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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: Clean Green Energy Beneath Our Feet, The Geysers in California

A. By tapping reservoirs of steam produced by hot rocks underground, engineers are using **geothermal energy**, which produces enough electricity at the Geysers in California to power nearly a million homes.

B. To counter the depletion of the underground reservoirs, managers began to import wastewater from surrounding communities and inject it into the ground.

C. Earthquakes have emerged as a consequence of the extraction of steam and the pumping of water into the reservoirs. So far, these have all been minor but there are fears of larger ones.

D. Currently, the Geysers provide one-fourth of California's renewable energy.

II. Matter, Chemistry, and the Environment

1. All material in the universe that has mass and occupies space is termed **matter**.
2. The ways in which various types of matter interact is 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 geothermally-heated water at the Geysers is made of **hydrogen** and **oxygen.** Both are elements.
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. Other than hydrogen and oxygen, especially abundant elements on our planet include **silicon**, **nitrogen**, and **carbon**. The periodic table organizes the elements according to their chemical properties and behavior.
4. **Atoms** are the smallest units that maintain the chemical properties of the element. Each element has a defined number of **protons** in its nucleus and this defines its atomic number. The combined number of protons and **neutrons** in the nucleus determines the element's mass number.
5. The nucleus is surrounded by negatively charged particles known as **electrons**, which balance the positive charge of the protons.

C. Isotopes

1. Atoms of a given element may contain different numbers of neutrons. Atoms of the same element with differing numbers of neutrons are referred to as **isotopes**.
2. Some isotopes are **radioactive** and decay into lighter radioisotopes until they become stable isotopes (not radioactive).

3. Each radioisotope decays at a rate determined by that isotope's **half-life**. Uranium-235, our source for nuclear power, decays with a half-life of about 700 million years, eventually forming a stable lead isotope.

D. Ions

1. Atoms may gain or lose electrons and become **ions**, electrically charged atoms. In this state, they may combine with other atoms.

E. Atoms bond to from molecules and compounds.

1. Atoms bond together and form **molecules**, combinations of two or more atoms. Some common gasses such as hydrogen, H_2, and oxygen, O_2, are typical.
2. A molecule composed of atoms to two or more different elements is called a **compound**. **Water** is a compound made of two hydrogen atoms bound to one oxygen atom. Another important compound is **carbon dioxide**, consisting of one carbon atom bonded to two oxygen atoms.
3. Atoms bond together as a result of an attraction for one another's electrons. These vary from equal sharing, such as in hydrogen gas, to water where the oxygen attracts the electrons more strongly, to compounds where the electron is transferred from one element to another. Compounds exhibiting this last type of bonding are known as *ionic compounds*, or *salts*.
4. Elements, molecules, and compounds can come together in mixtures without chemically bonding. Homogeneous mixtures are called *solutions*. Air in the atmosphere is a solution of many constituents, including nitrogen, oxygen, water vapor, **methane**, and **ozone**.

F. Water's chemistry facilitates life.

1. Water has properties that give it a unique capacity to support life. A partial negative charge at the oxygen atom and a partial positive charge at the hydrogen atom allow water molecules to adhere to one another in a weak attraction called a hydrogen bond.
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 aqueous solution, a small number of water molecules split apart, forming a hydrogen ion (H^+) and a hydroxide ion (OH^-). The product of these ion concentrations are always the same; if one increases, the other decreases.
2. Solutions in which H^+ concentration are greater than OH^- are **acidic**.

The reverse case creates solutions which are **basic**, or alkaline.

3. The **pH** scale quantifies the acidity or alkalinity. pH less than 7 indicates an acidic solution; pH greater than y indicates an alkaline solution. Pure water has a pH of 7.
4. The pH scale is logarithmic; each step represents a tenfold difference in hydrogen ion concentration.

H. Matter is composed of organic and inorganic compounds.

1. **Organic compounds** consist of carbon atoms and, generally, hydrogen atoms, and may include other elements. When carbon atoms bond together in long chains, the resulting molecules may be called **polymers**.
2. One class of organic compounds that is important in environmental science is **hydrocarbons**, which contain only atoms of carbon and hydrogen.
3. The lightest hydrocarbons, containing four or fewer carbon atoms, are gasses. Hydrocarbons with between four and 20 carbon atoms are generally liquids; those having more than 20 are usually solids.
4. Some hydrocarbons, such as the polycyclic aromatic hydrocarbons, PAHs, are found in gasoline and oil as well as in combustion products and are known to be toxic to wildlife and humans.

I. Macromolecules are building blocks of life.

1. Some polymers, proteins, nucleic acids, and carbohydrates play key roles as building blocks of life. Along with lipids, fats, oils, and waxes, these 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.

J. We create synthetic polymers.

1. Chemists work with the polymer concept and create polymers called **plastics**.
2. Polyethylene, polypropylene, polyurethane, and polystyrene are just a few of the many synthetic polymers in our manufactured products.
3. We value polymers because they are long-lasting and resist chemical breakdown – the same traits that make them a serious source of waste and pollution, which endangers wildlife and human health.

III. Energy: An Introduction

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

A. Energy comes in different forms.

1. **Potential energy** is the energy of position.
2. **Kinetic energy** is the energy of motion. It can be expressed as heat energy, light energy, sound energy, or electrical energy as well.
3. 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.
4. Nuclear energy, the energy in an atomic nucleus, and mechanical energy, such as that stored in a compressed spring, are also potential energies.

B. Energy is always conserved but can change in quality.

1. The **first law of thermodynamics** states that energy can change from one form to another, but cannot be created or lost. For example, when heated underground water surges to the surface, the kinetic energy of its movement will equal the potential energy it held underground.
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. Living organisms maintain their structure and function by consuming energy (food).
4. The nature of an energy source determines how easily people can harness it.
5. In every transfer of energy, some portion escapes. The degree to which

we successfully capture energy is termed the *energy conversion efficiency* and is the ratio of useful output of energy to the amount that needs to be input.

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

1. Some organisms use the sun's radiation to produce their own food. Such organisms are called **autotrophs** or **primary producers** and include green plants, algae, and cyanobacteria.
2. 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 and oxygen, transforming diffuse energy from the sun into concentrated energy the organism can use.

D. Photosynthesis produces food for plants and animals

1. 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.
2. The light reactions produce energy molecules that fuel reactions in the *Calvin cycle* where sugars are formed.
3. The net process of photosynthesis is defined by the chemical equation:
$$6CO_2 + 6H_2O + \text{ the sun's energy} \rightarrow C_6H_{12}O_6 \text{ (sugar)} + 6O_2$$
4. Animals depend on the sugars and oxygen from photosynthesis.

E. 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. Cells employ oxygen to convert glucose back into its original starting materials, water and carbon dioxide, and release energy to form chemical bonds or perform other tasks within cells.
3. The net equation for cellular respiration is the exact opposite of that for photosynthesis:
$$C_6H_{12}O_6 \text{ (sugar)} + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$
4. The energy released per glucose molecule in respiration is only two-thirds of the energy input per glucose molecule in photosynthesis, an example of the second law of thermodynamics.
5. Cellular respiration occurs in all living things and in both the autotrophs that create glucose and in **heterotrophs**, or consumers.

F. 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.
2. A more significant additional energy source is the geothermal heating

emanating from inside the earth, powered primarily by radiation from radioisotopes deep inside our planet.

3. **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.
4. 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:

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

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. 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 the Earth's surface.
2. Earth's center is a dense **core** consisting mostly of iron, solid in the inner core and molten in the outer core.
3. Surrounding the core is a less dense, elastic layer called the **mantle**. A portion of the upper mantle is the asthenosphere, which contains soft rock. Above that is the harder rock we know as the **lithosphere**.
4. The lithosphere includes the Earth's **crust**, the thin layer of rock that covers the surface.
5. The heat from inner Earth rises to the surface and dissipates. Where the asthenosphere approaches within a few miles of the surface, we can drill to tap geothermal energy. But the soil and rock just below the Earth's surface is fairly constant in temperature, (cooler than the air in summer and warmer than the air in winter), allowing homes to use geothermal energy efficiently.
6. The heat from the inner layers of the 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 which move at rates of roughly 2 to 15 cm per year.
2. The plates' movement has influenced Earth's climate and life's evolution.

C. There are three types of plate boundaries.

   1. At **divergent plate boundaries**, tectonic plates push apart as **magma** rises upward to the surface, creating new crust as it cools. An example is the Mid-Atlantic ridge.
   2. Where two plates meet, they may slip and grind alongside one another, forming a **transform plate boundary** or a *fault*. The San Andreas Fault in California is an example of this type of boundary.
   3. When plates collide at **convergent plate boundaries**, two scenarios are possible. One plate may slide beneath the other in a process called **subduction**. This can lead to volcanic eruptions. The Cascades in the Pacific Northwest are an example and led to the eruption of Mount Saint Helens in 1980 and 2004. 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**. The Himalayas were formed in this manner and continue to be uplifted.

D. Tectonics produce Earth's landforms.

   1. The Geysers in California are located above a region of subduction, which is why magma rises to the surface.
   2. Tectonic processes shape climate and life's evolution by changing areas of coastal regions to continental interiors and the reverse.

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. There are two main classes of igneous rock. *Intrusive* igneous rock forms when magma cools slowly and solidifies while it is below the Earth's surface, giving rise to rocks with large crystals such as granite. The second class is formed when molten rock is ejected from a volcano and cools quickly. This class is called *extrusive* igneous rock and its most common representative is basalt.

G. Sedimentary rock

1. Through weathering, 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. Sediments can also form chemically from the precipitation of substances out of solution.
3. **Sedimentary rock** is formed as sediments are physically pressed together; dissolved minerals bind the particles together in a process known as *lithification*. Sandstone, shale, and limestone are examples of sedimentary rock.
4. 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, such as from geologic forces deep underground, it may alter its form, becoming **metamorphic rock**. Metamorphic rock includes slate and marble.

V. Geologic and Natural Hazards

1. Earth's geothermal heating gives rise to creative forces that shape our planet. They can include hazards such as earthquakes and volcanoes.
2. Nine out of ten of the world's earthquakes and over half of the world's volcanoes occur on plate boundaries that are on the circum-Pacific belt, the so-called "ring of fire."

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

1. Plate boundaries and other places where faults occur may relieve built-up pressure in fits and starts. Each release of energy causes what we know as an **earthquake**.
2. Damage from earthquakes is generally greatest where soils are loose or saturated with water.
3. Engineers have developed ways to protect buildings from earthquakes and such designs are an important part of new building codes in earthquake-prone areas such as California and Japan.

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

1. Where molten rock, hot gas, or ash erupt through the Earth's surface, a **volcano** is formed, often creating a mountain over time as cooled lava accumulates.
2. At some volcanoes, such as Mount Kilauea in Hawaii, lava flows continuously downhill. At others, a volcano may let loose large amount of ahs and cinder in a sudden explosion, such as during Mount Saint Helen's 1980 eruption.

3. Volcanic eruptions exert environmental impacts. Large eruptions can depress temperatures throughout the world as a result of ash blocking sunlight and sulfuric acid hazes that block radiation and cool the atmosphere.

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. Mass wasting can be brought about by human land practices that expose or loosen soil. Mass wasting events can be colossal and deadly, such as the mudslides that occur after torrential hurricane rainfall or following volcanic eruptions.

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**, an immense swell or wave of water that can travel thousands of miles across oceans.

2. Residents of the United States are vulnerable to tsunamis as well. A Canary Island volcano could put Atlantic-coast cities at risk.

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 disaster, sometimes by choice.

   b. We use and engineer landscapes in ways that can increase the severity of natural hazards.

   c. As we change Earth's climate by emitting greenhouse gases, we alter patterns of precipitation, increasing risks of drought, flooding and fire. Rising sea levels increase coastal erosion.

2. We can reduce the impacts of hazards through the thoughtful use of technology and a solid understanding of geology and ecology.

VI. Conclusion

A. Geothermal heating provides one window into the broad phenomena of chemical and physical processes that shape our planet.

B. An understanding of matter and energy is essential for all science and particularly for finding solutions to environmental problems.

C. The physical processes of geology are important because they shape Earth's terrain and generate phenomena that can threaten our lives and property.

Key Terms for Chapter 2

acidic
atoms
autotrophs
basic
carbohydrates
carbon
carbon dioxide
cellular respiration
chemistry
chemosynthesis
compound
continental collisions
convergent plate boundary
core
crust
deoxyribonucleic acid (DNA)
divergent plate boundary
earthquake
electrons
element
energy
first law of thermodynamics
genes
geology
geothermal energy
half-life
heterotrophs
hydrocarbons
hydrogen
hydrothermal vents
igneous rock
ions
isotopes
kinetic energy
landslide
lava
law of conservation of matter
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
ribonucleic acid (RNA)
rock
rock cycle
second law of thermodynamics
sedimentary rock
sediments
silicon
subduction
transform plate boundary
tsunami
volcano
water