2

Earth's Physical Systems: Matter, Energy, and Geology

Chapter Objectives

This chapter will help students:

Explain the fundamentals of matter and chemistry and apply them to real-world situations

Differentiate among forms of energy and explain the basics of energy flow

Distinguish photosynthesis, cellular respiration, and chemosynthesis, and summarize their importance to living things

Explain how plate tectonics and the rock cycle shape the landscape around us and the earth beneath our feet

List major types of geologic hazards and describe ways to mitigate their impacts

Lecture Outline

I. Central Case Study: The Tohoku Earthquake: Has It Shaken the World's Trust in Nuclear Power?

A. Little did anyone know that this quake would initiate a series of events that would not only affect Japan, but also the future of nuclear power around the world.

B. The damage from the earthquake was supplemented by a following tsunami.

C. A **tsunami** is a powerful surge of seawater generated when an offshore earthquake displaces large volumes of rocks and sediment on the ocean bottom, suddenly pushing the overlying ocean water upward.

D. The raging water swept up to 9.6 km (6 mi) inland, scoured buildings from their foundations, and inundated towns, villages, and productive agricultural land.

E. This tsunami severely damaged the Fukushima Daiichi nuclear power plant.

F. Engineers and soldiers risked their lives amid radiation to avoid a full-blown catastrophe.

G. A 20-km (12-mi) area around the Fukushima Daiichi plant has been permanently evacuated, and the full extent of nuclear contamination is still being determined. Full recovery from these events is expected to take decades.

H. One of the longest-lasting legacies of these events may be the impact on the future of nuclear power in Japan and around the world. The Japanese government had championed a view that nuclear power was perfectly safe, but the events at Fukushima have shaken public support for nuclear power in Japan.

I. In North America and Europe, the events at Fukushima Daiichi caused a public already skeptical of the safety of nuclear power to become further wary of its use.

II. Matter, Chemistry, and the Environment

1. An understanding of matter itself helps us to fully appreciate all the processes of our world.
2. All material in the universe that has mass and occupies space is called **matter**. Types of matter and some of the important ways they interact are called **chemistry**.

A. Matter is conserved.

1. Matter may be transformed from one type of substance into others, but it cannot be created or destroyed. This principle is referred to as the **law of conservation of matter**.
2. The amount of matter stays constant as it is recycled in nutrient cycles and ecosystems. Pollution and waste will not simply disappear when we dispose of it.

B. Atoms and elements are the chemical building blocks.

1. The nuclear reactor at Fukushima used **uranium** to power its reactors, and uranium is an example of an element.

2. An **element** is a fundamental type of matter, a chemical substance with a given set of properties that cannot be broken down into substances with other properties.

3. Elements especially abundant on our planet include **hydrogen, oxygen, silicon, nitrogen**, and **carbon**.

4. The *periodic table of the elements* organizes the elements according to their chemical properties and behavior.

5. **Atoms** are the smallest units that maintain the chemical properties of the element.

6. Atoms of each element hold a defined number of **protons** in the atom's nucleus and this number is called the element's *atomic number*.

7. Most atoms also contain **neutrons** in their nuclei, and an element's *mass number* denotes the combined number of protons and neutrons in the atom.

8. An atom's nucleus is surrounded by negatively charged particles known as **electrons**, which balance the positive charge of the protons.

C. Isotopes

1. Atoms of the same element with differing numbers of neutrons are referred to as **isotopes**.

2. Some isotopes, called *radioisotopes*, are **radioactive** and "decay" by changing their chemical identity as they shed subatomic particles and emit high-energy radiation.

3. The greatest danger from radioisotopes occurs when they enter the bodies of organisms through the lungs, skin, or digestive system.

4. Each radioisotope decays at a rate determined by that isotope's **half-life**, the amount of time it takes for one-half of the atoms to give off radiation and decay.

D. Ions

1. Atoms may gain or lose electrons, thereby becoming **ions**, electrically charged atoms, or combinations of atoms.

2. The damaging radiation emitted by radioisotopes is called **ionizing radiation** because it generates ions when it strikes molecules.

E. Atoms bond to form molecules and compounds.

1. Atoms bond together and form **molecules**, combinations of two or more atoms.

2. A molecule composed of atoms of two or more different elements is called a **compound**.
    a. One compound is **water**, two hydrogen atoms bonded to an oxygen atom.
    b. Another is **carbon dioxide**, consisting of one carbon atom bonded to two oxygen atoms.
3. Atoms bond together because of an attraction for one another's electrons.
    a. When electrons are shared between atoms, a **covalent bond** forms.
    b. When an arrangement allows water molecules to adhere to one another in a type of weakly attractive interaction, this is called a *hydrogen bond*.
    c. In compounds in which strength of attraction is sufficiently unequal, an electron may be transferred from one molecule to another. This creates oppositely charged ions that form **ionic bonds**.
4. Elements, molecules, and compounds can also come together in mixtures without chemically bonding or reacting.
    a. Homogeneous mixtures are called *solutions*. Air in the atmosphere is a solution of many constituents, including nitrogen, oxygen, water vapor, carbon dioxide, **methane**, and **ozone**.

F. Water's chemistry facilitates life.
1. Water has unique properties that give it an amazing capacity to support life.
2. Hydrogen bonding gives water properties such as cohesion, high heat absorption capacity, a solid form that is less dense than the liquid form, and an ability to dissolve, or hold in solution, many other molecules, particularly ions and other partially charged molecules.

G. Hydrogen ions determine acidity.
1. In any aqueous solution, a small number of water molecules split apart, each forming a hydrogen ion (H^+) and a hydroxide ion (OH^-).
    a. Solutions in which the H^+ concentration is greater than OH^- concentration are **acidic**.
    b. The reverse case creates solutions that are **basic**, or alkaline.

2. The **pH** scale quantifies the acidity or alkalinity of solutions.
    a. pH less than 7 indicates an acidic solution.
    b. pH greater than 7 indicates an alkaline solution.
    c. Pure water has a pH of 7.
    d. The pH scale is logarithmic; each step represents a tenfold difference in hydrogen ion concentration.
3. Most biological systems have a pH between 6 and 8.

H. Matter is composed of organic and inorganic compounds.

1. **Organic compounds** consist of carbon atoms joined by covalent bonds.
2. One class of organic compounds that is important in environmental science is the **hydrocarbons**, which contain only atoms of carbon and hydrogen.
3. The lightest hydrocarbons, containing four or fewer carbon atoms, are gasses. Larger hydrocarbons are liquids; those having more than 20 are usually solids.
4. Some hydrocarbons from petroleum are known to pose health hazards to wildlife and people.
5. Some hydrocarbons from petroleum have become ubiquitous in our modern lifestyle because they are moldable into nearly any shape and resist chemical breakdown. While these **plastics** have many benefits for manufactured goods, they can be a persistent source of pollution due to their longevity in the environment.

I. Macromolecules are building blocks of life.

1. Organic compounds sometimes combine to form long chains of repeated molecules. These chains are called **polymers**, and there are three types of polymers that are essential to life: proteins, nucleic acids, and carbohydrates. Along with lipids, which are not polymers, these types of molecules are referred to as **macromolecules** because of their large sizes.
2. **Proteins** consist of long chains of organic molecules called *amino acids*. They serve many different functions in living cells, providing structural support, energy storage, and immune system functions. They also act as chemical messengers as hormones, and chemical reaction catalysts as *enzymes*.

3. **Nucleic acids** direct the production of proteins. **Deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)** carry the hereditary information for organisms. Nucleic acids are composed of nucleotides, each of which contains a sugar molecule, a phosphate group, and a nitrogenous base. Regions of DNA that code for specific functions are called **genes**.

4. **Carbohydrates** include simple sugars that are 3 to 7 carbon atoms long. Among these is glucose, which fuels living cells and serves as the base for complex carbohydrates. Complex carbohydrates include starch, an energy storage compound, chitin, a structural component of shells, and cellulose, the most abundant organic compound on Earth, found in the cell walls of plants.

5. **Lipids** include fats and oils (for energy storage), phospholipids (for cell membranes), waxes (for structure), and steroids (for hormone production). Although chemically diverse, these compounds are grouped together because they do not dissolve in water.

6. All of these macromolecules are found in cells, the most basic unit of organismal organization.

    a. The cells of *eukaryotes* (plants, animals, fungi, and protists) contain a membrane-enclosed nucleus and various membrane-enclosed *organelles* that perform specific functions.

    b. *Prokaryotes* (bacteria and archaea) are generally single-celled, and their cells lack membrane-enclosed organelles and a nucleus.

III. Energy: An Introduction

1. **Energy** is the capacity to change the position, physical composition, or temperature of matter—in other words, a force that can accomplish work.

A. Energy comes in different forms.

1. Two major forms of energy that scientists commonly distinguish are **potential energy**, energy of position, and **kinetic energy**, the energy of motion.

2. Chemical energy is a special type of potential energy that is held in the bonds between atoms. Converting a molecule with high-energy bonds into molecules with lower-energy bonds releases energy by changing potential energy into kinetic energy.

3. Nuclear energy, the energy that holds atomic nuclei together, and mechanical energy, such as that stored in a compressed spring, are also potential energies.

B. Energy is always conserved, but it changes in quality.

1. The **first law of thermodynamics** states that energy can change from one form to another, but cannot be created or destroyed.
2. The **second law of thermodynamics** states that energy tends to change from a more-ordered state to a less-ordered state, as long as no force counteracts this tendency. Systems tend to move toward increasing disorder, or *entropy*.
3. The order of an object or system can be increased through the input of additional energy from outside the system.

C. Some energy sources are easier to harness than others.

1. The nature of an energy source determines how easily people can harness it.
2. In each attempt we make to harvest energy, some portion escapes. We can express our degree of success in capturing energy in terms of the **energy conversion efficiency**, the ratio of the useful output of energy to the amount we need to input.

D. Light energy from the sun powers most living systems.

1. The energy that powers the Earth's biological systems comes primarily from the sun.
2. Some organisms use the sun's radiation directly to produce their own food. Such organisms called **autotrophs** or **primary producers** include green plants, algae, and cyanobacteria. Autotrophs turn light energy from the sun into chemical energy in a process called **photosynthesis**. In photosynthesis, sunlight powers a series of chemical reactions that converts water and carbon dioxide into sugars, transforming diffuse energy from the sun into concentrated energy the organism can use.

E. Photosynthesis produces food for plants and animals.

1. Photosynthesis occurs within cell organelles called *chloroplasts*, where the light-absorbing pigment *chlorophyll* uses solar energy to initiate a series of cellular reactions.
2. In a series of chemical reactions called *light reactions*, photosynthesis uses solar energy to split water molecules to form hydrogen ions and the oxygen we breathe.
3. The light reactions produce energy molecules that fuel reactions in the *Calvin cycle* where sugars are formed.

4. The net process of photosynthesis is defined by the chemical equation:

$$6CO_2 + 6H_2O + \text{the sun's energy} \rightarrow C_6H_{12}0_6 \text{ (sugar)} + 6O_2$$

5. Animals depend on the sugars and oxygen from photosynthesis.

F. Cellular respiration releases chemical energy.

1. Organisms make use of the chemical energy created by photosynthesis in a process called **cellular respiration**, which is vital to life.
2. The net equation for cellular respiration is the exact opposite of that for photosynthesis:

$$C_6H_{12}O_6 \text{ (sugar)} + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

3. Cellular respiration occurs in all living things—in both the autotrophs that create glucose and in **heterotrophs**, organisms that gain their energy by feeding on other organisms.

G. Geothermal energy also powers Earth's systems.

1. A minor energy source is the gravitational pull of the moon, which, in conjunction with the sun, causes ocean tides. Another significant energy source is geothermal heating emanating from inside Earth, powered primarily by radioactivity.
2. **Hydrothermal vents** are areas in the deep ocean from which jets of geothermally heated water emerge. Hydrothermal vent communities utilize chemical energy instead of light energy.
3. Communities of living organisms at these locations depend on bacteria at the base of the food web; these bacteria fuel themselves by **chemosynthesis** using the chemical bond energy of hydrogen sulfide:

$$6CO_2 + 6H_2O + 3\,H_2S \rightarrow C_6H_{12}O_6 \text{ (sugar)} + 3H_2SO_4$$

4. Chemosynthesis closely resembles the photosynthesis reaction.

IV. Geology: The Physical Basis for Environmental Science

1. A good place to begin understanding how our planet functions is right beneath our feet: rocks, soil, and sediments.
2. Understanding the physical nature of our planet also benefits our society.
3. Our planet is dynamic and this dynamism is what motivates **geology**, the study of Earth's physical features, processes, and history. Two geological processes of fundamental importance are plate tectonics and the rock cycle.

A. Earth consists of layers.

1. Most geological processes take place near Earth's surface, but our planet consists of multiple layers.

    a. Earth's center is a dense **core** consisting mostly of iron, solid in the inner core and molten in the outer core.

    b. Surrounding the core is a less dense, elastic layer called the **mantle**.

    c. A portion of the upper mantle called the **asthenosphere** contains especially soft rock.

    d. Above that is the harder rock we know as the **lithosphere**.

    e. The lithosphere includes Earth's **crust**, the thin layer of rock that covers the surface.

    f. The heat from inner Earth rises to the surface and dissipates.

2. A geothermal heat pump can be used to heat and cool a home.

3. The heat from the inner layers of Earth also drives convection currents that move mantle material. As this material moves, it drags lithospheric plates along the surface. This movement is known as **plate tectonics**.

B. Plate tectonics shape Earth's geography.

1. Our planet's surface consists of about 15 major tectonic plates that move at rates of roughly 2–15 cm per year. The plates' movement has influenced Earth's climate and life's evolution.

C. There are three types of plate boundaries.

1. The processes that occur at the boundaries between plates have major consequences.

2. At **divergent plate boundaries**, tectonic plates push apart as **magma** rises upward to the surface, creating new lithosphere as it cools.

3. Where two plates meet, they may slip and grind alongside one another, forming a **transform plate boundary**. *Faults* are fractures in Earth's crust.

4. **Convergent plate boundaries**, where two plates converge, or come together, can give rise to different outcomes.

    a. One plate may slide beneath the other in a process called **subduction**.

   b. When two plates of continental lithosphere meet, the continental crust on both sides resists subduction and instead crushes together, bending, buckling, and deforming layers of rock from both plates in a **continental collision**.

D. Tectonics produces Earth's landforms.

   1. Tectonic movements build mountains; shape the geography of oceans, islands, and continents; and give rise to earthquakes and volcanoes.

   2. The topography created by tectonic processes in turn shapes climate by altering patterns of rainfall, wind, ocean currents, and heating and cooling—all of which affect rates of weathering and erosion and the ability of plants and animals to inhabit different regions.

   3. Only in the last several decades have scientists learned about plate tectonics—this environmental system of such fundamental importance was completely unknown to humanity just half a century ago.

E. The rock cycle alters rock.

   1. Over geological time, rocks and the minerals that comprise them are heated, melted, cooled, broken down, and reassembled in a very slow process called the **rock cycle**.

   2. A **rock** is any solid aggregation of minerals. A **mineral** is any naturally occurring solid element of inorganic compound with a crystal structure, a specific chemical composition, and distinct physical properties.

F. Igneous rock

   1. If magma is released through the lithosphere, it may flow or splatter across Earth's surface as **lava**. Rock that forms when lava cools is called **igneous rock**.

   2. Igneous rock comes in two main classes: intrusive and extrusive igneous rock.

G. Sedimentary rock

   1. Through weathering and erosion, particles of rock blown by wind or washed away by water come to rest downhill, downstream, or downwind from their sources, eventually forming **sediments**.

   2. **Sedimentary rock** is formed as sediments are physically pressed together and as dissolved minerals seep through sediments and act as a kind of glue, binding sediment particles together (*cementation*). The formation of rock through these processes of compaction and cementation is termed *lithification*.

3. These processes also create the fossils of organisms and the fossil fuels we use for energy.

H. Metamorphic rock

1. When any type of rock is subjected to great heat and pressure, it may alter its form, becoming **metamorphic rock**.

V. Geologic and Natural Hazards

1. Plate tectonics gives rise to creative forces that shape our planet.

A. Earthquakes result from movement at plate boundaries and faults.

1. Along tectonic plate boundaries, and in other places where faults occur, Earth may relieve built-up pressure in fits and starts. Each release of energy causes what we know as an **earthquake**.
2. To minimize damage from earthquakes, engineers have developed ways to protect buildings from shaking.
3. Such designs are more expensive to build than conventional designs, so many buildings in poorer nations do not have such protections.

B. Volcanoes arise from rifts, subduction zones, or hotspots.

1. Where molten rock, hot gas, or ash erupt through Earth's surface, a **volcano** is formed, often creating a mountain over time as cooled lava accumulates.
2. Lava may also be emitted at *hotspots*, localized areas where plugs of molten rock from the mantle erupt through the crust.
3. At some volcanoes, lava flows slowly downhill. At other times, a volcano may let loose large amounts of ash and cinder in a sudden explosion. Sometimes a volcano can unleash a *pyroclastic flow*—a fast-moving cloud of toxic gas, ash, and rock fragments that races down the slopes at speeds up to 725 km/hr (450 mph), enveloping everything in its path.
4. Besides affecting people, volcanic eruptions exert environmental impacts.
5. One of the world's largest volcanoes—so large it is called a "supervolcano"—lies in the United States.

C. Landslides are a form of mass wasting.

1. A **landslide** occurs when large amounts of rock or soil collapse and flow downhill. Landslides are a severe and sudden manifestation

of **mass wasting**, the downslope movement of soil and rock due to gravity.

2. Most often, mass wasting erodes unstable hillsides, damaging property one structure at a time. Occasionally, mass wasting events can be colossal and deadly. Mudslides caused when volcanic eruptions melt snow and send huge volumes of destabilized mud racing downhill are called *lahars*, and these are particularly dangerous.

D. Tsunamis can follow earthquakes, volcanoes, or landslides.

1. Earthquakes, volcanic eruptions, and large coastal landslides can all displace huge volumes of ocean water instantaneously and trigger a tsunami.
2. Residents of the United States are vulnerable to tsunamis as well.
3. One of the best protections against tsunamis is advance warning.

E. We can worsen or mitigate the impacts of natural hazards.

1. Flooding, coastal erosion, wildfire, tornadoes, and hurricanes are “natural hazards” whose impacts can be worsened by the choices that we make.
    a. As the population grows, more people live in areas susceptible to natural disasters.
    b. Many of us choose to live in areas that we deem attractive, but that are also prone to hazards.
    c. We use and engineer landscapes in ways that can increase the frequency or severity of natural hazards.
    d. As we change Earth’s climate by emitting greenhouse gases, we alter patterns of precipitation, increasing risks of drought, fire, flooding, and mudslides. Rising sea levels increase coastal erosion.
2. We can reduce or mitigate the impacts of hazards through the thoughtful use of technology, engineering, and policy, informed by a solid understanding of geology and ecology.

VI. Conclusion

A. Physical phenomena are in some way tied to nearly every significant process in environmental science.

B. An understanding of matter is essential for all science.

C. Likewise, an understanding of energy is both of fundamental scientific importance and of considerable practical relevance.

D. Physical processes of geology, such as plate tectonics and the rock cycle, are centrally important because they shape Earth's terrain and form the foundation for living systems that overlie the landscape.

Key Terms

acidic
asthenosphere
atoms
autotrophs
basic
carbohydrates
carbon
carbon dioxide
cellular respiration
chemistry
chemosynthesis
compound
continental collision
convergent plate boundary
core
covalent bond
crust
deoxyribonucleic acid (DNA)
divergent plate boundary
earthquake
electrons
element
energy conversion efficiency
energy
first law of thermodynamics
genes
geology
half-life
heterotrophs
hydrocarbons
hydrogen
hydrothermal vents
igneous rock
ionic bonds
ionizing radiation
ions
isotopes
kinetic energy
landslide
lava
law of conservation of matter
lipids
lithosphere
macromolecules
magma
mantle
mass wasting
matter
metamorphic rock
methane
mineral
molecules
neutrons
nitrogen
nucleic acids
organic compounds
oxygen
ozone
pH
photosynthesis
plastics
plate tectonics
polymers
potential energy
primary producers
proteins
protons
radioactive