants alone dropped an average of 72 percent while gross domestic product grew by 219 percent (Figure 6.7.1). This progress reflects efforts by state, local and tribal governments; EPA; private sector companies; environmental groups and others.
- The emissions reductions have led to dramatic improvements in the quality of the air that we breathe.
- These air quality improvements have enabled many areas of the country to meet national air quality standards set to protect public health and the environment. For example, all of the 41 areas that had unhealthy levels of carbon monoxide in 1991 now have levels that meet the healthbased national air quality standard. A key reason is that the motor vehicle fleet is much cleaner because of Clean Air Act emissions standards for new motor vehicles.
- Airborne lead pollution, a widespread health concern before EPA phased out lead in motor vehicle gasoline under Clean Air Act authority, now meets national air quality standards in most areas of the country.

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9.8: Appendix

9.8.1: Sources

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9.8.2: Websites

Wikimedia Commons commons.wikimedia.org/wiki/ Source of various photos and images

Environmental Protection Agency http://www.epa.gov/

National Aeronautics and Space Administration (NASA) http://www.nasa.gov/

National Weather Service www.srh.noaa.gov/jetstream/atmos/layers.htm

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CHAPTER OVERVIEW

10: Climate Change

10.1: The Carbon Cycle

10.2: Human Impacts on the Carbon Cycle

10.3: The Science of Climate Change

10.4: Greenhouse Gases

10.5: Tools Scientists Use to Study Climate Change

10.6: Consequences of Climate Change

10.7: Looking Forward- Climate Strategies

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10.1: The Carbon Cycle

Carbon, just like all other elements, cycles through the environment and is constantly in the process of changing forms and locations. In this section, as in many other pieces of scientific literature, we will periodically refer to carbon by its chemical symbol, C. There is no new carbon in the world, rather, all carbon is continuously recycled from one form to another. All plants, animals (including humans!), fungi, bacteria, and archaea are made of mostly carbon-based molecules such as lipids, carbohydrates, proteins, and nucleic acids. Carbon is also prevalent in soils, rocks and sediments, water bodies (dissolved), and the atmosphere. These locations where carbon resides are known as pools or reservoirs, and the processes that move carbon from one location to another are called fluxes. Figure 7.1.1 shows a simplified version of the global carbon cycle.

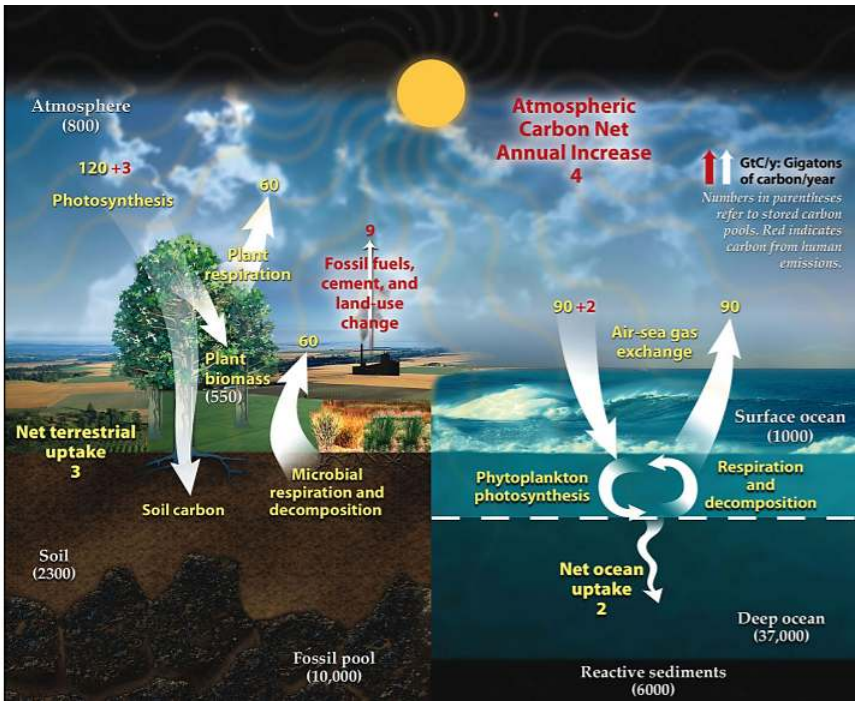


Figure 10.1.1: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.

Some reservoirs hold on to carbon for only a short time. **Aerobic** (oxygen-using) organisms convert carbohydrates created by other organisms into **carbon dioxide** (CO_2) almost instantaneously, which they exhale into the atmosphere. When considering the flux of respiration, living organisms are the **source** of carbon, and the atmosphere is the **sink**. The carbon stays in the reservoir of living organisms for a relatively short time, depending on their life span, from hours and days to years and decades. In contrast, the **residence time** of carbon in the fossil pool is dramatically different. Fossil fuels form over a course of 300-400 million years, forming from ancient plants and animals that decomposed slowly under very specific, **anaerobic** (without oxygen) conditions in wetland environments. Their bodies were gradually transformed by the heat and pressure of the Earth's crust into the fossil fuels that we mine today to provide petroleum oil, natural gas, and coal (see more on this in chapter 4).

Reservoirs and fluxes of importance

The two largest reservoirs of carbon on Earth are the oceans, which cover the majority of Earth's surface, and the **lithosphere** (the mineral fraction of Earth: soils, rocks, and sediments). Each of these reservoirs holds more carbon than all of the other reservoirs combined. Much of the carbon stored in these reservoirs, especially deep in the lithosphere or in deep ocean environments, has an extremely long residence time, and does not actively participate in rapid fluxes. The notable exceptions here, of course, are fossil fuels, which are mined by humans and converted into gaseous forms of carbon through combustion.

Biomass, which is biological material derived from living, or recently living organisms, is a much smaller reservoir of carbon. The amount of carbon stored in all of the terrestrial vegetation (550 Gt C) (Gt = gigatonne = 10^9 metric tons = 10^{15} g) is just a fraction of that stored in the oceans (38,000 Gt C) and lithosphere (18,000 Gt C). All of the carbon that is currently stored in all of the

vegetation on Earth got there through the process of **photosynthesis**. Plants and other photosynthetic organisms are called **primary producers**, because they "fix" atmospheric CO_2 into organic carbon, such as sugar, a form that is usable by animals and other organisms that need to consume their carbon molecules.

Photosynthetic organisms, such as plants, algae, and cyanobacteria, bring in CO_2 from the atmosphere and, using energy from the sun, convert CO_2 and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (Equation 10.1.1). These glucose molecules are simple sugars that **autotrophs** ("self-feeders") can "burn" for energy, or transform into other usable carbon molecules through the process of cellular respiration (described in the next paragraph), or to build plant biomass. Photosynthesis takes place in organelles called **chloroplasts**, shown in Figure 10.1.2. Photosynthesis accounts for 123 Gt of C per year that is removed from the atmosphere and stored in plant biomass. Such a massive amount of photosynthesis occurs on Earth that no other single flux moves as much carbon in the same timeframe.

$$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2 \tag{10.1.1}$$

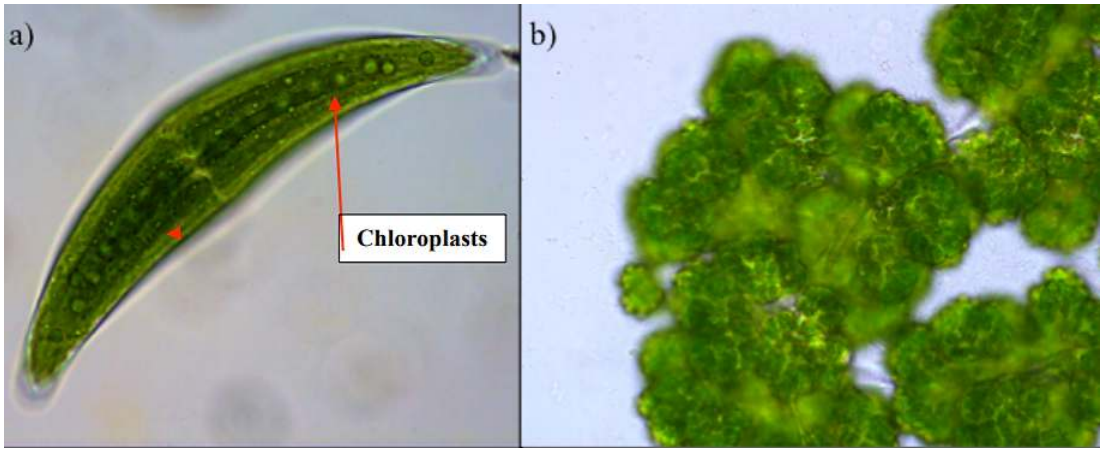


Figure 10.1.2: Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll a they contain, and are the site of photosynthesis. Chlorophyll a is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) Closterium moniliferum Ralfs, (Chlorophyta) green coccoid algae; b) Botryococcus braunii Kützing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

Biomass in the carbon cycle, including plants and animals, is the reservoir of carbon that we are most likely most familiar with, and also the reservoir that is most readily available to us. We all participate in the flux of **consumption** of carbon when we eat food. All of our food is simply plant and/or animal biomass. Our body takes the carbon molecules contained in this biomass, and uses them, along with the oxygen we breathe in, for **cellular respiration** to create the adenosine triphosphate (ATP) we need for energy. The products of cellular respiration include the CO_2 we exhale, water, and energy that is stored in ATP (Equation 10.1.2). Our bodies also builds additional biomass out of the carbon molecules in this food, allowing us to create new cells for growth or replenishment. This is the only way we, and all other **heterotrophs** ("other-eaters"), can bring in the carbon we need to build and maintain our bodies. Remember, you are what you eat!

$$C_6H_{12}O_6 + CO_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \tag{10.1.2}$$

Cellular respiration is an important flux in the carbon cycle, and one that contributes carbon to the atmosphere. Remember that animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through their food. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO_2 through photosynthesis. Any carbon molecules that are left over after the organism has acquired sufficient energy through cellular respiration make up the biomass of the plant. As plants and animals die and decompose, their bodies are consumed by decomposer organisms such as fungi and bacteria. Through the flux of **decomposition**, some decaying biomass is converted into atmospheric carbon by the decomposers, while most of the biomass is buried into the soil, contributing to soil carbon. In oxygen-rich environments, decomposers rapidly consume dead and decaying biomass using the same process of aerobic cellular respiration described above. In oxygen-deficient environments, decomposers complete other metabolic pathways, and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include **methane** (CH_4), **nitrous oxide** (N_2O), and the foul-smelling hydrogen sulfide (H_2S).

The biomass reservoir of the carbon cycle is also important to us as a source of energy. Through the flux of **combustion**, we convert the **potential energy** held in biomass into heat energy that we can use, and release carbon dioxide in the process. If you have ever burned logs on a campfire, or even burned food on the stove, you have completed this flux of biomass combustion. Of course, this happens naturally as well, the best example being natural forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration. The difference is that in cellular respiration, energy is released in a controlled fashion, and captured in ATP molecules. In combustion, all of this energy is released rapidly in the form of light and heat.

As all of the fluxes we've discussed so far involve the atmosphere, we have not yet discussed the flux that connects the atmosphere to the oceans. Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae or cyanobacteria (also called phytoplankton in Figure 10.1.1), and second through the chemical reaction of **ocean-atmosphere exchange**. The ocean, as with all surface water bodies, always contains some dissolved CO_2. This CO_2 is in **equilibrium** with the CO_2 in the air. Some atmospheric CO_2 is constantly dissolving into the ocean, while some dissolved CO_2 is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in Figure 10.1.1, however, this is no longer the case. In the section Human impacts on the carbon cycle, we will discuss why this is the case.

Activity: Better understanding the carbon cycle

To further review the carbon cycle, and better understand the human impacts on it, use this interactive graphic from Woods Hole laboratories: http://www.whoi.edu/feature/carboncycle/. As you will see, the information described in this text is only a small portion of the total carbon cycle on Earth. Finally, complete Table 10.1.1 as a way to review the sink/source relationship within this cycle. See if you can correctly identify the source and sink of carbon for each of these important fluxes in the carbon cycle.

Table 10.1.1: Practice understanding the sink/source relationship with cycles

Carbon flux	Carbon source	Carbon sink
Cellular respiration	Carbohydrates in living organisms	CO_2 in the atmosphere
Photosynthesis		
Consumption		
Combustion		
Decomposition		
Ocean/atmosphere exchange		
Fossil fuel formation		

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10.2: Human Impacts on the Carbon Cycle

Humans, just like all other living organisms, have impacted the global carbon cycle since the dawn of our species. However, the magnitude of our impacts has changed dramatically throughout history. The **Industrial Revolution**, which occurred around the turn of the 19th century, began to make major changes in the use of resources around the world. Beginning in Britain, industrialization eventually affected the whole world. The development of coal-fueled steam power, and later transportation following the discovery of large oil deposits, had enormous influence on the economic and social structure of the world. As the world accelerated in the production and transportation of manufactured goods, the production and consumption of fossil fuels grew. As economic growth continued to increase, so did the production of carbon dioxide through fossil fuel combustion. See Figure 10.2.2 later in this text.

Some of the human impacts on the carbon cycle have been quantified for you in Figure 7.1.1. Changes to fluxes in the carbon cycle that humans are responsible for include: increased contribution of CO_2 and other **greenhouse gases** to the atmosphere through the combustion of fossil fuels and biomass; increased contribution of CO_2 to the atmosphere due to land-use changes; increased CO_2 dissolving into the ocean through ocean-atmosphere exchange; and increased terrestrial photosynthesis. The first two impacts, both contributing excess CO_2 to the atmosphere at a rate of 4 Gt of carbon per year have, by far, the largest impact on our planet. For this reason, this is the change that we will most often focus on throughout this section. The excess CO_2 in the atmosphere is responsible for the increased CO_2 dissolving into the ocean, which we will discuss later in this section. This is also, in part, responsible for the increased terrestrial photosynthesis that can be observed, as additional CO_2 is available to plants for photosynthesis. However, intensive agricultural and forestry practices also contribute to the change in this flux.

One characteristic example of a human impact on the carbon cycle is illustrated in Figure 10.2.1. Throughout most of our recent human history, people have been physically altering the landscape around them in order to have more control over their surroundings and increase their odds of survival. One way that people have done this is through agriculture. In order for most forms of agriculture to be successful, native vegetation is eliminated or minimized. Resources from this native vegetation, such as wood, may be used for combustion to provide heat, sanitation, or fuel for cooking. Combustion may also be used as an efficient way to clear the land and make way for crops or grazing lands for livestock. Often, settlements are formed around these newly fashioned agricultural fields, and the land is used in a similar fashion for many years in the future.

Let's identify the ways in which humans are impacting the carbon cycle in this scenario of agricultural establishment. You should be able to identify from the above paragraph that the flux of combustion will release CO_2 previously held in vegetation into the atmosphere. In addition, remember that the land that used to house native vegetation is now home to agricultural lands. In most controlled agricultural environments, there is less total vegetative biomass than there would be under natural conditions. This decreased biomass leads to lower total photosynthesis rates, thereby decreasing the amount of CO_2 that is removed from the atmosphere and turned into plant biomass. Also, open soil on the fields between crops, during the winter months, or as a result of overgrazing allows for the air to penetrate deep into the soil structure. This provides the environment necessary for enhanced aerobic respiration by soil microorganisms. This decreases soil carbon, which can lead to erosion and soil degradation, and also releases additional CO_2 to the atmosphere.

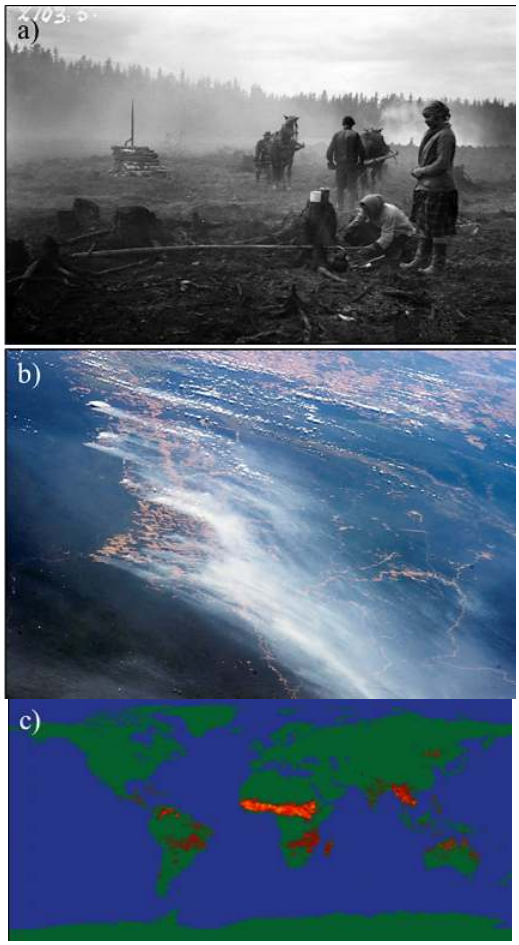


Figure 10.2.1: Impacts of slash and burn agriculture and biomass burning. a) Slash and burn agriculture in Maaninka, Finland. This kind of agriculture was still in use in Finland at the end of the 1920s. b) Slash and burn agriculture at the margins of the Amazon Rainforest in South America captured by astronauts on the International Space Station in August, 2014. Credit: Astronaut photograph ISS040-E-103496. c) Global distribution of biomass fires, represented by red, orange, and yellow dots (lighter colors indicates more fires), based on nighttime measurements obtained by the DMSP Operational Linescan System. Credit: Julia Cole, NASA Earth Observatory

As you learned in Chapter 5, biomass is an important form of energy to human civilization. Prior to the Industrial Revolution, this was essentially the only form of fuel to which most people on Earth had access. In many **less-industrialized countries**, combustion of biomass such as wood or animal dung is still the primary energy source that many citizens, particularly in rural areas, depend on for domestic use (heating, sanitation, and cooking) as it is inexpensive, relatively efficient, and readily available. Figure 10.2.1c shows the global distribution of biomass fires in the world. While the burning of biomass for domestic use contributes to some of these fires, it is the so-called **slash-and-burn agriculture** that makes up a larger contribution. Take a minute to compare the areas highlighted in Figure 10.2.1c to the countries of the world that are currently experiencing rapid population growth (Chapter 3). If you need a refresher, use the CIA World Factbook website to view current global population growth values by country: www.cia.gov/library/publicat.../2002rank.html.

While biomass burning still has a significant impact on the global carbon cycle, human impacts on fluxes such as fossil fuel extraction and combustion continue to grow. For a review of the impacts of non-renewable energy sources such as fossil fuels, see Chapter 4. Burning of any fossil fuel (coal, natural gas, crude oil) moves carbon from a previously-sequestered state deep within the Earth's crust into carbon dioxide in the atmosphere. As countries become more industrialized, their reliance on and combustion of fossil fuels tends to increase. Look at the graph in Figure 10.2.2, which compares CO_2 emissions from fossil fuels of regions across the globe.

How has the use and distribution of fossil fuels changed throughout the past 250 years?

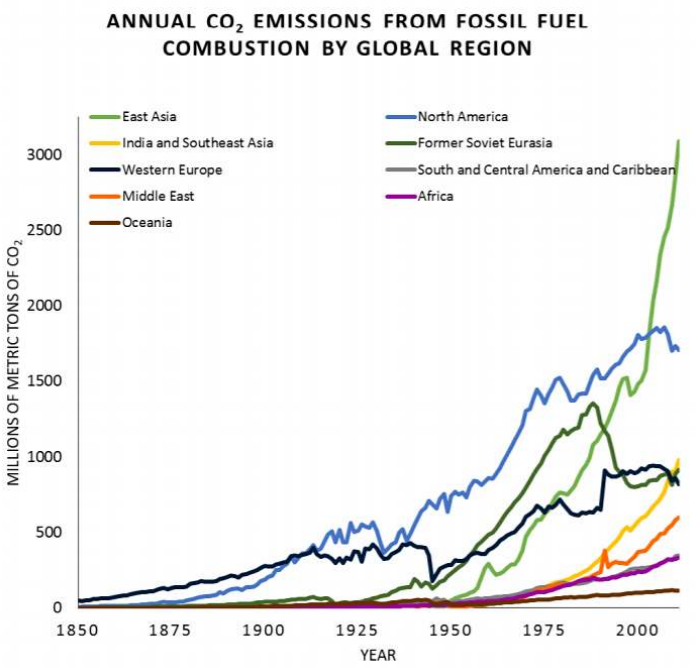


Figure 10.2.2: Total annual CO_2 emissions from fossil fuel combustion 1850-2011 by global region. Data from the Carbon Dioxide Information Analysis Center (CDIAC) cdiac.esd.ornl.gov/

The data shown in Figure 10.2.2 reveals much about the regions of the world it depicts. The effects of historic events such as the Great Depression of 1929-1939, World Wars, the fall of the Soviet Union in 1991, and the Kuwait oil fires of 1991 can be seen. Furthermore, between 1850 and 2011, different regions have gone in and out of the lead position as top producer of CO_2 from fossil fuel emissions. Population is one reason why fossil fuel use has changed throughout time. This is particularly apparent when comparing the data for Western Europe to that of India and Southeast Asia.

As countries industrialize, their relationship with agriculture also changes. **More-industrialized countries** rely very little on slash-and-burn agriculture. Their agricultural practices, however, are no less impactful on the environment. The growing population (Chapter 3) in many countries has required agriculture to become industrialized in order to meet demand. As a person living in the United States, **industrialized agriculture** probably produces the vast majority of the food you eat, including grains, fruits and vegetables, dairy and eggs, meats, and even fish. Industrialized agriculture can refer to a variety of practices, but has several main components: the use of motorized machinery; the use of chemicals such as fertilizers, pesticides, hormones, and/or antibiotics; and the intense and efficient production of one product across a large area of land.

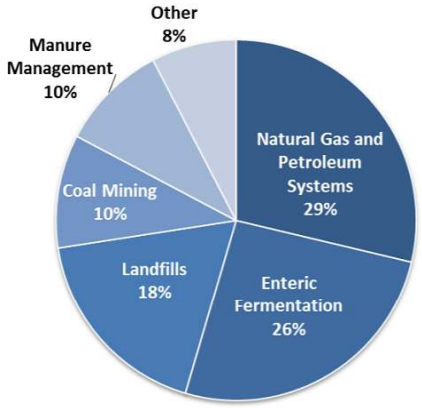


Figure 10.2.3: US methane emissions by source. 36% of the US methane production comes from agriculture: enteric fermentation (production of methane by anaerobic bacteria within the ruminant gut) and manure management. All emissions estimates from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2013. US EPA

One example of the impacts of industrialized agriculture is the production of methane (CH_4), a potent greenhouse gas. You will learn more methaneabout methane later in this section. As you saw earlier, methane is a common product of anaerobic

metabolisms. The gut of **ruminant animals** (such as sheep, cattle, and goats) has evolved to allow the animals to digest the very tough carbon molecules, such as cellulose, in grass. They do this through symbiosis, or cooperation, with anaerobic bacteria who live in the gut tract. These anaerobic bacteria produce methane and other gases as a result of their metabolism when they break down molecules like cellulose. This is sometimes called enteric fermentation. The methane gas is excreted from the animal, and this contributes significantly to total methane emissions (Figure 10.2.3). A similar type of bacteria live in the fecal matter, or manure, of livestock. As the manure is handled or stored for future use, methane is also released to the environment.

The methane excretions of one cow or a few sheep would be miniscule and insignificant. If you were a small farmer with only enough livestock to feed your family, your contribution to total methane emissions would be close to zero. However, the demand for animal protein from meat, dairy, and eggs is very large in the United States. As of January 2015, the United States had a total cattle inventory of 89.9 million animals, and in 2014, 25.5 billion pounds of beef was consumed in the United States (statistics: National Cattlemen's Beef Association). The impacts of enteric fermentation and manure management for almost 90 million animals are very significant, as seen in Figure 10.2.3. In both cases, carbon that was previously stored in biomass (cattle feed) is moved into the atmosphere, this time in the form of CH_4. This is another example of how humans have impacted the carbon cycle.

Previously in this chapter, you identified other ways the carbon cycle is impacted by human agriculture. Through industrialized agriculture, we must also account for the fossil fuels that are used. In order to deliver agricultural products to consumers, fossil fuels are used numerous times: deliveries of fertilizer, feed, and/or seed to farms; farm machinery; delivery of products to processers; food processing; delivery of foods to supermarkets; etc.

As animal products, especially meat, are expensive, the demand is typically greater in more industrialized countries than it is in less-industrialized countries. This makes industrialized agriculture, and especially industrialized animal agriculture, one of the major contributors to greenhouse gas emissions in more-industrialized countries.

Knowledge check – answer these questions on your own to further explore the impacts of biomass and fossil fuel burning on the global carbon cycle.

1. Why is there a correlation between population growth rate and global distribution of biomass fires?

2. Do you think this correlation is more likely due to personal biomass fires for activities such as cooking, or due to slash-and-burn agriculture? Why?

3. Given any other knowledge you might have about the areas highlighted in Figure 10.2.1c, what other environmental impacts may be occurring here besides carbon cycle alterations?

4. Compare the production of CO_2 emissions from fossil fuel combustion across world regions in 1900, 1950, and 2011 in Figure 10.2.2. What has accounted for these differences?

5. Has the total worldwide production of CO_2 from fossil fuels increased evenly relative to human population growth during the time period displayed in Figure 10.2.2? Why or why not?

6. What are the differences in contributions of greenhouse gas emissions from more industrialized countries and less-industrialized countries? What are the similarities?

Resources

Carbon Dioxide Information Analysis Center cdiac.esd.ornl.gov/

NOAA Earth System Research Laboratory: Carbon Cycle Science www.esrl.noaa.gov/research/themes/carbon/

Sass, Ronald. Q2: What are the Causes of Global Climate Change? OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd...c233619bca33@3

USDA Climate Change and Agriculture in the United States: Effects and Adaptation www.usda.gov/oce/climate_chan...griculture.htm

US EPA Overview of Greenhouse Gases: Methane http://epa.gov/climatechange/ghgemis...gases/ch4.html

Woods Hole Oceanographic Institution: Carbon Around the Earth http://www.whoi.edu/feature/carboncycle/

Terms list

Aerobic

Less-industrialized country

Anaerobic

Lithosphere

Autotroph

Methane

Biomass

More-industrialized country

Carbon

Nitrous oxide

Carbon dioxide

Ocean-atmosphere

Cellular respiration exchange

Chloroplast

Photosynthesis

Combustion

Potential energy

Consumption

Primary producer

Decomposition

Reservoir

Equilibrium

Residence time

Flux

Ruminant animal

Greenhouse gas

Sink

Heterotroph

Slash-and-burn agriculture

Industrial Revolution

Source

Industrialized agriculture

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10.3: The Science of Climate Change

What is causing global climate change?

Scientists have identified the source of our current global climate change as being the increased human-caused emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), since the industrial revolution. Greenhouse gases are defined as large (at least three atoms) gas molecules that participate in the **greenhouse effect**. While you already know about the "big three" greenhouse gases (CO_2, CH_4, and N_2O), it's important to realize that **water vapor** (H_2O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, is it still an essential component of the natural greenhouse effect that occurs in our atmosphere.

The Earth receives energy from the sun and in turn radiates energy back into space. When these two energies are equal, a stable temperature of the Earth is achieved. This temperature can be calculated from basic physics and is equal to about -18°C (0°F). This thermal equilibrium temperature is obviously much colder than that of the surface of the Earth. The actual average value of the Earth's surface temperature is about 15°C (59°F). The difference between these temperatures is due primarily to the natural greenhouse gas concentrations in the atmosphere, causing the greenhouse effect. If the Earth had no naturally occurring atmospheric greenhouse gases, the temperature at the surface of the Earth would equal the thermal equilibrium temperature. The influence of these greenhouse gases, mainly water and some CO_2, moderates the Earth's climate and makes life possible (Figure 10.3.1).

As **solar radiation** reaches the Earth's atmosphere, there are a variety of possibilities for its fate. Some solar radiation is reflected by the Earth and its atmosphere, and does not contribute to warming. Some passes through the atmosphere and reaches the surface of the Earth. When this solar radiation is absorbed by objects on Earth's surface, it is re-emitted as infrared radiation (heat) that escapes to space. However, some of this heat is intercepted in the atmosphere by greenhouse gases. These gases absorb and re-emit the radiation in all directions. This creates a warming impact on the Earth's surface Radiation can be bounced around from one greenhouse gas molecule to another, becoming trapped, and increasing its warming potential. For this reason, an increased greenhouse gas concentration causes an increase in the overall warming potential of the Earth's atmosphere.

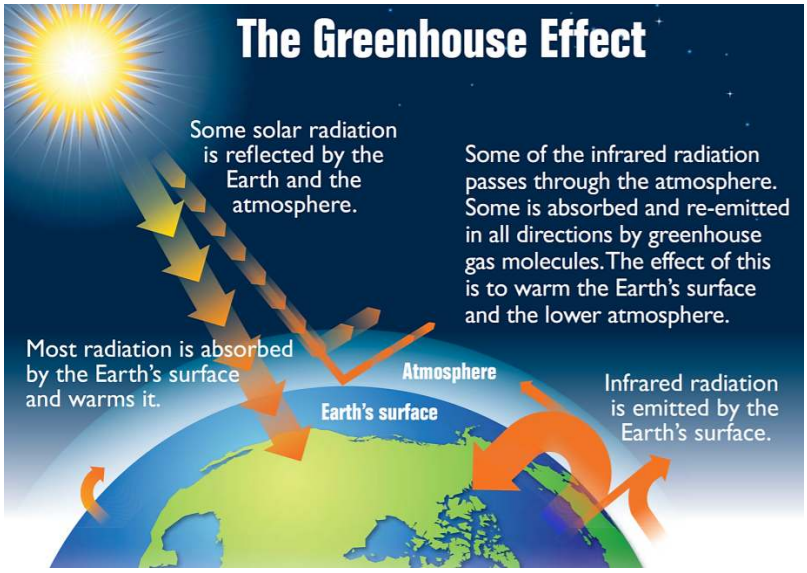


Figure 10.3.1: This diagram shows the Earth's greenhouse effect. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, certain gases in the atmosphere, called greenhouse gases, absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth's surface warmer than it otherwise would be. While this greenhouse effect occurs naturally, making life as we know it possible, human activities in the past century have substantially increased the amount of greenhouse gases in the atmosphere, causing the atmosphere to trap more heat and leading to changes in the Earth's temperature. Credit: US EPA

On a geological time scale, the climate has changed many times in the past, even before the presence of humans. These changes occurred naturally because man had not yet evolved. A well-known example of past climate change is the occurrence of ice ages. Ice ages have occurred repeatedly throughout Earth's history, the most severe ice age of which scientists have reliable data occurred

around 650,000 years ago. During this time, glacial ice covered much of Canada, the northern United States, and northern Europe; the level of the ocean decreased 120 m, and the temperature decreased by 5°C.

A geologic history of ice events is preserved in the ice sheets covering Antarctica and Greenland. This history has been uncovered over the past decades by scientists who have cored deeply into the ice and deciphered the temperature and atmospheric composition records stored in the ice. This process of obtaining **ice cores** is shown in Figure 10.3.2. The temperature at which the ice originally formed can be obtained from an interpretation of the measured ratio of the **stable isotopes** (see Chapter 1 supplement for a description of isotopes) of oxygen in the molecules of water forming the ice. The atmospheric gas composition is taken from air bubbles trapped in the ice at the time of formation. From these data, scientists have gathered a set of reliable data that track atmospheric temperature and gas concentrations that dates back 800,000 years. These data helped scientists come to the conclusion that the Earth's temperature and greenhouse gas concentrations are directly correlated to one another (Figure 10.3.3). During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO_2 concentrations below 200 **parts per million** (ppm). We can also see from these data, that CO_2 concentrations can be naturally elevated to as high as 300 ppm, correlating with increased temperatures.

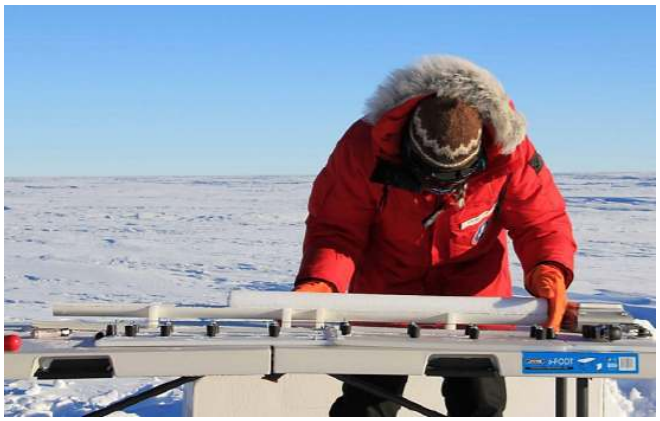


Figure 10.3.2: On Dec. 8, 2010, Michelle Koutnik, of the University of Copenhagen's Center for Ice and Climate, prepared ore of Antarctic ice to be wrapped and put into core tubes for transport back to labs at Brigham Young University in Utah. But first, Koutnik measured the core's length, diameter and weight. The traverse was the first of two field campaigns to study snow accumulation on the West Antarctic Ice Sheet and tie the information back to larger-scale data collected from satellites. 120 m, and the global average Credit: NASA/Lora Koenig.

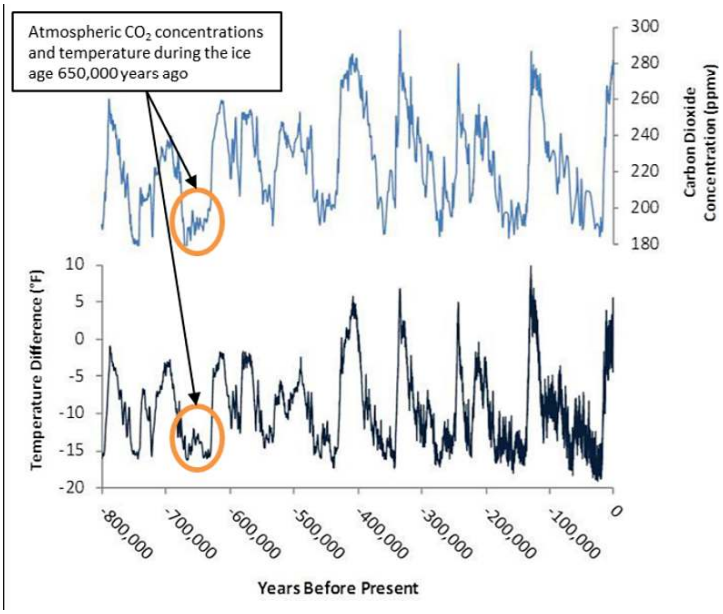


Figure 10.3.3: Estimates of the Earth's changing CO_2 concentration (top) and Antarctic temperature (bottom), based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO_2 concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO_2 concentrations. NOTE: The past century's temperature changes and rapid CO_2 rise (to 400 ppm in 2015) are not shown here. Source: Based on data appearing in NRC (2010).

The 100,000 year major cycle of the ice ages and some variations within the cycles agree very well with predicted periodic relationships between the Earth's orbit around the sun, generally referred to as the **Milankovitch cycles**. Milankovitch cycles describe the very slight "wobbles" that occur in the Earth's tilt and path as it moves around the sun. The Earth is always slightly tilted on its axis with respect to the sun. The angle of this tilt, however, changes periodically, varying from about 22° to about 25°. A less severe tilt will cause milder summers and winters close to the poles, preventing full summer ice melt in the northern- and southernmost regions, and allowing for a buildup of ice from year to year.

The path through which the Earth travels on its journey around the sun also changes from a more circular to a more elongated shape. Again, a round orbit will cause milder summers and winters close to the poles. These are very long term changes, and the results of the Milankovitch cycles can be observed in the changes in temperature and atmospheric CO_2 concentration shown in Figure 10.3.3. The climate change event that scientists are currently documenting is occurring much more rapidly than could be explained by Milankovitch cycles. Therefore, scientists agree that the cause of our currently changing climate is due to human impacts and not natural forces.

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10.4: Greenhouse Gases

We will be covering the four major categories of greenhouse gases that have been impacted by humans the most. See Table 10.4.1 for a numeric comparison of these greenhouse gases.

• Carbon dioxide, CO_2

• Methane, CH_4

• Nitrous oxide, N_2O

• Synthetic **fluorinated gases**, including **hydrofluorocarbons** (HFCs), **perfluorocarbons** (PFCs), and **sulfur hexafluoride** (SF_6)

Carbon dioxide (CO_2) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we'll discuss here. Remember that CO_2 is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO_2 is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry (Chapter 4). To get an idea of how CO_2 concentration has changed over time, watch this video compiled by the National Oceanic and Atmospheric Administration (NOAA): http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html. This video contains atmospheric CO_2 concentrations measured directly, dating back to 1958, as well as atmospheric CO_2 concentrations measured indirectly from ice core data, dating back to 800,000 BCE. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases leads to an increase in the surface temperature of the Earth.

While CO_2 is produced by aerobic cellular respiration, gases such as CH_4 and N_2O are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH_4 emissions, as you saw in section 7.1. In addition to anaerobic bacteria, methane is also a significant component of natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. For a review of how fossil fuels are mined, see Chapter 4. Finally, landfills contribute significantly to CH_4 emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH_4 include swamps and wetlands, and volcanoes.

The vast majority of N_2O production by humans comes from agricultural land management. While some N_2O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N_2O emissions. Some N_2O is also emitted from transportation and industry.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO_2, CH_4, and N_2O, are responsible for most of the human-caused global climate change over the past century. Figure 7.9 shows the increases in all three gases following the industrial revolution. Ice core data shows us that the atmospheric CO_2 concentration never exceeded 300 ppm before the industrial revolution. As of early 2015, the current atmospheric CO_2 concentration is 400 ppm. Comparing Figure 10.4.1 to Figure 7.3.3, above, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels?

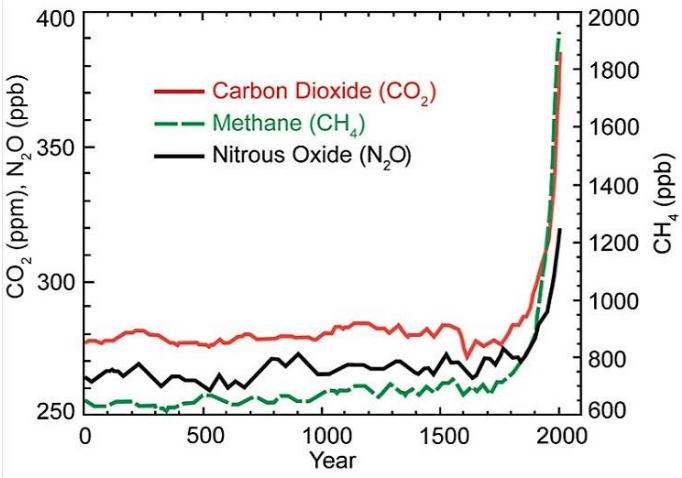


Figure 10.4.1: Increase in greenhouse gas concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Source: USGCRP (2009)

One class of greenhouse gas chemicals that has no natural sources is the fluorinated gases. These include HFCs, PFCs, and SF6, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in Table 10.4.1. Some of these chemicals, as well as the older **chlorofluorocarbons** (CFCs), have been phased out by international environmental legislation under the Montreal Protocol (see Chapter 6). Due to their long lifespan, many of these now banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the **global warming potential**, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO_2 is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO_2 always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in Table 10.4.1. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH_4 and N_2O compared to CO_2. How does this impact the comparison of the environmental effects of agricultural practices in lessindustrialized and more-industrialized countries that we completed in section 7.1?

Greenhouse gas	Chemical formula or abbreviation	Lifetime in atmosphere	Global warming potential (100-year)
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12 years	28-36
Nitrous oxide	N_2O	114 years	298
Hydrofluorocarbons	Abbreviation: HFCs	1-270 years	12-14,800
Perfluorocarbons	Abbreviation: PFCs	2,600-50,000 years	7,390
Sulfur hexafluoride	SF6	3,200 years	22,800

Other climate influencers

In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near-surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the

surface temperature. This primarily occurs due to a decrease in the **albedo** of light-colored surfaces by the darker-colored carbon black, soot, dust, or particulate matter. As you know, it is more comfortable to wear a white shirt on a hot summer day than a black shirt. Why is this? Because the lighter-colored material bounces more solar radiation back toward space than the darker-colored material does, allowing it to stay cooler. The darker-colored material absorbs more solar radiation, increasing its temperature. Just as the white shirt has a higher albedo than the black shirt, light-colored objects in nature (such as snow) have a higher albedo than dark-colored objects (such as soot or dust). As humans increase the amount of carbon black, soot, dust, and particulates in the atmosphere, we decrease the albedo of light-colored surfaces, causing them to absorb more solar radiation and become warmer than they would without human influence. An example of this can be seen in the snow on Figure 10.4.2.



Figure 10.4.2: A photograph of the extreme dust deposition from the deserts of the Colorado Plateau onto the Colorado Rockies snowpack in 2009. Taken from the high point of the Senator Beck Basin in the San Juan Mountains, it captures the extent of the impact of darkening in which the snow albedo dropped to about 30%, more than doubling the absorption of sunlight. Credit: S. McKenzie Skiles, Snow Optics Laboratory, NASA/JPL

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10.5: Tools Scientists Use to Study Climate Change

Scientists must gather together all data that is available to them in order to make meaningful conclusions and predictions regarding climate change. When they bring these data together, the prediction they make is in the form of a scientific **model.** A model is a projection of what might happen in the future based on knowledge of current and past events. The models that are published to predict climate change must pass a rigorous scientific peer-review process, and often require the combination of findings of hundreds of experiments. These large-scale models are typically beyond the capacity of a standard desktop computer, and must be run by large super-computers housed at research universities or government laboratories. For more information on how scientists build and test models, follow the link below and click on the slideshow animation, paying special attention to the sections "Model Overview" and "Testing Models." http://www.epa.gov/climatechange/science/future.html

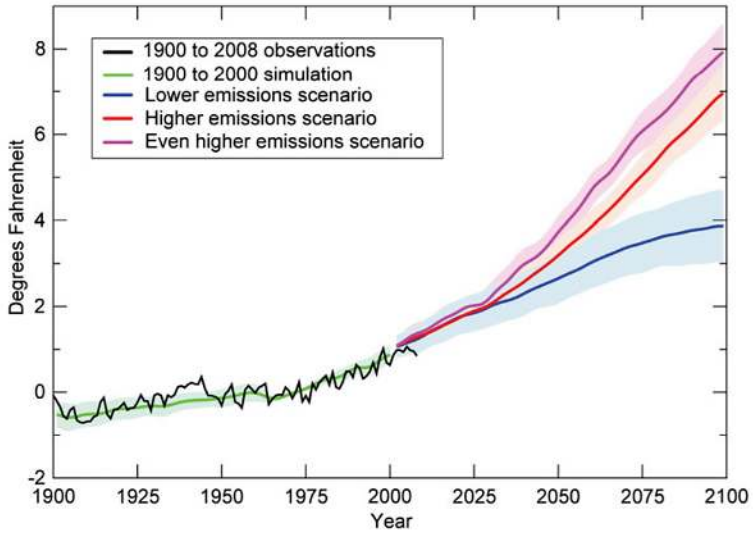


Figure 10.5.1: Observed and projected changes in global average temperature under three nopolicy emissions scenarios. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. A wider range of model types shows outcomes from 2 to 11.5°F. Changes are relative to the 1960-1979 average. Source: USGCRP 2009

Figure 10.5.1 is one example of a scientific model of the impacts of climate change. Within this figure, we see the directly-measured observations of global average temperature (black line). We also see models of four different scenarios: 1900 to 2000 simulation using actual greenhouse emissions (green line), and 2000 to 2100 simulation using very high (purple line), high (red line), and low (blue line) greenhouse gas emissions scenarios.

Why did scientists make a model of the data from 1900 to 2000 in Figure 10.5.1 when they could just look up the data in published literature? This is an important component of model testing. In order to ensure accuracy of the model, you should not only be able to predict future events, but past events as well. Scientists use this as a way to "calibrate" their model. Since this model reliably predicts past events, chances are good that it will reliably predict future events as well.

Another example of a climate model is shown in Figure 10.5.2 this time comparing climate projections with and without the influences of humans on greenhouse gas emissions. This large model is a combination of the work of many different models, in order to achieve the most accurate outcome.

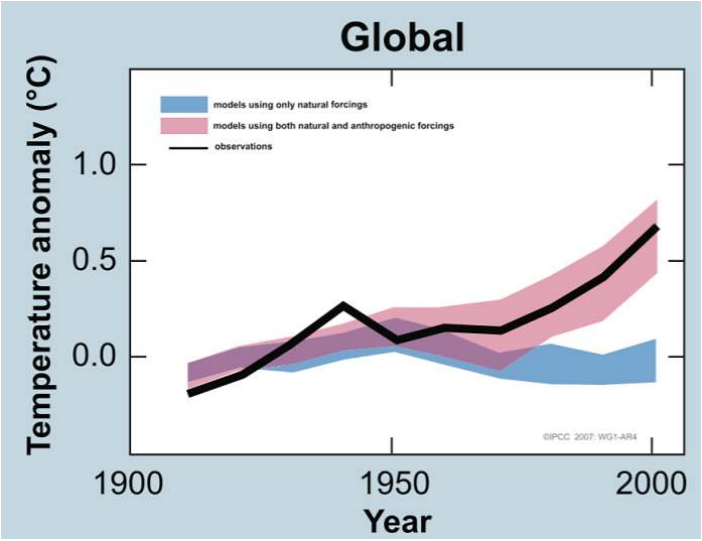


Figure 10.5.2: Comparison between observed average global temperatures and corresponding modeled temperatures with and without anthropogenic climate forces (IPCC, Working group 1, 2007).

In Figure 10.5.2, the decadal averages of observations are shown for the period 1906 to 2005 (black line). All temperatures are plotted relative to zero being defined as the corresponding average for the period from 1901 to 1950. The blue shaded band shows the 5% to 95% confidence interval for 19 simulations from 5 climate models using only the natural forcing effects due to solar activity and volcanoes. The red shaded band shows the 5% to 95% confidence interval for 58 different simulations from 14 climate models using both natural and anthropogenic forces. These different simulations and the different models are used by different scientific groups and represent different treatments of the Earth's systems. It is thus quite encouraging that model calculations are in major agreement with the assumption that global temperature change from 1900 to 2000 is due to both natural and anthropogenic effects, with anthropogenic effects being the major causes in its recent dramatic increase. You will see more examples of climate models as you make your way into the final section of the climate change chapter: consequences of climate change.

Resources

NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/

NOAA Paleoclimatology: Astronomical Theory of Climate Change www.ncdc.noaa.gov/paleo/milankovitch.html

Sass, Ronald. Q2: What are the Causes of Global Climate Change? OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd...c233619bca33@3

University of San Diego Virtual Museum: Climate Change earthguide.ucsd.edu/virtualmu...ge2/01_1.shtml

US EPA: Future Climate Change http://www.epa.gov/climatechange/science/future.html

US EPA: Overview of Greenhouse Gases http://epa.gov/climatechange/ghgemissions/gases.html

Terms list

Albedo

Chlorofluorocarbon

Confidence interval

Fluorinated gases

Global warming potential

Greenhouse effect

Hydrofluorocarbon

Ice age

Ice core

Landfill

Milankovitch cycles

Model

Parts per million

Perfluorocarbon

Solar radiation

Stable isotopes

Sulfur hexafluoride

Thermal equilibrium temperature

Water vapor

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10.6: Consequences of Climate Change

As part of your assigned reading for this section, read the article “The Coming Storm” by Don Belt published in National Geographic: http://ngm.nationalgeographic.com/pr...desh/belt-text In this section, we will discuss the effects of climate change, both those that have already been observed, as well as future predictions based on scientific climate models (see section 7.5 for a discussion of scientific models). Here, the differences between the terms **global warming** and **climate change** become apparent. Global warming refers to the increase in the average temperature of the Earth’s atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. We have already observed this increase occurring, as you saw in Figure 7.5.2 from section 7.5. We have also seen, and expect to continue to see, other changes occurring in the **climate** of the Earth. Furthermore, changes have been observed, and we expect to continue to observe, changes in other chemical, physical, and biological aspects of the Earth’s environment. We will only discuss some of the consequences of climate change in this section, including changes in temperature, precipitation, ocean level, and ocean acidity. There are many more changes that have been seen, and are projected to continue in the future. These include: changes in the amount and distribution of ice and snow, changes in seasonality, ecosystem shift, and habitat changes of plant and animal populations, in addition to others. For more information about these consequence of climate change, visit this site: http://www.epa.gov/climatechange/sci...ors/index.html.

Temperature and precipitation

Temperature and **precipitation** are the two most direct impacts on the Earth’s climate due to climate change. By now, you should already understand why an increase in greenhouse gas levels in the atmosphere causes an increase in temperature. But why does it also impact precipitation patterns? As you already know, water vapor is an important component of the Earth’s atmosphere (see Chapter 6). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. Here in Georgia, we have very hot and humid summers. The high summer humidity in this region is possible due to the increased capability warm air has to hold water vapor. Simply put, warmer air can hold more water than cooler air. As air cools, its ability to hold water vapor decreases, and any excess water will leave the air as liquid water. A great example of this is the formation of dew on surfaces overnight. During the day, the temperature is warmer than it is at night, and the air has a relatively high holding capacity for water vapor. When the sun sets, the air cools, decreasing its capacity to hold water vapor. That extra water must go somewhere, and it does that by accumulating on surfaces. Similarly, when warm and cool air fronts collide, the chances for rain and thunderstorms increase. Furthermore, an increase in temperature enhances evaporation occurring at the Earth’s surface. This increased evaporation leads to greater concentrations of water vapor in the atmosphere which can lead to increased precipitation.

The change in temperature that we have already seen in the Earth’s average atmospheric temperature is relatively small (about 0.6 °C, according to Figure 7.5.2 from section 7.5). However, as with many of the aspects of climate change, the potential for greater changes increases dramatically as time progresses in the future. This can be seen in Figure 10.6.1, which displays a model of the predicted temperature increase. Notice that these changes occur relatively rapidly, and are not uniform across the globe. What might be some of the reasons for this?

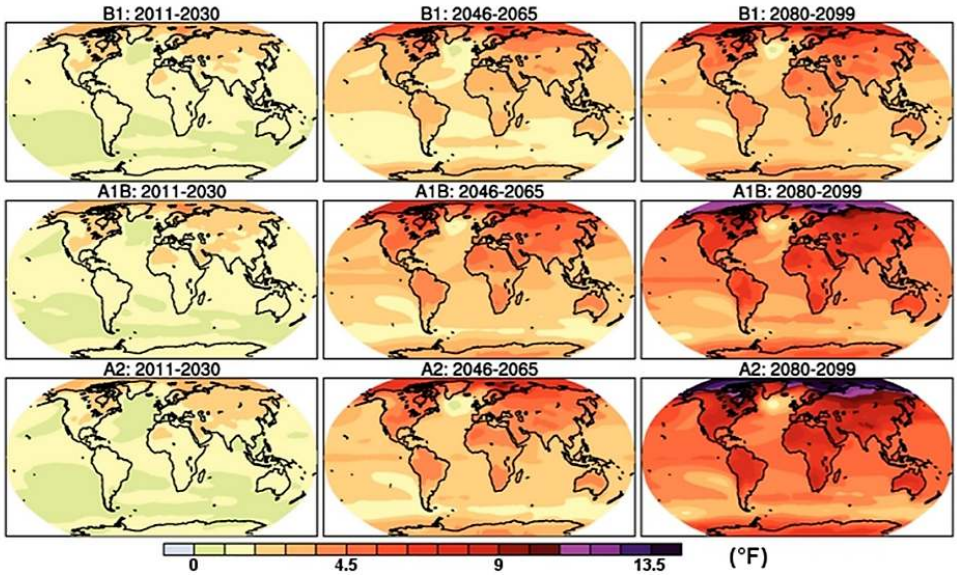


Figure 10.6.1: Projected changes in global average temperatures under three emissions scenarios (rows) for three different time periods (columns). Changes in temperatures are relative to 1961- 1990 averages. The scenarios come from the IPCC Special Report on Emissions Scenarios: B1 is a low emissions scenario, A1B is a medium-high emissions scenario, and A2 is a high emissions scenario. Source: IPCC Working Group I: The Physical Science Basis, 2007.

Changes in precipitation occur due to a variety of factors, including changes in atmospheric water vapor content due to changing temperature, as discussed above. Also at play is the heightened **evaporation** rate of water on Earth's surface under warmer temperatures. More evaporation leads to more precipitation. Finally, shifts in wind patterns impact the distribution of precipitation events. As you can see in Figure 10.6.2, there are some areas of the globe that are expected to have an increase in precipitation, while others are expected to have a dramatic decrease. Some major population centers projected to have a moderate to severe precipitation increase include (population estimates of the metropolitan area given in parentheses): New York, United States (20.1 million); Bogotá, Colombia (12.1 m.); and Manila, Philippines (11.9 m.). What sort of challenges might these cities face in the future as they deal with this change in their climate?

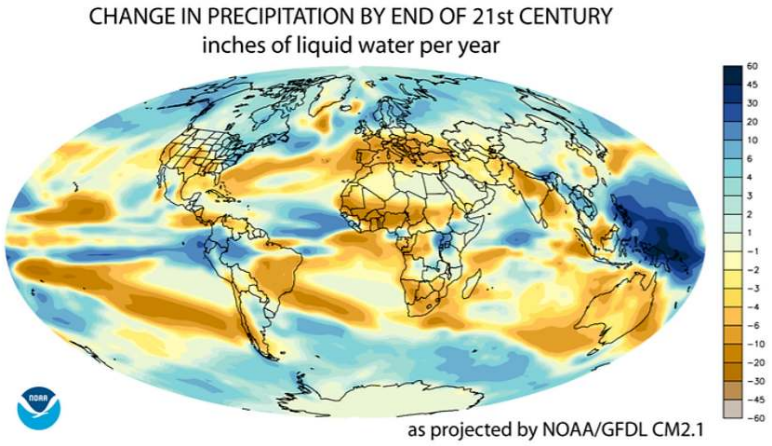


Figure 7.6.1). The plotted precipitation differences were computed as the difference between the 2081 to 2100 20-year averages minus the 1951 to 2000 50-year average. Blue areas project increases in precipitation; brown areas project decreases.

In contrast, many more major metropolitan areas are projected to have a moderate to severe precipitation decrease (droughts) by the end of the 21st century. These include Delhi, India (21.8 m.); Lagos, Nigeria (21 m.); São Paulo, Brazil (20.9 m.); Kolkata, India (14.6 m.); Istanbul, Turkey (14.4 m.); Los Angeles, United States (13.3 m.); Rio de Janeiro, Brazil (12 m.); Paris, France (12 m.); and Lahore, Pakistan (11.3 m.). The largest challenge that these areas are likely to face is a dwindling water supply for drinking and agriculture. See Chapter 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations and farms.

Additional challenges may be felt by all areas of the world with regard to changes in the seasonality or timing of precipitation, as well the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All of these factors affect the availability of soil water for plants, the flow of rivers and streams, and the overall accessibility of water worldwide. Furthermore, scientists predict an increase in the number and severity of storms as climate change progresses. For a full discussion of the potential impacts of this, see the assigned article.

Sea level rise While we know that water continuously cycles around the world (see Chapter 8 for information on the water cycle), and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as **glaciers**) are decreasing. This contributes to an increase in sea level worldwide (Figure 10.6.3).

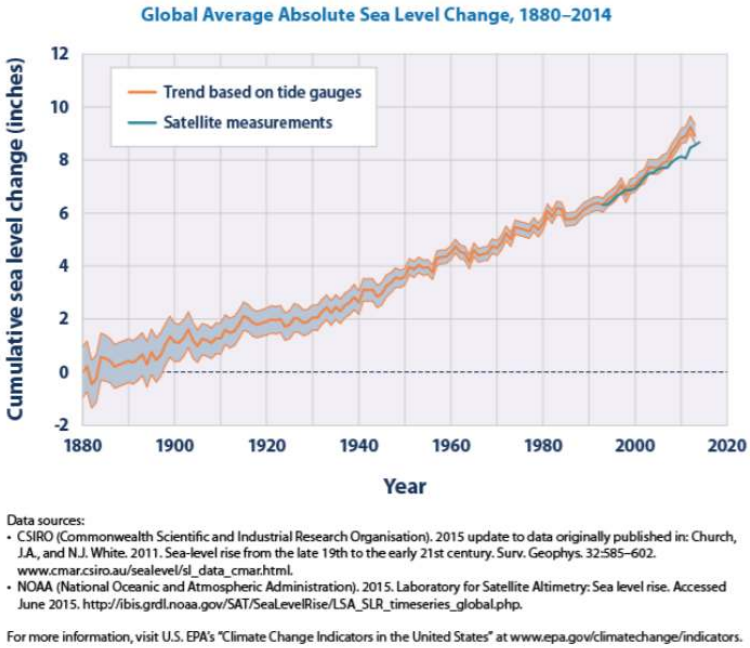


Figure 10.6.3: *This graph shows average absolute cumulative changes in sea level for the world's oceans since 1880, based on a combination of tide gauge measurements and recent satellite measurements. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.*

From the data in Figure 10.6.3, we see that sea level has increased at an average of 0.06 inches (0.15 cm) per year over the time period shown above. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches (0.28 to 0.36 cm) per year since 1993. There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting **land ice** (such as the glacier shown in Figure 10.6.4) contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through **runoff.** We also observe **sea ice** melting (see http://www.epa.gov/climatechange/sci ence/indicators/index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the water stays in the same locations, and the overall sea level does not change.



Figure 10.6.4: Glacier Retreat

The second factor that influences sea level rise is a phenomenon called thermal expansion. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance (see Chapter 1 supplemental material). This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. Figure 10.6.5 depicts the measured land area lost due to increasing sea level since 1996. Note that the Southeast (defined here as the Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.

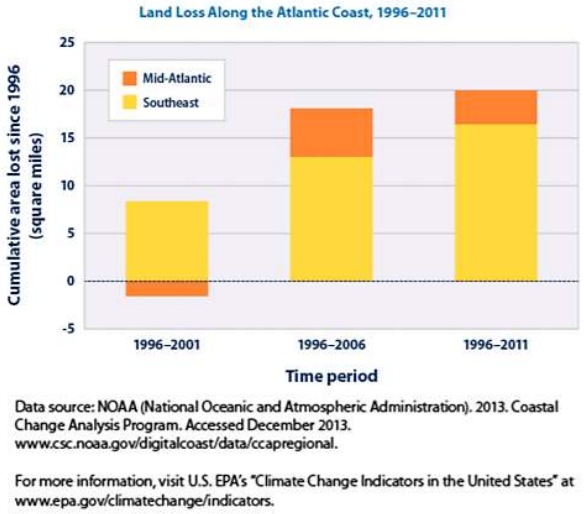


Figure 7.6.5: *This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.*

While the ecological effects of sea level rise remain in the United States, we don't project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

Ocean acidification

Dissolved CO_2 is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of aragonite, a mineral form of the molecule calcium carbonate, $CaCO_3$. These organisms rely on the formation of carbonate ions (see Chapter 1 supplemental material for information on ions), CO_3^{2-}, from dissolved CO_2, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where bicarbonate (HCO_3^-) is formed as an intermediate, and hydrogen ions (H^+) are generated (equations 10.6.1 and 10.6.2).

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \tag{10.6.1}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \tag{10.6.2}$$

To have a better visualization of this process, follow along with the interactive graphic at: http://www.whoi.edu/home/oceanus_ima...ification.html.

As you can see, both equations 10.6.1 and 10.6.2 each produce one H^+. This is significant to water chemistry because an increase in H+ concentration means a decrease in the pH of the water. You can see in Figure 10.6.6 that a lower pH means that the liquid is more acidic. As shown in the interactive graphic, an increase in CO_2 in the atmosphere causes additional CO_2 to be dissolved in the ocean. This means that more CO_2 in the atmosphere leads to more acidic ocean environments.

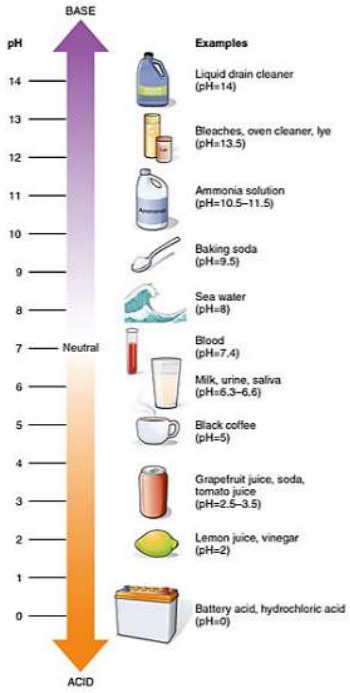


Figure 7.6.6: *The pH scale and relative acidity. Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.*

Unfortunately for shell-building animals, the buildup of H^+ in the more acidic ocean environment blocks the absorption of calcium and CO_3^{2-}, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world's oceans, as shown in Figure 10.6.7.

The increasing acidity of the world's oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO_2 levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through coral bleaching, caused by the effects of climate change including ocean acidification and increased temperature. For more information, visit the NOAA Coral Reef Conservation Program website: coralreef.noaa.gov/threats/climate/.

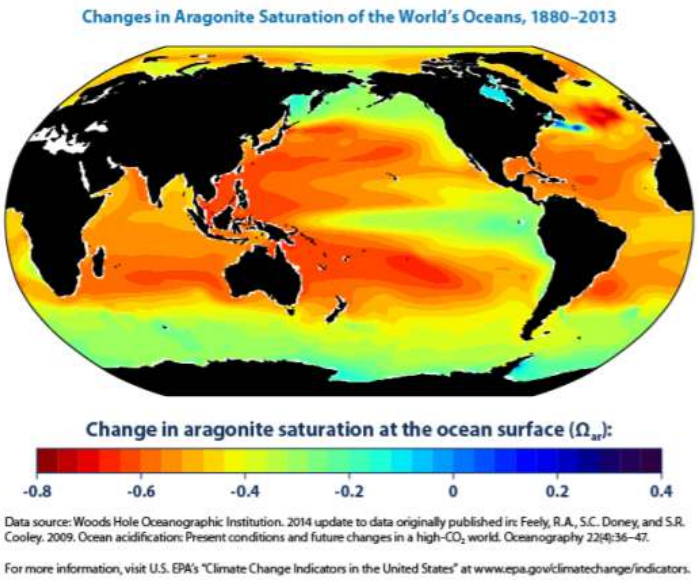


Figure 10.6.7: This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

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10.7: Looking Forward- Climate Strategies

While the situation surrounding global climate change is in serious need of our attention, it is important to realize that many scientists, leaders, and concerned citizens are making solutions to climate change part of their life's work. The two solutions to the problems caused by climate change are **mitigation** and **adaptation**, and we will likely need a combination of both in order to prosper in the future.

Adaptation strategies

We know that climate change is already occurring, as we can see and feel the effects of it. For this reason, it is essential to also adapt to our changing environment. This means that we must change our behaviors in response to the changing environment around us. Some adaptation strategies are discussed in the required article reading.

Adaption strategies will vary greatly by region, depending on the largest specific impacts in that area. For example, in the city of Delhi, India, a dramatic decrease in rainfall is projected over the next century (Figure 7.6.2). This city will likely need to implement policies and practices relating to conservation of water, for example: rainwater harvesting, water re-use, and increased irrigation efficiency. Rain-limited cities near oceans, such as Los Angeles, California may choose to use desalination to provide drinking water to their citizens. **Desalination** involves taking the salt out of seawater to make it potable (Chapter 8).

Cities with low elevations near oceans may need to implement adaptation strategies to rising sea levels, from seawalls and levees to relocation of citizens. One adaptations strategy gaining use is the creation or conservation of **wetlands**, which provide natural protection against storm surges and flooding.

Mitigation strategies

In general, a strategy to mitigate climate change is one that reduces the amount of greenhouse gases in the atmosphere or prevents additional emissions. Mitigations strategies attempt to "fix" the problems caused by climate change. Governmental regulations regarding fuel efficiency of vehicles is one example of an institutionalized mitigation strategy already in place in the United States and in many other countries around the world. Unlike some other countries, there are no **carbon taxes** or charges on burning fossil fuels in the United States. This is another governmental mitigation strategy that has been shown to be effective in many countries including India, Japan, France, Costa Rica, Canada, and the United Kingdom.

In addition to government measures and incentives, technology can also be harnessed to mitigate climate change. One strategy for this is the use of **carbon capture and sequestration** (CCS). Through CCS, 80-90% of the CO_2 that would have been emitted to the atmosphere from sources such as a coal-fired power plant is instead captured and then stored deep beneath the Earth's surface. The CO_2 is often injected and sequestered hundreds of miles underground into porous rock formations sealed below an impermeable layer, where it is stored permanently (Figure 7.7.1).

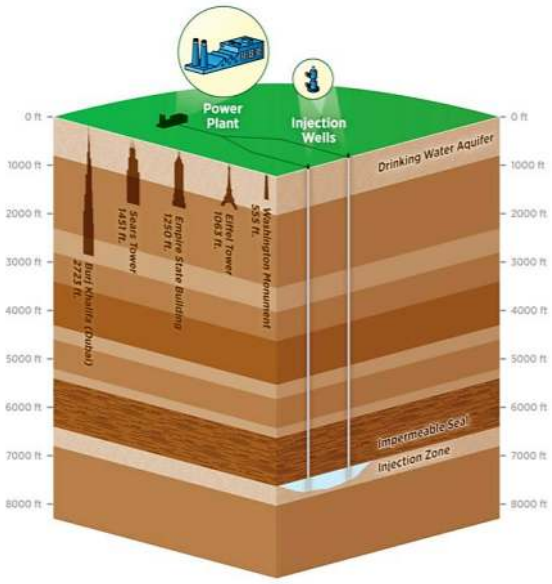


Figure 7.7.1: *Carbon capture and sequestration schematic with landmarks shown to scale for depth reference. Source: US EPA.*

Scientists are also looking into the use of soils and vegetation for carbon storage potential. Proper management of soil and forest ecosystems has been shown to create additional carbon sinks for atmospheric carbon, reducing the overall atmospheric CO_2 burden. Increasing soil carbon further benefits communities by providing better-quality soil for agriculture and cultivation.

Technologies related to alternative energy sources (Chapter 5) mitigate climate change by providing people with energy not derived from the combustion of fossil fuels. Finally, simple activities such as energy conservation, choosing to walk or bike instead of driving, and disposing of waste properly are activities that, when done by large numbers of people, actively mitigate climate change by preventing carbon emissions.

Take a moment to identify ways that you personally can be involved in the mitigation of or adaptation to climate change. What changes can you make in your own life to prevent excess carbon emissions? Similar to your ecological footprint, which you should have already calculated in lab, you can also calculate your carbon footprint. Use the EPA's carbon footprint calculator to do so, and investigate the Reduce Your Emissions section to find ways to decrease your carbon footprint.

Resources

Belt, Don. "The Coming Storm." National Geographic Magazine, May 2011. http://ngm.nationalgeographic.com/pr...desh/belt-text

IPCC Fourth Assessment Report: Climate Change 2007 Synthesis Report. 4. Adaptation and mitigation options www.ipcc.ch/publications_and.../en/spms4.html

NOAA Coral Reef Conservation Program: Climate Change coralreef.noaa.gov/threats/climate/

NOAA Geophysical Fluid Dynamics Laboratory: Will the wet get wetter and the dry drier? www.gfdl.noaa.gov/will-the-we...-the-dry-drier

Ontl, Todd and Lisa Schulte (2012) Soil Carbon Storage. Nature Education Knowledge 3(10):35 http://www.nature.com/scitable/knowl...orage-84223790

US EPA Carbon Dioxide Capture and Sequestration http://www.epa.gov/climatechange/ccs/

US EPA Carbon Footprint Calculator http://www3.epa.gov/carbon-footprint-calculator/

US EPA Climate Change Indicators in the United States http://www.epa.gov/climatechange/sci...ors/index.html

Terms list

Acidity

Climate

pH

Adaptation

Climate change

Precipitation

Aragonite

Coral bleaching

Runoff

Bicarbonate

Desalination

Sea ice

Calcium carbonate

Evaporation

Thermal expansion

Carbon capture and sequestration

Glacier

Wetland

Global warming

Carbon footprint

Hydrogen ions

Carbon tax

Land ice

Carbonate

Mitigation

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CHAPTER OVERVIEW

11: Water

11.1: Introduction
11.2: Properties of Water
11.3: Global Water Distribution Use
11.4: The Hydrologic Cycle
11.5: Water Scarcity and Storage
11.6: Water Quality (Pollution)
11.7: Water Management
11.8: Bibliography

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11.1: Introduction

> *"Whiskey is for drinking. Water is for fighting"*

Why do scientists spend time looking for water on other planets? Why is water so important? It is because water is essential for life as we know it. Water is one of the more abundant molecules and the one most critical to life on Earth. Approximately 60–70 percent of the human body is made up of water. Without it, life as we know it simply would not exist. The quotation above, which has been attributed to Mark Twain, suggested (by the quote above) that water was extremely important. In recent years, we have seen a rise in conflicts and dispute about water. Fortunately, most of the conflicts have ended up in the courts instead of the battlefields. This chapter is devoted to this precious resource that sustains our planet and its living things.

Water is an important commodity for life on Earth and is something we all need in our daily activities. It is referred to by many people as the "essence of life", "blue gold" and "more precious than oil". What makes water so important is its unique and special properties. These special properties of water include water's high heat capacity and heat of vaporization, its ability to dissolve numerous polar molecules, its cohesive and adhesive properties, and its dissociation into ions that leads to the generation of pH. Understanding these characteristics helps us understand and appreciate its importance in maintaining life on Earth. Before we discuss these properties, we will review the molecular structure of water, which gives rise to these special properties.

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11.2: Properties of Water

A water molecule is composed of one oxygen and two hydrogen atoms that are joined together by **polar covalent** bonds. Covalent mean that the atoms share electrons, instead of completely giving up electrons to one another. **Polar** means that the electrons are not shared equally. These polar covalent bonds (Figure 8.2.1), along with the molecular shape, cause the water molecule to have a slightly positive charge on the hydrogen end and a slightly negative charge on the oxygen side. Water's charges are generated because oxygen is more electronegative than hydrogen, making it more likely that a shared electron would be found near the oxygen nucleus than the hydrogen nucleus, thus generating the partial negative charge near the oxygen. This gives water molecules their properties of attraction.

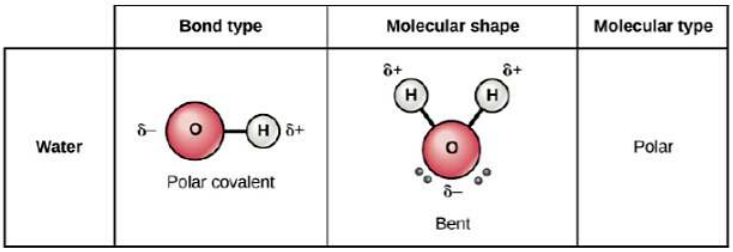


Figure 11.2.1: Polarity of the water molecule due to the uneven distribution of electrons in its covalent bond. C (From OpenStax Concepts of Biology text)

Hydrogen Bonds

Due to water's polarity, each water molecule attracts other water molecules as oppositely charged ends of the molecules attract each other. When this happens, a weak interaction occurs between the *positive* hydrogen end from one molecule and the *negative oxygen* end of another molecule. This interaction is called a **hydrogen bond**. This hydrogen bonding contributes to the following water's unique properties.

1. Water is the universal solvent

2. Exists in nature as a solid, liquid, and gas

3. The density of ice is less than liquid water

4. Water has a high surface tension

5. Water has a high heat capacity

6. Water exists as a liquid at room temperature It is important to note here that even we are only focusing on water in this text book, hydrogen bonding also occurs in other substances that have polar molecules.

Physical State of Water on Earth

Water on Earth can naturally exist as either solid, liquid or gas depending on the prevailing temperature and pressure conditions. The formation of hydrogen bonds (described above) is an important quality of liquid water that is crucial to life as we know it on Earth. As water molecules make hydrogen bonds with each other, liquid water takes on some unique physical and chemical characteristics when compared to other liquids. In liquid water, hydrogen bonds are constantly being formed and broken as the water molecules slide past each other. The energy of the moving water molecules (kinetic energy) is responsible for breaking the bonds. When heat is added to water (increasing temperature), the kinetic energy of the molecules goes up and more bonds are broken. As more heat is added to boiling water, the higher kinetic energy of the water molecules causes the hydrogen bonds to break completely and allow them to escape into the air as water vapor. On the other hand, when the temperature of water is reduced and water freezes, the water molecules form a crystalline structure maintained by hydrogen bonding (since there isn't enough energy to break the hydrogen bonds). The crystalline structure, ice, has a more open structure than the liquid form of water. The open structure of ice (Figure 11.2.2) makes ice less dense than liquid water, a phenomenon not seen in the solidification of other liquids.

The lower density of ice, illustrated in Figure 11.2.2, causes it to float at the surface of liquid water, such as an iceberg in the ocean or ice cubes in a glass of ice water. In lakes and ponds, ice will form on the surface of water creating an insulating barrier that

protects animals and plant life that live in the water from freezing. Without this layer of insulating ice, plants and animals living in the water would freeze in the solid block of ice and not survive. The ice crystals that form upon freezing would rupture the delicate membranes essential for the function of living cells, irreversibly damaging them.

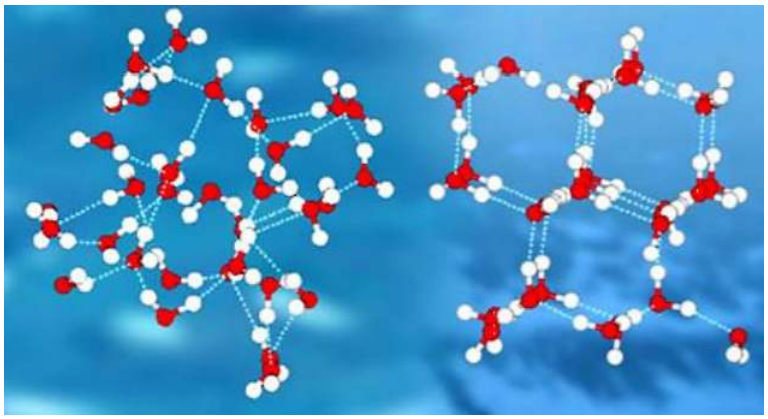


Figure 11.2.2: Hydrogen bonding makes ice less dense than liquid water. The lattice structure water is more condensed (left structure) than that of ice (right structure). The lattice structure of ice makes it less dense than freely flowing molecules of liquid water, enabling ice to float on liquid water. (Image credit: Lynn Yarris, http://www2.lbl.gov/Science-Articles...ter-solid.html)

High Heat Capacity

Water has the highest **specific heat capacity** of any liquid. Water's high heat capacity is a property caused by hydrogen bonding among the water molecules. **Specific heat** is defined as the amount of heat one gram of a substance must absorb or lose to change its temperature by one degree Celsius. For water, this amount is one **calorie**. It takes water a long time to heat up and a long time to cool down. In fact, the specific heat capacity of water is about five times more than that of sand. This explains why land cools faster than the sea. Due to its high heat capacity, warm-blooded animals use water to disperse heat more evenly and maintain temperature in their bodies: it acts in a similar manner to a car's cooling system, transporting heat from warm places to cool places, causing the body to maintain a more even temperature.

Heat of Vaporization

Water also has a high **heat of vaporization**, the amount of energy required to change one gram of a liquid substance to a gas. A considerable amount of heat energy (586 calories) is required to accomplish this change in water. This process occurs on the surface of water. As liquid water heats up, hydrogen bonding makes it difficult to separate the liquid water molecules from each other, which is required for it to enter the gas phase (steam). Thus, water acts as a heat sink and requires much more heat to boil than liquids such as ethanol, whose hydrogen bonds are weaker. Eventually, as water reaches its boiling point of 100° Celsius (212° Fahrenheit), the heat can break the hydrogen bonds between the water molecules, and the kinetic energy between the water molecules allows them to escape from the liquid as a gas. Even when below its boiling point, water's individual molecules acquire enough energy from other water molecules such that some surface water molecules can escape and vaporize: this process is known as **evaporation**.

Since hydrogen bonds need to be broken for water to evaporate means that a substantial amount of energy is used in the evaporation process. As the water evaporates, energy is taken up by the process, cooling the environment where the evaporation is taking place. In many living organisms, including in humans, the evaporation of sweat, which is 90 percent water, allows the organism to cool so that homeostasis of body temperature can be maintained.

Water is a Solvent

Since water is a polar molecule with slightly positive and slightly negative charges, ions and polar molecules can readily dissolve in it. Water is, therefore, referred to as a **solvent**, because it is capable of dissolving more substances (polar substances) than any other liquid. The charges associated with these molecules will form hydrogen bonds with water, surrounding the particle with water molecules. This is very important as it enables water to dissolve various chemicals and distribute them within living organisms, including taking toxic substances out of living things, and in the environment.

Water's Cohesive and Adhesive Properties

Have you ever filled a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass (Figure 11.2.3)



Figure 11.2.3: Water in a glass form a dome shape above the glass due to cohesive forces of attraction among water molecules. Photo Credit: Sam Mutiti

This water can stay above the glass because of its **cohesive** properties. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together at the liquid-gas (water-air) interface, although there is no more room in the glass. Cohesion allows for the development of **surface tension**, the capacity of a substance to resist rupture when placed under tension or stress. This is also why water forms droplets when placed on a dry surface rather than being flattened out by gravity (Figure 11.2.3)



Figure 11.2.4: Beading up of water due strong cohesive forces between water molecules (Water USGS, right hand photo credit: J Schmidt; National Park Service).

When a steel needle is placed carefully on water it does not sink even though steel is denser (heavier) than the water. Cohesion and surface tension keep the hydrogen bonds of water molecules intact and support the item floating on the top. It is even possible for an insect to "float" on water if it sits gently without breaking the surface tension, as shown in Figure 11.2.5.



Figure 11.2.5: The weights of the needle and water strider are pulling the surface downward; at the same time, the surface tension is pulling it up, suspending them on the surface of the water and keeping them from sinking. (Credit: Cory Zanker (left) and Tim Vickers (right)

Another important property of water is **adhesion**, or the attraction between water molecules and other molecules. This attraction is sometimes stronger than water's cohesive forces, especially when water is exposed to charged surfaces such as on the inside of thin glass tubes known as capillary tubes. Adhesion is observed when water "climbs" up the tube placed in a glass of water: notice that the water appears to be higher on the sides of the tube than in the middle. This is because the water molecules are attracted to the charged glass walls of the capillary tube more than they are to each other and, therefore, adhere to it. This type of adhesion is called **capillary action**, and is illustrated in Figure 11.2.6. This process is also involved in the movement of water and nutrients from the soil around the root systems to other parts of plants above the ground.

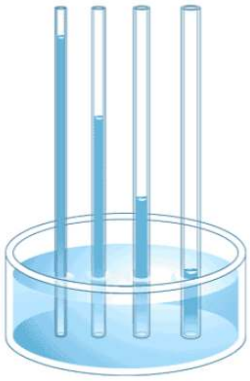


Figure 11.2.6: Capillary action in a glass tube is caused by the adhesive forces exerted by the internal surface of the glass exceeding the cohesive forces between the water molecules themselves. (Credit: moodle.clsd.k12.pa.us/distric...s/0-13-115540-7/ch23/ch23_s5_1.html)

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11.3: Global Water Distribution Use

Most of the water on the planet is in oceans and unavailable for human consumption due to its high salinity (Figure 11.3.1).

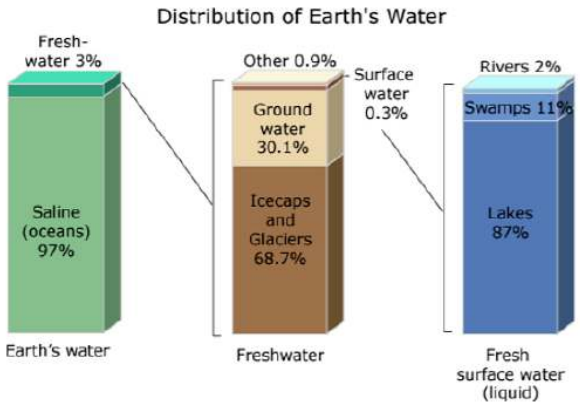


Figure 11.3.1: Graphical representation of available water: water.usgs.gov/edu/earthwherewater.html

Of all the water in the world, only about 0.64% is fresh water that is available for consumption (the other fresh water is locked up in ice). Of this available fresh water, 98.4% is found as groundwater below the surface of the Earth and only 1.4% is surface water in rivers and lakes.

The largest percentage of water withdrawn in the US goes to thermoelectric cooling (Figure 11.3.2). In some countries, such as Egypt, irrigation accounts for over 70% of water withdrawn. Irrigation is water that is applied by a water system to sustain plant growth. Irrigation also includes water that is used for frost protection, application of chemicals, weed control, field preparation, crop cooling, harvesting, dust suppression, and leaching salts from the root zone.

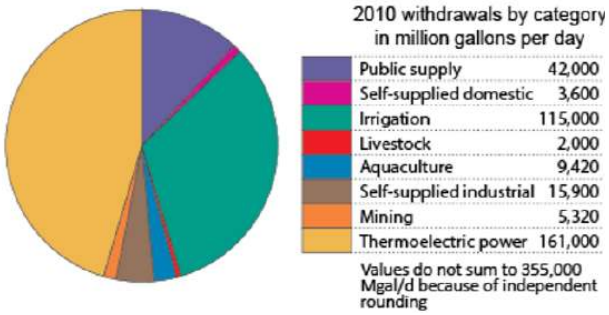


Figure 11.3.2: Estimated 2010 water withdrawals. Irrigation and thermoelectric power usages account for most water withdrawals. water.usgs.gov/watuse/images/...y-pie-2010.png More water use terminology can be found at: water.usgs.gov/watuse/wuglossary.html

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11.4: The Hydrologic Cycle

The major water reservoirs on Earth are oceans, glaciers, groundwater, rivers, and lakes. Water spends different amounts of time in the various reservoirs. The main factors that control the amount of time water stays in a reservoir are the amount of water in the reservoir and how fast water moves in and out. The hydrologic cycle (water cycle) represents a continuous global cycling of water from one reservoir to another (Figure 11.4.1).

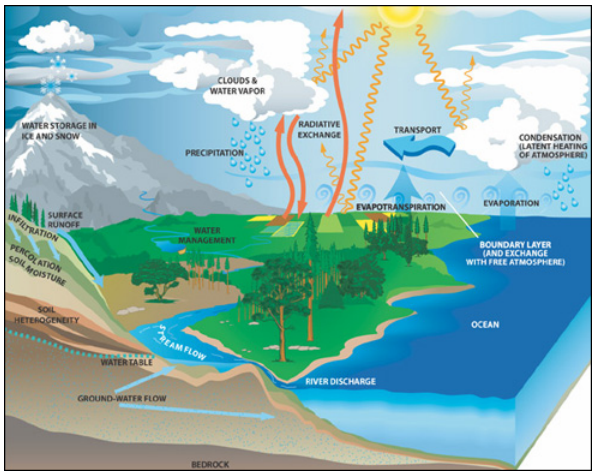


Figure 11.4.1: The water cycle at the global scale showing water moving through all the major reservoirs, including the ocean reservoir (source https://science.nasa.gov/earth-scien...an-water-cycle).

To gain a deeper appreciation of the water cycle, let us follow a water molecule through the water cycle. Starting in the ocean (an arbitrary starting point) the water molecule can become part of the water that is converted into vapor and enter the atmosphere. Heat energy from the sun, which drives the water cycle, heats water in the oceans and cause evaporation. Evaporation is the process by which water changes from a liquid to a gas or vapor. Evaporation is the primary pathway that water takes from the liquid state back into the water cycle as atmospheric water vapor. Nearly 90% of moisture in the atmosphere comes from evaporation, with the remaining 10% coming from transpiration. **Transpiration** is the process by which moisture is carried through plants from roots to small pores (**stoma**) on the underside of leaves, where it changes to vapor and is released to the atmosphere. Transpiration is essentially evaporation of water from plant leaves. Rising air currents take the vapor up into the atmosphere, along with water from **evapotranspiration**, which is a combination of water transpired from plants and that evaporated from the soil. The vapor rises into the air where cooler temperatures cause it to condense into clouds. **Condensation** is the process by which water vapor is converted from gaseous state back into liquid state. Clouds might eventually grow bigger and moist enough to release the water molecule in the form of precipitation. **Precipitation** is water falling from the clouds in the atmosphere in form of ice (snow, sleet, hail) or liquid (e.g. rain, drizzle). Precipitation that falls as snow can accumulate as ice caps and glaciers.

Did you know that the largest glacier on Earth is the Severny Island ice cap in the Russian Arctic?

Precipitation that falls as liquid usually ends up as **surface flow** and **stream flow**. **Surface runoff** is precipitation which travels over the soil surface to the nearest stream channel. **Stream flow** is the movement of water in a natural channel, such as a river. Most precipitation falls directly onto the ocean and returns the water molecule back to restart the journey. This is also true for surface runoff, most of the water eventually returns to the ocean via stream flow. This also returns the water molecule back the ocean to start the journey again.

A portion of the water that falls as precipitation can enter lakes where it can evaporate back into the atmosphere, condense, and fall back as precipitation again. Water in the lake can also be taken up by plants and transpired back into the atmosphere. Some of the water that falls as precipitation can infiltrate into the ground and become part of groundwater. **Infiltration** is the process by which water enters the subsurface by gravitation pull. Some of the water infiltrates into the ground and replenishes **aquifers** (saturated subsurface rock), which store huge amounts of freshwater for long periods of time. Some infiltration stays close to the land surface and can seep back into surface-water bodies (and the ocean) as **groundwater discharge**, and some groundwater finds openings in the land surface and emerges as freshwater **springs**. Plant roots absorb yet more groundwater to end up as evapotranspiration from the leaves. Over time, though, all this water keeps moving and most of it ends up in the ocean.

Components of the Hydrologic Cycle

Most precipitation falls in the form of rain but there are other forms such as snow, hail, and sleet. Once it runs sufficiently, surface water runoff is generated when the ground is saturated or impervious. **Surface water** is a major component of the hydrological cycle and one that we interact with very regularly. It includes lakes, wetlands, stormwater **runoff** (overland flow), ponds, potholes, rivers and streams.

Streams and Rivers

A river forms from water moving from a higher altitude to lower altitude, under the force of gravity. When rain falls on the land, it either evaporates, seeps into the ground or becomes runoff (water running on the surface). When water runs on the land surface it usually converges as it moves towards lower elevation. The converging runoff can concentrate into single channels of conveyance called creeks, stream, or rivers. Usually these start as small rill and rivulets that would join up downhill into larger streams and creeks which can also join up downstream to form even bigger rivers. The streams and rivers that join up to form a larger river are called **tributaries**, Figure 11.4.2. The land area drained by a river and all its tributaries is called a **watershed** or catchment or river basin.

The area adjacent to a river that floods frequently is a called a floodplain. **Floodplains** are areas that rivers use to temporarily store excess water during storm events and frequently contain very fertile soils. This has historically encouraged humans to move into floodplains and use them for agriculture, resulting in a reduction in the capacity of the floodplain to act as temporally storage for excess water during storm events, causing increased damaging flooding downstream. Properly functioning floodplains reduce the negative impacts of floods (by reducing severity of flood), and they assist in filtering stormwater and protecting the water quality of rivers. They also act as areas of recharge for groundwater.

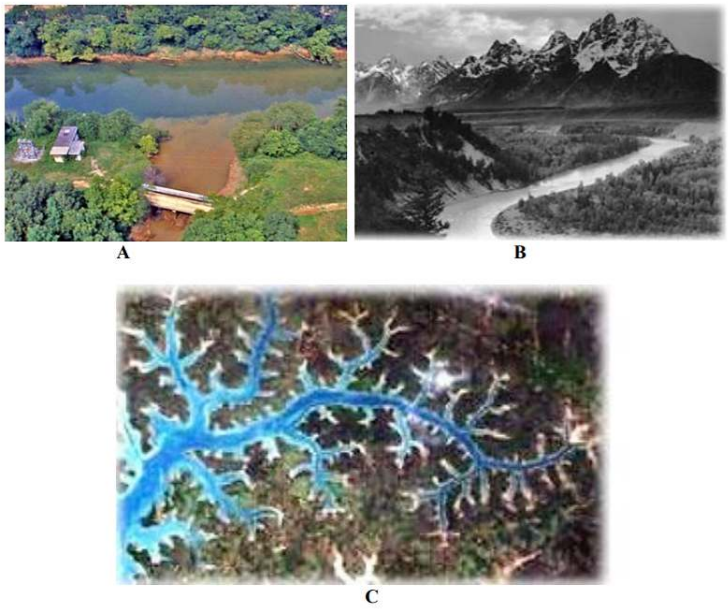


Figure 11.4.2: River systems. (A) A river with a small tributary (B) A meandering river with a mature floodplain (C) A satellite image of river system with multiple tributaries (Source USGS)

The US has numerous rivers that run throughout the nation's landscape. It is estimated that the US has over 200, 000 rivers with the Mississippi River being the largest by volume despite it only being the second longest. The Missouri River is the longest river in US. Most states have at least one important river. In Georgia, the main rivers are the Flint, Ochlockonee, Suwannee, Saint Marys, Satilla, Ogeechee, Altamaha, Oconee, Savannah, Chattahoochee, Tallapoosa, Coosa, Ocmulgee and the Tennessee rivers (Figure 11.4.3).

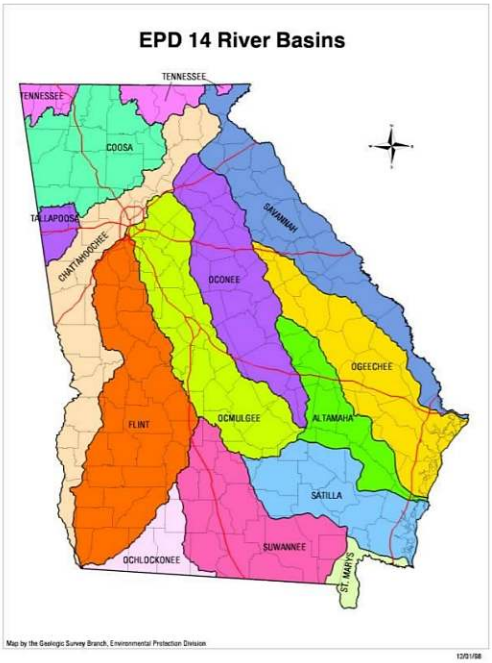


Figure 11.4.3: Major watershed of Georgia representing the main rivers in the state. (Source Georgia Environmental Protection Division: georgiaadoptastream.com)

These rivers are very important for supplying water to the cities and populations of the states. The rivers also contain important biological communities and provide opportunities for recreation such as swimming, fishing, and white water rafting. Rivers are so important and largely control settlement patterns all over the world. Major cities, communities, factories, industries, and power stations are located along rivers. It is, therefore, very important to protect the quality and integrity of rivers all over the world.

Unfortunately, most of the rivers in the world are too polluted to support certain human activities, especially swimming, fishing, and drinking. Close to half of the rivers in the US have been deemed too polluted to support swimming and fishing. A lot of the rivers have also been channelized, dredged, or impounded by dams which have ruined their ability to support a lot of human and biological activities. It is estimated that over 600, 000 river miles have been dammed in the US. Benefits of dams to humans include providing a source of water (reservoirs and farms ponds), recreation waters and reducing local flooding. On the other side, dams can also have negative impacts on people and the environment. They can lead to increased severe flooding downstream of the dam, especially during high rain events.

The impoundments can trap stream sediments resulting in reduced sediment supply downstream as well as increased deposition behind the dam. This shift in sediments flow can disrupt and damage aquatic habitats and can increase downstream stream erosion due to lack of sediment supply. The impoundments can also prevent certain aquatic organisms from migrating either upstream or downstream, therefore reducing their range and abilities to survive environmental changes as well cutting them off from spawning areas. Construction of dams can also result in displacement of the local people and loss of traditional lands and cultural history. Reservoirs and ponds usually form behind these impoundments.

Lakes, Reservoirs and ponds

If water flows to a place that is surrounded by higher land on all sides, a lake will form (Figure 11.4.4). A lake, pond or reservoir is a body of standing water on the land surface. When people build dams to stop rivers from flowing, the lakes that form are called reservoirs. It is estimated that over 300 million water bodies in the world are lakes, reservoirs, and ponds. Most of the Earth's lakes (about 60%) are found in Canada. Even though lakes and rivers contain less than 1% of the Earths water, the US gets over two thirds (70%) of its water (for drinking, industry, irrigation, and hydroelectric power generation) from lakes and reservoirs. Lakes are also the cornerstone of the US's freshwater fishing industry and are the backbone of the nation's state tourism industries and inland water recreational activities. (http://water.epa.gov/type/lakes/)



Figure 11.4.4: Lake Sinclair in Baldwin and Putnam counties (Photo Credits: GCSU Hydrology Research lab)

Wetland

A **wetland** is an area which is home to standing water for notable parts of the year, has saturated soils for a large part of the year and has plants that require large amounts of water to survive. Wetlands include swamps, marshes, and bogs. Wetlands are identified using three characteristics: soils (water-saturated soils are present), hydrology (shallow water table) and vegetation (wetland plants that are adapted to areas that are saturated with water for long periods of time). Wetlands are very important areas of biological diversity and productivity. These are also important areas where geochemical and biological cycles/ processes are consistently taking place. For instance, wetlands are considered as areas of significant carbon sequestration (storage), which impacts global climate change. They also act as filters for storm-water runoff before it enters rivers and lakes.

Oceans

As you have probably already guessed, oceans are an important component of the hydrologic cycle because they store majority of all water on Earth (about 95%). Most of the major rivers drain into them. The five oceans covering the surface of the Earth are the Atlantic, Indian, Pacific, Arctic and the Southern Ocean (Figure 11.4.5).

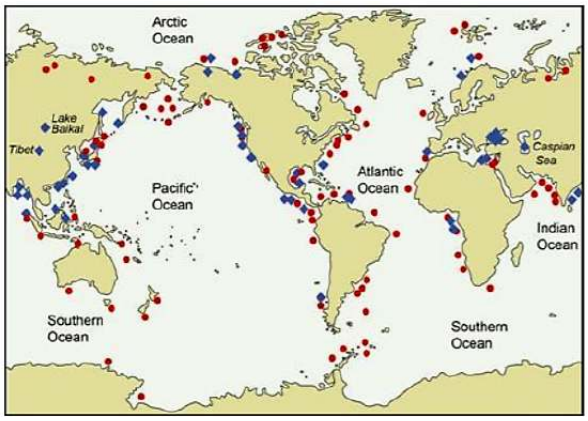


Figure 11.4.5: The five oceans found on planet Earth. The Pacific Ocean is the largest. Source: woodshole.er.usgs.gov/projec...es/primer.html

Approximately 90 % of the water that is evaporated into the hydrologic cycle comes from the ocean. Oceans are an important and large part of the hydrologic cycle, with lots biological diversity and many landforms. D*id you know that the average depth of the oceans is about 3.6 km with a maximum depth that can exceed 10 kilometers in areas known as ocean trenches?* The ocean is also home to many forms of life uniquely adapted to survive in this habitat. Unfortunately, humans have degraded the oceans and their life through pollution, overfishing, carbon dioxide acidification and resource exploitation. Figure 8.4.6 shows a couple of examples of human impacts on the ocean environment.



Figure 11.4.6: Trash washed up on the beach (A) and seal tangles up and being struggled by plastic trash in the ocean (B).

Also watch the video from the Habitable Planet: Oceans Video vwww.learner.org/courses/envs...nit=3&secNum=1

Groundwater

Storage and Flow

Almost 99% of the available fresh water is found below the surface as groundwater. Groundwater is not created by some mysterious processes below ground, but is part of the recycled water in the hydrologic cycle. When precipitation falls, some of the water runs off on the surface while some infiltrates into the ground. Groundwater is replenished when water moves from the surface, through unsaturated rocks or sediment (**unsaturated**), all the way down the **saturated parts** (saturated zone) in a process called infiltration and becomes groundwater (Figure 11.4.7). The top of the saturated portion is called the **water table**, which is the boundary between saturated and unsaturated zone.

Groundwater is found in **aquifers**, which are bodies of rock or sediment that store (and yield) large amounts of usable water in their pores. Aquifer productivity is controlled by **porosity** and **permeability**. Porosity is the percentage of open space in a rock or sediment body. Permeability is the ability of subsurface material to transmit fluids. Groundwater is found in the saturated zone of a rock body where all pores are filled with water. An important concept is that surface water always moves from higher elevation to lower elevation while groundwater always moves from higher energy (hydraulic head) to lower energy.

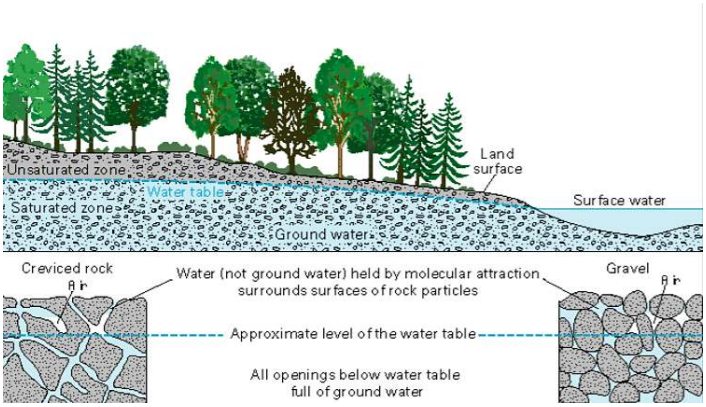


Figure 11.4.7: Model of groundwater system showing the different components of an unconfined groundwater system: water.usgs.gov/edu/earthgwaquifer.html

Groundwater will continue to flow until it emerges as a spring, or discharges into surface water bodies on the land or in the ocean. To utilize groundwater, we drill holes (wells) into the ground and pump the water out.

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11.5: Water Scarcity and Storage

Water has been identified as one of the major environmental crisis facing the world today. More than one billion people in the world lack access to clean drinking water. The demand for water has grown at a very fast pace in response to the rate of global population growth. Figures 11.5.1, and 11.5.2 illustrate this change in water use over time. It is predicted that over the next two decades, the average supply of water per person will drop by a third.

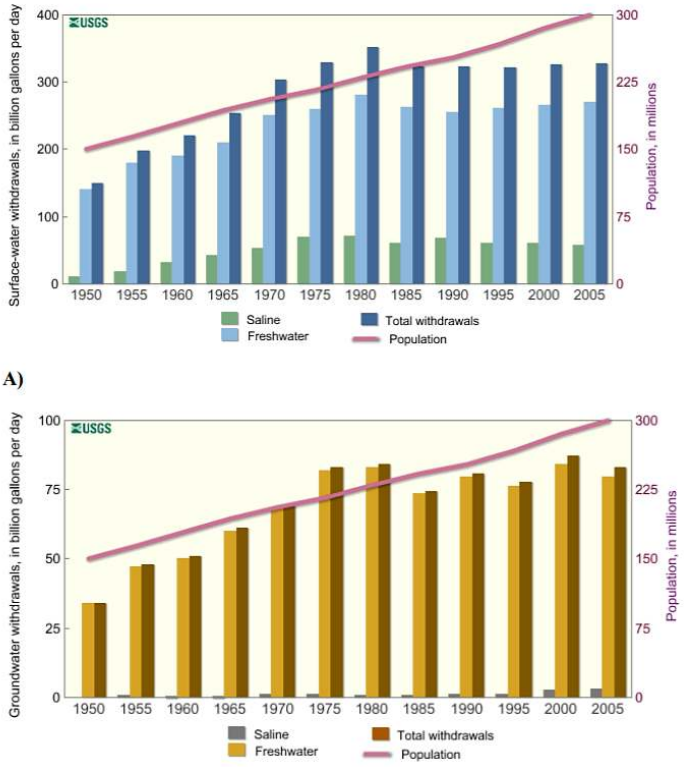


Figure 11.5.1: Trends in fresh and saline water withdrawals in response to population growth (A) surface water withdrawals (B) Groundwater withdrawal trends: water.usgs.gov/edu/wugw.html

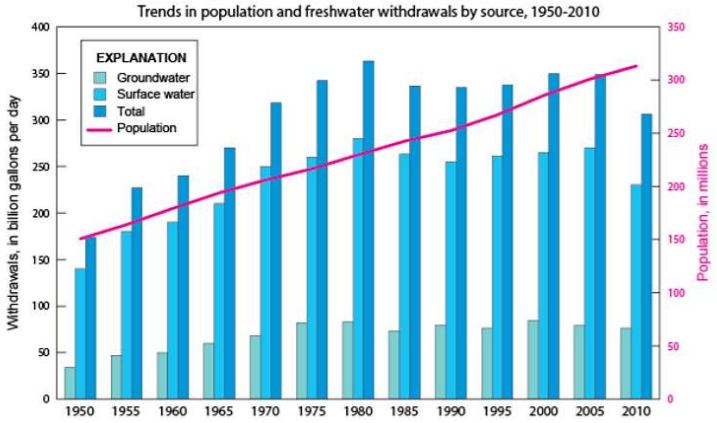


Figure 11.5.2: Both groundwater and surface water withdrawals had increased over time until 1980 when the withdrawals peaked and stabilized.

Water Scarcity and Availability

There is enough fresh water on Earth to supply every human being with enough drinking water. The main problem we face with regards to water is that it is unevenly distributed, polluted, mismanaged and wasted. Tony Allan, the author of Virtual Water, asserts that water follows money. This refers to the fact that rich countries and societies with money and affluence have more access to

safe drinking water even when they live in regions without much water. It also means that areas with large supplies of water can still have water scarcity if they lack the financial resources to build the infrastructure to supply people with safe clean drinking water. Water scarcity is caused by the demand for water being greater than the supply. Scarcity can be defined as either **physical scarcity** or **economic scarcity**.

Physical water scarcity is a situation where there is an actual shortage of water, regardless of quality or infrastructure. It is estimated that about 1.2 million people around the world are experiencing physical water scarcity. Economic scarcity is a condition where countries lack the financial resources and/or infrastructure to supply their citizens with reliable safe drinking water. About 1.6 billion people are experiencing economic water shortage; most of them live in less industrialized countries. For a lot of places in the world, scarcity is a transient condition that can be reduced or eliminated by installing the right infrastructure. The major problem in less industrialized countries is the lack of political, financial, and physical structures to provide water to everyone. A few rich people in these countries get the clean water while the majority of the people who cannot afford to pay for it are left out. Examples of such communities include many villages in Africa, Asia, and South America. Figure 11.5.3 shows communities in southeast Kenya that are experiencing severe water shortages primarily due to lack of infrastructure. Women in these communities must walk long distances to get untreated and contaminated water for drinking and other household needs.



Figure 11.5.3: Communities in southeast Kenya without ready access to safe drinking water. (A) Groundwater in the area is too salty for consumption. B) Maasai women in Amboseli National Park collecting water from a wetland. (C) Women in Magwede village in SE Kenya walking long distances to get water from a Kiosk. D) Children collecting water in Bungule Village from a water kiosk that is only open for about an hour every day. Photo credit: Jonathan Levy, Sam Mutiti and Christine Mutiti

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11.6: Water Quality (Pollution)

Water pollution is a major problem facing many of our surface water and groundwater sources. Contamination can both be natural due to geologic or meteorological events and anthropogenic (human causes). Human sources of contamination can be categorized as either point source or nonpoint source. **Point-source pollution** is water pollution coming from a single point, such as a sewage-outflow pipe. **Non-point source (NPS)** pollution is pollution discharged over a wide land area such as agricultural runoff and urban stormwater runoff, not from one specific location. Non-point source pollution contamination occurs when rainwater, snowmelt, or irrigation washes off plowed fields, city streets, or suburban backyards. As this runoff moves across the land surface, it picks up soil particles and pollutants, such as nutrients and pesticides.

Types of Water Pollution

Contamination of water resources comes in the form of chemical, biological, and physical pollution. **Chemical pollution** includes things such as toxic metals, organic compounds, acidic waters from mining activities and industry, pharmaceuticals and many other chemical compounds from industries and wastewater treatment plants. Another form of chemical pollution is radioactive waste which has a significant potential to cause harm to living things. Most of the radioactive pollution comes from agricultural practices such as tobacco farming, where radioactive phosphate fertilizer is used. **Physical pollution** includes sediment pollution, trash thrown in the water bodies, thermal and other suspended load. Temperature typically affects the metabolism of aquatic fauna in a negative way and can encourage eutrophication. **Biological pollution** usually refers to pathogenic bacteria, viruses, and parasitic protozoa. Common pathogenic microbes introduced into natural water bodies are pathogens from untreated sewage or surface runoff from intensive livestock grazing. Biological pollution is a common cause of illness and death in less industrialized countries where population density, water scarcity and inadequate sewage treatment combine to cause widespread parasitic and bacterial diseases.

Sources of water pollution

Most of the common inorganic chemical water pollutants are produced by non-point sources, mainly intensive agriculture, and high-density urban areas. Specific inorganic chemicals and their major sources are: ammonium nitrate and a host of related phosphate and nitrogen compounds used in agricultural fertilizers; heavy metals (present in urban runoff and mine tailings area runoff). However, some inorganic contaminants such as chlorine and related derivatives are produced from point sources, ironically employed in water treatment facilities. Moreover, some of the large dischargers of heavy metals to aquatic environments are fixed point industrial plants.

High concentrations of nitrogen (N) and phosphorus (P) in water can cause **eutrophication**. You are seeing this whenever you notice the greenish tint to the water in our local streams and rivers during low-flow times, or if you have ever seen a green farm pond. These nutrients are primarily coming from:

• treated wastewater (laden with P and N) being dumped into the river from sewage plants,

• agricultural areas where farmers allow livestock direct access to the stream, and

• agricultural areas where there is intense fertilizer application, and from landscapes (homes, gardens, golf courses) with fertilizer runoff

The N and P act as fertilizers in the water and promote algae blooms. As the algae dies, it is decomposed by aerobic bacteria in the water. These bacteria use up the oxygen in the water and the low dissolved oxygen (DO) levels can results in “fish kills” where large numbers of fish, and other aquatic life, die because of suffocation. The dead zone in the Gulf of Mexico is a huge area of low DO that has a large negative impact on the fishing industry along the Gulf Coast near the mouth of the Mississippi River. The dead zone occurs annually when fertilizers, from farm fields in the Midwest, wash down the Mississippi river.

Improper storage and use of automotive fluids produce common organic chemicals causing water pollution. These chemicals include methanol and ethanol (present in wiper fluid); gasoline and oil compounds such as octane, nonane (overfilling of gasoline tanks); most of these are considered non-point sources since their pathway to watercourses is mainly overland flow.

However, leaking underground and above ground storage tanks can be considered point sources for some of these chemicals, and even more toxic organic compounds such as perchloroethylene. Grease and fats (such as lubrication and restaurant effluent) can be

either point or non-point sources depending upon whether the restaurant releases grease into the wastewater collection system (point source) or disposes of such organics on the exterior ground surface or transports to large landfills.

The most significant **physical pollutant** is excess sediment in runoff from agricultural plots, clear-cut forests, improperly graded slopes, urban streets, and other poorly managed lands, especially when steep slopes or lands near streams are involved. Other physical pollutants include a variety of plastic refuse products such as packaging materials; the most pernicious of these items are ring shaped objects that can trap or strangle fish and other aquatic fauna (Figure 8.4.6). Other common physical objects are timber slash debris, waste paper and cardboard. Finally, power plants and other industrial facilities that use natural water bodies for cooling are the main sources of thermal pollution.

Groundwater can also become contaminated from both natural and anthropogenic sources of pollution. Naturally occurring contaminants are present in the rocks and sediments. As groundwater flows through sediments, metals such as iron and manganese are dissolved and may later be found in high concentrations in the water. Industrial discharges, urban activities, agriculture, groundwater withdrawal, and disposal of waste all can affect groundwater quality. Contaminants from leaking fuel tanks or fuel or toxic chemical spills may enter the groundwater and contaminate the aquifer. Pesticides and fertilizers applied to lawns and crops can accumulate and migrate to the water table.

Leakage from septic tanks and/or waste-disposal sites also can contaminate ground water. A septic tank can introduce bacteria to the water, and pesticides and fertilizers that seep into farmed soil can eventually end up in water drawn from a well. Or, a well might have been placed in land that was once used as a garbage or chemical dump site.

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11.7: Water Management

Pollution control begins with testing and monitoring of water quality. Water quality is usually monitored using easy to measure indicators such as pH, specific conductance (commonly referred to as conductivity), temperature, fecal and total coliform bacteria, dissolved oxygen, macroinvertebrates, and algae. Polluted sites typically have reduced DO levels, lower pH (more acidic), higher nutrient levels, more bacteria, and higher temperatures compared to less impacted or pristine sites.

Non-point source control relates mostly to land management practices in the fields of agriculture, mining and urban design and sanitation. Agricultural practices leading to the greatest improvement of sediment control include: contour grading, avoidance of bare soils in rainy and windy conditions, polyculture farming resulting in greater vegetative cover, and increasing fallow periods. Minimization of fertilizer, pesticide and herbicide runoff is best accomplished by reducing the quantities of these materials, as well as applying fertilizers during periods of low precipitation. Other techniques include avoiding of highly water soluble pesticides and herbicides, and use of materials that have the most rapid decay times to benign substances.

The main water pollutants associated with mines and quarries are aqueous slurries of minute rock particles, which result from rainfall scouring exposed soils and also from rock washing and grading activities. Runoff from metal mines and ore recovery plants is typically contaminated by the minerals present in the native rock formations. Control of this runoff is chiefly achieved by preventing rapid runoff and designing mining operations that avoid tailings either on steep slopes or near streams.

In the case of urban stormwater control, good urban planning and design can minimize stormwater runoff. By reducing impermeable surfaces (pavement that doesn't allow water through), then cities can reduce the amount of surface water runoff the carries pollutants into surface water and causes flooding. Additionally, the use of native plant and xeriscape techniques reduces water use and water runoff, and minimizes the need for pesticides and nutrients. Regarding street maintenance, a periodic use of street sweeping can reduce the sediment, chemical and rubbish load into the storm sewer system.

The two common approaches to water management fall under either voluntary programs or the regulatory program. The regulatory approach has been very successful in controlling and reducing point source pollution, which was the focus of regulations when they were first introduced. Voluntary programs, together with new amendments to regulations, have had great success in increasing conservation and reducing diffuse nonpoint source pollution. One of the most widely used voluntary programs is **Watershed Management** while the regulatory approach is centered on the Clean Water Act (CWA).

Watershed Management

The watershed management approach recognizes that water contamination problems are complex and not localized to a section of a river. Water pollution problems are caused by multiple activities within the watershed and, therefore, require holistic approaches in the entire watershed. A **watershed** (drainage basin or catchment) is an area of land that drains to a single outlet and is separated from other watersheds by a drainage divide. Rainfall that falls in a watershed will generate runoff (if not trapped or infiltrated into groundwater) to that watershed's outlet. Topographic elevation is used to define a watershed boundary. A focal point of water management plans is the Best Management Practices (BMPs) section. BMPs are designed to consider all of the various uses of water, maximize conservation and minimize pollution.

The regulatory approach

Water management through policy and laws seeks to clean up polluted water, prevent further pollution and apply punitive measures for polluters. In the US water-related regulations go as far back as 1899 with the Rivers and Harbors Act, also known as the Refuse Act that prohibited the dumping of solid waste and obstruction of waterways. This regulation, however, did not include waste flowing from streets and sewers. In 1948 another regulation, the Federal Water Pollution Act (which is the basis of the Clean Water Act) was enacted. This regulation covered contamination from sewage outfalls. It was created to reduce contamination of both interstate groundwater and surface waters. Through this regulation funding was made available to states and local governments for water quality management.

One of the major water-related regulations in the US is the Clean Water Act (CWA) of 1972. The regulation was very comprehensive with lots of programs and empowered the Environmental Protection Agency (EPA) to create goals, and objective laws for its implementation. The legislation has programs for both point and nonpoint source pollution. One other major piece of regulation governing water was the 1974 Safe Drinking Water Act (SDWA).

In 1974, amended in 1986, the SDWA was enacted to establish standards for many chemical constituents for public water supplied by public water agencies. In the regulations, maximum contaminant level goals (MCLG), which are non-enforceable and maximum contaminant levels (MCLs) that are enforceable where created. MCLG are what would be ideal and desirable while MCL are what should be attained in any drinking water supplied by a public municipal agency. For any carcinogen, the MCLG is 0 even though many contaminants have MCLs and detection limits in the parts per billion (ppb) range. Some of them (e.g. dioxin) have MCLs in the parts per trillion (ppt). To give you a sense of how small this ppt is, it is the same as 0.4 mm divided by the distance to the moon.

A Closer Look at the Clean Water Act

The 1972 Clean Water Acts was an overhaul of the 1948 Federal Pollution Control Act. The current regulation includes numerous programs for water quality improvement and protection. The EPA works with its federal, state and tribal regulatory partners to monitor and ensure compliance with clean water laws and regulations in order to protect human health and the environment. The Clean Water Act is the primary federal law governing water pollution. One of the objectives of the CWA was to restore and maintain the integrity of the nation's physical, chemical, and biological waters quality. The ultimate goals of the act are to establish zero pollutant discharge, as well as fishable & swimmable waters in the country. One main component of the CWA is regulations on industrial and municipal discharges into navigable US waters. The act is designed to be a partnership between states and the federal government. The federal government sets the agenda and standards while the state carries out the implementation of the law. States also have the power to set standards that are more stringent than the federal standards if needed. Under the CWA, discharge into US waters is only legal if authorized by a permit. Perpetrators of the law can be punished using administrative, civil, or criminal charges. The second component of the act is providing funding for constructing municipal waste water treatment plants and other projects to improve water quality (Title II and Title VI).

The act covers both point sources (discharge from sources such as pipes) and nonpoint sources (pollution from diffuse sources such as stormwater runoff). Point sources are explicitly covered under section 402, National Pollutant Discharge Elimination System (NPDES). This section requires industries and municipalities to get permits from the EPA before discharging into US waters. The permits require the use of control technology to reduce and prevent pollution.

Water in Crisis (case studies)

▪ Your instructor will assign you a specific case study for the course if needed.

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Index

A

accuracy
1.4: Accuracy, Precision, and Significant Figures
age structure diagram
4.3: Age structure diagrams
approximation
1.5: Approximation

C

carbohydrates
2.2: Biological Molecules
carbon cycle
10.1: The Carbon Cycle
classical physics
1.2: An Introduction
coal
7.2: Coal

D

derived units
1.3: Physical Quantities and Units

E

electricity
7.1: Fossil Fuels
English units
1.3: Physical Quantities and Units
exponential growth
3.2: Population Growth Models

F

fertility
4.6: Fertility
fossil fuels
7.1: Fossil Fuels
fundamental units
1.3: Physical Quantities and Units

G

greenhouse gases
10.2: Human Impacts on the Carbon Cycle

H

hydrocarbon
7.1: Fossil Fuels

I

Industrial Revolution
10.2: Human Impacts on the Carbon Cycle

K

kilogram
1.3: Physical Quantities and Units

L

law
1.2: An Introduction
life expectancy
4.5: Life Expectancy
lipids
2.2: Biological Molecules
logistic growth
3.2: Population Growth Models

M

Meter
1.3: Physical Quantities and Units
method of adding percents
1.4: Accuracy, Precision, and Significant Figures
metric system
1.3: Physical Quantities and Units
model
1.2: An Introduction
modern physics
1.2: An Introduction
Montreal Protocol
9.2: Ozone
mortality rates
4.4: The Demographic Transition Model
mountaintop removal
7.2: Coal

N

natural gas
7.1: Fossil Fuels

O

oil
7.1: Fossil Fuels
oil spills
7.3: Oil
order of magnitude
1.3: Physical Quantities and Units
ozone
9.2: Ozone
Ozone hole
9.2: Ozone

P

percent uncertainty
1.4: Accuracy, Precision, and Significant Figures
petroleum
7.3: Oil
physical quantity
1.3: Physical Quantities and Units
physics
1.2: An Introduction
physics, energy, work, kinetic energy, potential energy, chemical energy, thermal energy
6: Energy
precision
1.4: Accuracy, Precision, and Significant Figures

R

relativity
1.2: An Introduction
renewable energy
8.1: Introduction

S

scientific method
1.2: An Introduction
second
1.3: Physical Quantities and Units
SI units
1.3: Physical Quantities and Units
significant figures
1.4: Accuracy, Precision, and Significant Figures
strip mining
7.2: Coal

T

theory
1.2: An Introduction

U

underground mining
7.2: Coal
units
1.3: Physical Quantities and Units

Glossary

Sample Word 1 | Sample Definition 1

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    - InfoPage - *Undeclared*
    - Table of Contents - *Undeclared*
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    - 2.6: Appendix - *CC BY-NC-SA 4.0*
  - 3: Population Ecology - *CC BY-NC-SA 4.0*
    - 3.1: Introduction - *CC BY-NC-SA 4.0*
    - 3.2: Population Growth Models - *CC BY-NC-SA 4.0*
    - 3.3: Factors Limiting Population Growth - *CC BY-NC-SA 4.0*
    - 3.4: Life Tables and Survivorship - *CC BY-NC-SA 4.0*
    - 3.5: Population Ecology Practice Problems - *CC BY-NC-SA 4.0*
  - 4: Human Demography - *CC BY-NC-SA 4.0*
    - 4.1: The Human Population - *CC BY-NC-SA 4.0*
    - 4.2: Demography - *CC BY-NC-SA 4.0*
    - 4.3: Age structure diagrams - *CC BY-NC-SA 4.0*
    - 4.4: The Demographic Transition Model - *CC BY-NC-SA 4.0*
    - 4.5: Life Expectancy - *CC BY-NC-SA 4.0*
    - 4.6: Fertility - *CC BY-NC-SA 4.0*
    - 4.7: Appendix - *CC BY-NC-SA 4.0*
  - 5: Motion and Forces - *CC BY 4.0*
    - 5.1: Kinematics - *CC BY 4.0*
      - 5.1.1: Introduction to One-Dimensional Kinematics - *CC BY 4.0*
      - 5.1.2: Displacement - *CC BY 4.0*
      - 5.1.3: Vectors, Scalars, and Coordinate Systems - *CC BY 4.0*
      - 5.1.4: Time, Velocity, and Speed - *CC BY 4.0*
      - 5.1.5: Acceleration - *CC BY 4.0*
      - 5.1.6: Motion Equations for Constant Acceleration in One Dimension - *CC BY 4.0*
      - 5.1.7: Falling Objects - *CC BY 4.0*
      - 5.1.8: Projectile Motion - *CC BY 4.0*
      - 5.1.9: Centripetal Acceleration - *CC BY 4.0*
      - 5.1.E: Kinematics (Exercise) - *CC BY 4.0*
    - 5.2: Dynamics - *CC BY 4.0*
      - 5.2.1: Introduction to Dynamics- Newton's Laws of Motion - *CC BY 4.0*
      - 5.2.2: Development of Force Concept - *CC BY 4.0*
      - 5.2.3: Newton's First Law of Motion- Inertia - *CC BY 4.0*

        - 5.2.4: Newton's Second Law of Motion- Force and Acceleration - *CC BY 4.0*
        - 5.2.5: Newton's Third Law of Motion- Symmetry in Forces - *CC BY 4.0*
        - 5.2.6: Normal Force and Tension - *CC BY 4.0*
        - 5.2.7: Spring Force- Hooke's Law - *CC BY 4.0*
        - 5.2.8: Friction - *CC BY 4.0*
        - 5.2.9: Newton's Universal Law of Gravitation - *CC BY 4.0*
        - 5.2.10: Centripetal Force - *CC BY 4.0*
        - 5.2.E: Dynamics (Exercise) - *CC BY 4.0*
    - 6: Energy - *CC BY-NC 4.0*
        - 6.1: What is Energy? - *CC BY-NC 4.0*
        - 6.2: Work and Kinetic Energy - *CC BY-NC 4.0*
        - 6.3: Potential Energy - *CC BY-NC 4.0*
        - 6.4: Chemical Energy - *CC BY-NC 4.0*
        - 6.5: Thermal Energy - *CC BY-NC 4.0*
    - 7: Non-Renewable Energy - *CC BY-NC-SA 4.0*
        - 7.1: Fossil Fuels - *CC BY-NC-SA 4.0*
        - 7.2: Coal - *CC BY-NC-SA 4.0*
        - 7.3: Oil - *CC BY-NC-SA 4.0*
        - 7.4: Natural Gas - *CC BY-NC-SA 4.0*
        - 7.5: Fossil Fuels and Greenhouse Gases - *CC BY-NC-SA 4.0*
        - 7.6: Nuclear Energy - *CC BY-NC-SA 4.0*
        - 7.7: Electric Power Generation - *CC BY-NC-SA 4.0*
        - 7.8: Appendix - *CC BY-NC-SA 4.0*
    - 8: Alternative Energy - *CC BY-NC-SA 4.0*
        - 8.1: Introduction - *CC BY-NC-SA 4.0*
        - 8.2: Solar Energy - *CC BY-NC-SA 4.0*
        - 8.3: Biomass Energy - *CC BY-NC-SA 4.0*
        - 8.4: Wind Power - *CC BY-NC-SA 4.0*
        - 8.5: Geothermal Power - *CC BY-NC-SA 4.0*
        - 8.6: Hydroelectric Power (Hydropower) - *CC BY-NC-SA 4.0*
        - 8.7: Other Alternative Renewable Energy Sources - *CC BY-NC-SA 4.0*
        - 8.8: Policy and Conservation - *CC BY-NC-SA 4.0*
        - 8.9: Appendix - *CC BY-NC-SA 4.0*
    - 9: Air Pollution - *CC BY-NC-SA 4.0*
        - 9.1: Composition and Structure of the Atmosphere - *CC BY-NC-SA 4.0*
        - 9.2: Ozone - *CC BY-NC-SA 4.0*
        - 9.3: Outdoor Air Pollution - *CC BY-NC-SA 4.0*
        - 9.4: Indoor Air Pollution - *CC BY-NC-SA 4.0*
        - 9.5: Effects of Air Pollution on Human Health - *CC BY-NC-SA 4.0*
        - 9.6: Acid Rain - *CC BY-NC-SA 4.0*
        - 9.7: Air Pollution Legislation - *CC BY-NC-SA 4.0*
        - 9.8: Appendix - *CC BY-NC-SA 4.0*
    - 10: Climate Change - *CC BY-NC-SA 4.0*
        - 10.1: The Carbon Cycle - *CC BY-NC-SA 4.0*
        - 10.2: Human Impacts on the Carbon Cycle - *CC BY-NC-SA 4.0*
        - 10.3: The Science of Climate Change - *CC BY-NC-SA 4.0*
        - 10.4: Greenhouse Gases - *CC BY-NC-SA 4.0*
        - 10.5: Tools Scientists Use to Study Climate Change - *CC BY-NC-SA 4.0*
        - 10.6: Consequences of Climate Change - *CC BY-NC-SA 4.0*
        - 10.7: Looking Forward- Climate Strategies - *CC BY-NC-SA 4.0*
    - 11: Water - *CC BY-NC-SA 4.0*
        - 11.1: Introduction - *CC BY-NC-SA 4.0*
        - 11.2: Properties of Water - *CC BY-NC-SA 4.0*
        - 11.3: Global Water Distribution Use - *CC BY-NC-SA 4.0*
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        - Index - *Undeclared*
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    - 3.1: Introduction - *CC BY-NC-SA 4.0*
    - 3.2: Population Growth Models - *CC BY-NC-SA 4.0*
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    - 3.5: Population Ecology Practice Problems - *CC BY-NC-SA 4.0*
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    - 4.1: The Human Population - *CC BY-NC-SA 4.0*
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    - 4.3: Age structure diagrams - *CC BY-NC-SA 4.0*
    - 4.4: The Demographic Transition Model - *CC BY-NC-SA 4.0*
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    - 4.6: Fertility - *CC BY-NC-SA 4.0*
    - 4.7: Appendix - *CC BY-NC-SA 4.0*
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      - 5.1.6: Motion Equations for Constant Acceleration in One Dimension - *CC BY 4.0*
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      - 5.1.8: Projectile Motion - *CC BY 4.0*
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      - 5.2.1: Introduction to Dynamics- Newton's Laws of Motion - *CC BY 4.0*
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        - 5.2.6: Normal Force and Tension - *CC BY 4.0*
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        - 5.2.9: Newton's Universal Law of Gravitation - *CC BY 4.0*
        - 5.2.10: Centripetal Force - *CC BY 4.0*
        - 5.2.E: Dynamics (Exercise) - *CC BY 4.0*
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        - 6.1: What is Energy? - *CC BY-NC 4.0*
        - 6.2: Work and Kinetic Energy - *CC BY-NC 4.0*
        - 6.3: Potential Energy - *CC BY-NC 4.0*
        - 6.4: Chemical Energy - *CC BY-NC 4.0*
        - 6.5: Thermal Energy - *CC BY-NC 4.0*
    - 7: Non-Renewable Energy - *CC BY-NC-SA 4.0*
        - 7.1: Fossil Fuels - *CC BY-NC-SA 4.0*
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        - 7.5: Fossil Fuels and Greenhouse Gases - *CC BY-NC-SA 4.0*
        - 7.6: Nuclear Energy - *CC BY-NC-SA 4.0*
        - 7.7: Electric Power Generation - *CC BY-NC-SA 4.0*
        - 7.8: Appendix - *CC BY-NC-SA 4.0*
    - 8: Alternative Energy - *CC BY-NC-SA 4.0*
        - 8.1: Introduction - *CC BY-NC-SA 4.0*
        - 8.2: Solar Energy - *CC BY-NC-SA 4.0*
        - 8.3: Biomass Energy - *CC BY-NC-SA 4.0*
        - 8.4: Wind Power - *CC BY-NC-SA 4.0*
        - 8.5: Geothermal Power - *CC BY-NC-SA 4.0*
        - 8.6: Hydroelectric Power (Hydropower) - *CC BY-NC-SA 4.0*
        - 8.7: Other Alternative Renewable Energy Sources - *CC BY-NC-SA 4.0*
        - 8.8: Policy and Conservation - *CC BY-NC-SA 4.0*
        - 8.9: Appendix - *CC BY-NC-SA 4.0*
    - 9: Air Pollution - *CC BY-NC-SA 4.0*
        - 9.1: Composition and Structure of the Atmosphere - *CC BY-NC-SA 4.0*
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        - 9.6: Acid Rain - *CC BY-NC-SA 4.0*
        - 9.7: Air Pollution Legislation - *CC BY-NC-SA 4.0*
        - 9.8: Appendix - *CC BY-NC-SA 4.0*
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        - 10.2: Human Impacts on the Carbon Cycle - *CC BY-NC-SA 4.0*
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        - 10.6: Consequences of Climate Change - *CC BY-NC-SA 4.0*
        - 10.7: Looking Forward- Climate Strategies - *CC BY-NC-SA 4.0*
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