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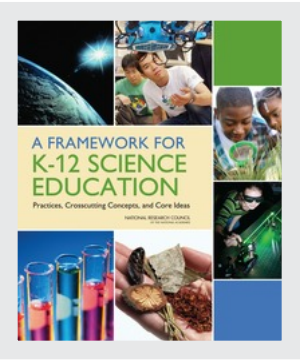

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas

DETAILS

400 pages | 8.25 x 10 | HARDBACK
ISBN 978-0-309-21441-4 | DOI 10.17226/13165

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5

Dimension 3
DISCIPLINARY CORE IDEAS—PHYSICAL SCIENCES

Most systems or processes depend at some level on physical and chemical subprocesses that occur within it, whether the system in question is a star, Earth's atmosphere, a river, a bicycle, the human brain, or a living cell. Large-scale systems often have emergent properties that cannot be explained on the basis of atomic-scale processes; nevertheless, to understand the physical and chemical basis of a system, one must ultimately consider the structure of matter at the atomic and subatomic scales to discover how it influences the system's larger scale structures, properties, and functions. Similarly, understanding a process at any scale requires awareness of the interactions occurring—in terms of the forces between objects, the related energy transfers, and their consequences. In this way, the physical sciences—physics and chemistry—underlie all natural and human-created phenomena, although other kinds of information transfers, such as those facilitated by the genetic code or communicated between organisms, may also be critical to understanding their behavior. An overarching goal for learning in the physical sciences, therefore, is to help students see that there are mechanisms of cause and effect in all systems and processes that can be understood through a common set of physical and chemical principles.

The committee developed four core ideas in the physical sciences—three of which parallel those identified in previous documents, including the *National Science Education Standards* and *Benchmarks for Science Literacy* [1, 2]. The three core ideas are PS1: Matter and Its Interactions, PS2: Motion and Stability: Forces and Interactions, and PS3: Energy.

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We also introduce a fourth core idea: PS4: Waves and Their Applications in Technologies for Information Transfer—which introduces students to the ways in which advances in the physical sciences during the 20th century underlie all sophisticated technologies available today. This idea is included in recognition of the fact that organizing science instruction around disciplinary core ideas tends to leave out the applications of those ideas. The committee included this fourth idea to stress the interplay of physical science and technology, as well as to expand students' understanding of light and sound as mechanisms of both energy transfer (see LS3) and transfer of information between objects that are not in contact. Modern communication, information, and imaging technologies are applications of scientific understandings of light and sound and their interactions with matter. They are pervasive in our lives today and are also critical tools without which much of modern science could not be done. See Box 5-1 for a summary of these four core ideas and their components.

The first three physical science core ideas answer two fundamental questions—"What is everything made of?" and "Why do things happen?"—that are not unlike questions that students themselves might ask. These core ideas can be applied to explain and predict a wide variety of phenomena that occur in people's everyday lives, such as the evaporation of a puddle of water, the transmission of sound, the digital storage and transmission of information, the tarnishing of metals, and photosynthesis. And because such explanations and predictions rely on a basic understanding of matter and energy, students' abilities to conceive of the interactions of matter and energy are central to their science education.

The historical division between the two subjects of physics and chemistry is transcended in modern science, as the same physical principles are seen to apply from subatomic scales to the scale of the universe itself. For this reason we have chosen to present the two subjects together, thereby ensuring a more coherent approach to the core ideas across all grades. The designation of physical science courses at the high school level as either physics or chemistry is not precluded by our grouping of these disciplines; what is important is that all students are offered a course sequence that gives them the opportunity and support to learn about all these ideas and to recognize the connections between them.

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BOX 5-1

CORE AND COMPONENT IDEAS IN THE PHYSICAL SCIENCES

Core Idea PS1: Matter and Its Interactions

PS1.A: Structure and Properties of Matter

PS1.B: Chemical Reactions

PS1.C: Nuclear Processes

Core Idea PS2: Motion and Stability: Forces and Interactions

PS2.A: Forces and Motion

PS2.B: Types of Interactions

PS2.C: Stability and Instability in Physical Systems

Core Idea PS3: Energy

PS3.A: Definitions of Energy

PS3.B: Conservation of Energy and Energy Transfer

PS3.C: Relationship Between Energy and Forces

PS3.D: Energy in Chemical Processes and Everyday Life

Core Idea PS4: Waves and Their Applications in Technologies for Information Transfer

PS4.A: Wave Properties

PS4.B: Electromagnetic Radiation

PS4.C: Information Technologies and Instrumentation

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Core Idea PS1 Matter and Its Interactions

How can one explain the structure, properties, and interactions of matter?

The existence of atoms, now supported by evidence from modern instruments, was first postulated as a model that could explain both qualitative and quantitative observations about matter (e.g., Brownian motion, ratios of reactants and products in chemical reactions). Matter can be understood in terms of the types of atoms present and the interactions both between and within them. The states (i.e., solid, liquid, gas, or plasma), properties (e.g., hardness, conductivity), and reactions (both physical and chemical) of matter can be described and predicted based on the types, interactions, and motions of the atoms within it. Chemical reactions, which underlie so many observed phenomena in living and nonliving systems alike, conserve the number of atoms of each type but change their arrangement into molecules. Nuclear reactions involve changes in the types of atomic nuclei present and are key to the energy release from the sun and the balance of isotopes in matter.

PS1.A: STRUCTURE AND PROPERTIES OF MATTER

How do particles combine to form the variety of matter one observes?

While too small to be seen with visible light, atoms have substructures of their own. They have a small central region or nucleus—containing protons and neutrons—surrounded by a larger region containing electrons. The number of protons in the atomic nucleus (atomic number) is the defining characteristic of each element; different isotopes of the same element differ in the number of neutrons only. Despite the immense variation and number of substances, there are only some 100 different stable elements.

Each element has characteristic chemical properties. The periodic table, a systematic representation of known elements, is organized horizontally by increasing atomic number and vertically by families of elements with related chemical properties. The development of the periodic table (which occurred well before atomic substructure was understood) was a major advance, as its patterns suggested and led to the identification of additional elements with particular properties. Moreover, the table's patterns are now recognized as related to the atom's outermost electron patterns, which play an important role in explaining chemical reactivity and bond formation, and the periodic table continues to be a useful way to organize this information.

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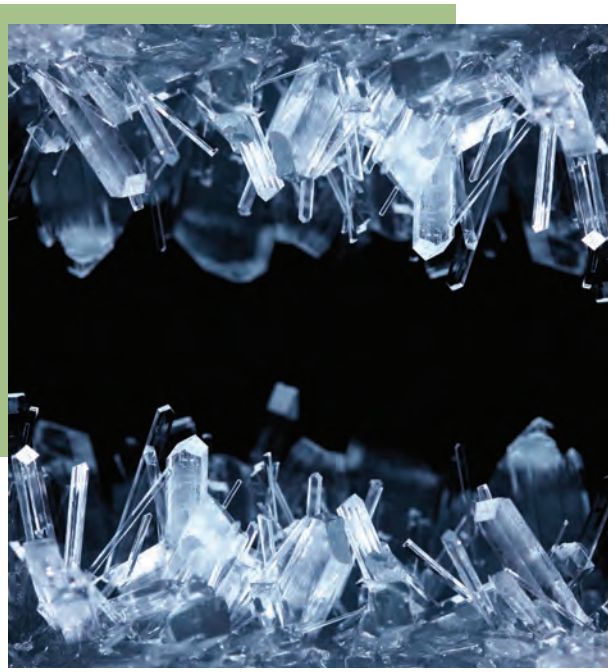
The substructure of atoms determines how they combine and rearrange to form all of the world's substances. Electrical attractions and repulsions between charged particles (i.e., atomic nuclei and electrons) in matter explain the structure of atoms and the forces between atoms that cause them to form molecules (via chemical bonds), which range in size from two to thousands of atoms (e.g., in biological molecules such as proteins). Atoms also combine due to these forces to form extended structures, such as crystals or metals. The varied properties (e.g., hardness, conductivity) of the materials one encounters, both natural and manufactured, can be understood in terms of the atomic and molecular constituents present and the forces within and between them.



Within matter, atoms and their constituents are constantly in motion. The arrangement and motion of atoms vary in characteristic ways, depending on the substance and its current state (e.g., solid, liquid). Chemical composition, temperature, and pressure affect such arrangements and motions of atoms, as well as the ways in which they interact. Under a given set of conditions, the state and some properties (e.g., density, elasticity, viscosity) are the same for different bulk quantities of a substance, whereas other properties (e.g., volume, mass) provide measures of the size of the sample at hand.

Materials can be characterized by their intensive measureable properties. Different materials with different properties are suited to different uses. The ability to image and manipulate placement of individual atoms in tiny structures allows for the design of new types of materials with particular desired functionality (e.g., plastics, nanoparticles). Moreover, the modern explanation of how particular atoms influence the properties of materials or molecules is critical to understanding the physical and chemical functioning of biological systems.

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Grade Band Endpoints for PS1.A

By the end of grade 2. Different kinds of matter exist (e.g., wood, metal, water), and many of them can be either solid or liquid, depending on temperature. Matter can be described and classified by its observable properties (e.g., visual, aural, textural), by its uses, and by whether it occurs naturally or is manufactured. Different properties are suited to different purposes. A great variety of objects can be built up from a small set of pieces (e.g., blocks, construction sets). Objects or samples of a substance can be weighed, and their size can be described and measured. (Boundary: volume is introduced only for liquid measure.)

By the end of grade 5. Matter of any type can be subdivided into particles that are too small to see, but even then the matter still exists and can be detected by other means (e.g., by weighing or by its effects on other objects). For example, a model showing that gases are made from matter particles that are too small to see and are moving freely around in space can explain many observations, including the inflation and shape of a balloon; the effects of air on larger particles or objects (e.g., leaves in wind, dust suspended in air); and the appearance of visible scale water droplets in condensation, fog, and, by extension, also in clouds or the contrails of a jet. The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish (e.g., sugar in solution, evaporation in a closed container). Measurements of a variety of properties (e.g., hardness, reflectivity) can be used to identify particular materials. (Boundary: At this grade level, mass and weight are not distinguished, and no attempt is made to define the unseen particles or explain the atomic-scale mechanism of evaporation and condensation.)

By the end of grade 8. All substances are made from some 100 different types of atoms, which combine with one another in various ways. Atoms form molecules that range in size from two to thousands of atoms. Pure substances are made from a single type of atom or molecule; each pure substance has characteristic physical and chemical properties (for any bulk quantity under given conditions) that can be used to identify it.

Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. In a liquid, the molecules are constantly in contact with each other; in a gas, they are widely spaced except when they happen to collide. In a solid, atoms are closely spaced and vibrate in position but do not

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change relative locations. Solids may be formed from molecules, or they may be extended structures with repeating subunits (e.g., crystals). The changes of state that occur with variations in temperature or pressure can be described and predicted using these models of matter. (Boundary: Predictions here are qualitative, not quantitative.)

By the end of grade 12. Each atom has a charged substructure consisting of a nucleus, which is made of protons and neutrons, surrounded by electrons. The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. Stable forms of matter are those in which the electric and magnetic field energy is minimized. A stable molecule has less energy, by an amount known as the binding energy, than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart.

PS1.B: CHEMICAL REACTIONS

How do substances combine or change (react) to make new substances? How does one characterize and explain these reactions and make predictions about them?

Many substances react chemically with other substances to form new substances with different properties. This change in properties results from the ways in which atoms from the original substances are combined and rearranged in the new substances. However, the total number of each type of atom is conserved (does not change) in any chemical process, and thus mass does not change either. The property of conservation can be used, along with knowledge of the chemical properties of particular elements, to describe and predict the outcomes of reactions. Changes in matter in which the molecules do not change, but their positions and their motion relative to each other do change also occur (e.g., the forming of a solution,

Understanding chemical reactions and the properties of elements is essential not only to the physical sciences but also is foundational knowledge for the life sciences and the earth and space sciences.

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a change of state). Such changes are generally easier to reverse (return to original conditions) than chemical changes.

"Collision theory" provides a qualitative model for explaining the rates of chemical reactions. Higher rates occur at higher temperatures because atoms are typically moving faster and thus collisions are more frequent; also, a larger fraction of the collisions have sufficient energy to initiate the process. Although a solution or a gas may have constant chemical composition—that is, be in a steady state—chemical reactions may be occurring within it that are dynamically balanced with reactions in opposite directions proceeding at equal rates.

Any chemical process involves a change in chemical bonds and the related bond energies and thus in the total chemical binding energy. This change is matched by a difference between the total kinetic energy of the set of reactant molecules before the collision and that of the set of product molecules after the collision (conservation of energy). Some reactions release energy (e.g., burning fuel in the presence of oxygen), and others require energy input (e.g., synthesis of sugars from carbon dioxide and water).

Understanding chemical reactions and the properties of elements is essential not only to the physical sciences but also is foundational knowledge for the life sciences and the earth and space sciences. The cycling of matter and associated transfers of energy in systems, of any scale, depend on physical and chemical processes. The reactivity of hydrogen ions gives rise to many biological and geophysical phenomena. The capacity of carbon atoms to form the backbone of extended molecular structures is essential to the chemistry of life. The carbon cycle involves transfers between carbon in the atmosphere—in the form of carbon dioxide—and carbon in living matter or formerly living matter (including fossil fuels). The proportion of oxygen molecules (i.e., oxygen in the form O_2) in the atmosphere also changes in this cycle.

Grade Band Endpoints for PS1.B

By the end of grade 2. Heating or cooling a substance may cause changes that can be observed. Sometimes these changes are reversible (e.g., melting and freezing), and sometimes they are not (e.g., baking a cake, burning fuel).

By the end of grade 5. When two or more different substances are mixed, a new substance with different properties may be formed; such occurrences depend on the substances and the temperature. No matter what reaction or

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change in properties occurs, the total weight of the substances does not change. (Boundary: Mass and weight are not distinguished at this grade level.)

By the end of grade 8. Substances react chemically in characteristic ways. In a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. The total number of each type of atom is conserved, and thus the mass does not change. Some chemical reactions release energy, others store energy.

By the end of grade 12. Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in total binding energy (i.e., the sum of all bond energies in the set of molecules) that are matched by changes in kinetic energy. In many situations, a dynamic and condition-dependent balance between a reaction and the reverse reaction determines the numbers of all types of molecules present.

The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions. Chemical processes and properties of materials underlie many important biological and geophysical phenomena.

PS1.C: NUCLEAR PROCESSES

What forces hold nuclei together and mediate nuclear processes?

Phenomena involving nuclei are important to understand, as they explain the formation and abundance of the elements, radioactivity, the release of energy from the sun and other stars, and the generation of nuclear power. To explain and predict nuclear processes, two additional types of interactions—known as strong and weak nuclear interactions—must be introduced. They play a fundamental role in nuclei, although not at larger scales because their effects are very short range.

The strong nuclear interaction provides the primary force that holds nuclei together and determines nuclear binding energies. Without it, the electromagnetic forces between protons would make all nuclei other than hydrogen unstable. Nuclear processes mediated by these interactions include fusion, fission, and the radioactive decays of unstable nuclei. These processes involve changes in nuclear

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binding energies and masses (as described by $E = mc^2$), and typically they release much more energy per atom involved than do chemical processes.

Nuclear fusion is a process in which a collision of two small nuclei eventually results in the formation of a single more massive nucleus with greater net binding energy and hence a release of energy. It occurs only under conditions of extremely high temperature and pressure. Nuclear fusion occurring in the cores of stars provides the energy released (as light) from those stars. The Big Bang produced matter in the form of hydrogen and smaller amounts of helium and lithium. Over time, stars (including supernova explosions) have produced and dispersed all the more massive atoms, starting from primordial low-mass elements, chiefly hydrogen.

Nuclear fission is a process in which a massive nucleus splits into two or more smaller nuclei, which fly apart at high energy. The produced nuclei are often not stable and undergo subsequent radioactive decays. A common fission fragment is an alpha particle, which is just another name for a helium nucleus, given before this type of "radiation" was identified.

In addition to alpha particles, other types of radioactive decays produce other forms of radiation, originally labeled as "beta" and "gamma" particles and now recognized as electrons or positrons, and photons (i.e., high-frequency electromagnetic radiation), respectively. Because of the high-energy release in nuclear transitions, the emitted radiation (whether it be alpha, beta, or gamma type) can ionize atoms and may thereby cause damage to biological tissue.

Nuclear fission and radioactive decays limit the set of stable isotopes of elements and the size of the largest stable nucleus. Spontaneous radioactive decays follow a characteristic exponential decay law, with a specific lifetime (time scale) for each such process; the lifetimes of different nuclear decay processes range from fractions of a second to thousands of years. Some unstable but long-lived isotopes are present in rocks and minerals. Knowledge of their nuclear lifetimes allows radiometric dating to be used to determine the ages of rocks and other materials from the isotope ratios present.

In fission, fusion, and beta decay processes, atoms change type, but the total number of protons plus neutrons is conserved. Beta processes involve an additional type of interaction (the weak interaction) that can change neutrons into protons or vice versa, along with the emission or absorption of electrons or positrons and of neutrinos. Isolated neutrons decay by this process.

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Grade Band Endpoints for PS1.C

By the end of grade 2. [Intentionally left blank.]

By the end of grade 5. [Intentionally left blank.]

By the end of grade 8. Nuclear fusion can result in the merging of two nuclei to form a larger one, along with the release of significantly more energy per atom than any chemical process. It occurs only under conditions of extremely high temperature and pressure. Nuclear fusion taking place in the cores of stars provides the energy released (as light) from those stars and produced all of the more massive atoms from primordial hydrogen. Thus the elements found on Earth and throughout the universe (other than hydrogen and most of helium, which are primordial) were formed in the stars or supernovas by fusion processes.

By the end of grade 12. Nuclear processes, including fusion, fission, and radioactive decays of unstable nuclei, involve changes in nuclear binding energies. The total number of neutrons plus protons does not change in any nuclear process. Strong and weak nuclear interactions determine nuclear stability and processes. Spontaneous radioactive decays follow a characteristic exponential decay law. Nuclear lifetimes allow radiometric dating to be used to determine the ages of rocks and other materials from the isotope ratios present.

Normal stars cease producing light after having converted all of the material in their cores to carbon or, for more massive stars, to iron. Elements more massive than iron are formed by fusion processes but only in the extreme conditions of supernova explosions, which explains why they are relatively rare.

Core Idea PS2 Motion and Stability: Forces and Interactions

How can one explain and predict interactions between objects and within systems of objects?

Interactions between any two objects can cause changes in one or both of them. An understanding of the forces between objects is important for describing how their motions change, as well as for predicting stability or instability in systems at any scale. All forces between objects arise from a few types of interactions: gravity, electromagnetism, and the strong and weak nuclear interactions.

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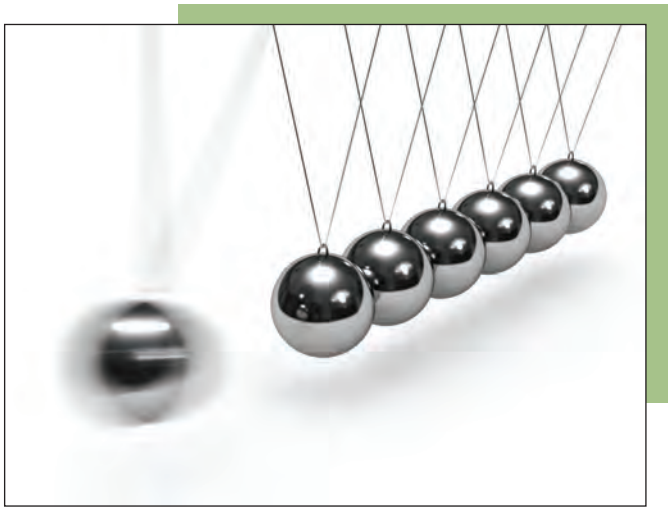
PS2.A: FORCES AND MOTION

How can one predict an object's continued motion, changes in motion, or stability?

Interactions of an object with another object can be explained and predicted using the concept of forces, which can cause a change in motion of one or both of the interacting objects. An individual force acts on one particular object and is described by its strength and direction. The strengths of forces can be measured and their values compared.



What happens when a force is applied to an object depends not only on that force but also on all the other forces acting on that object. A static object typically has multiple forces acting on it, but they sum to zero. If the total (vector sum) force on an object is not zero, however, its motion will change. Sometimes forces on an object can also change its shape or orientation. For any pair of interacting objects, the force exerted by the first object on the second object is equal in strength to the force that the second object exerts on the first but in the opposite direction (Newton's third law).

At the macroscale, the motion of an object subject to forces is governed by Newton's second law of motion. Under everyday circumstances, the mathematical expression of this law in the form $F = ma$ (total force = mass times acceleration) accurately predicts changes in the motion of a single macroscopic object of a given mass due to the total force on it. But at speeds close to the speed of light, the second law is not applicable without modification. Nor does it apply to objects at the molecular, atomic, and subatomic scales, or to an object whose mass is changing at the same time as its speed.

An understanding of the forces between objects is important for describing how their motions change, as well as for predicting stability or instability in systems at any scale.

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For speeds that are small compared with the speed of light, the momentum of an object is defined as its mass times its velocity. For any system of interacting objects, the total momentum within the system changes only due to transfer of momentum into or out of the system, either because of external forces acting on the system or because of matter flows. Within an isolated system of interacting objects, any change in momentum of one object is balanced by an equal and oppositely directed change in the total momentum of the other objects. Thus total momentum is a conserved quantity.

Grade Band Endpoints for PS2.A

By the end of grade 2. Objects pull or push each other when they collide or are connected. Pushes and pulls can have different strengths and directions. Pushing or pulling on an object can change the speed or direction of its motion and can start or stop it. An object sliding on a surface or sitting on a slope experiences a pull due to friction on the object due to the surface that opposes the object's motion.

By the end of grade 5. Each force acts on one particular object and has both a strength and a direction. An object at rest typically has multiple forces acting on it, but they add to give zero net force on the object. Forces that do not sum to zero can cause changes in the object's speed or direction of motion. (Boundary: Qualitative and conceptual, but not quantitative addition of forces are used at this level.) The patterns of an object's motion in various situations can be observed and measured; when past motion exhibits a regular pattern, future motion can be predicted from it. (Boundary: Technical terms, such as magnitude, velocity, momentum, and vector quantity, are not introduced at this level, but the concept that some quantities need both size and direction to be described is developed.)

By the end of grade 8. For any pair of interacting objects, the force exerted by the first object on the second object is equal in strength to the force that the second object exerts on the first but in the opposite direction (Newton's third law). The motion of an object is determined by the sum of the forces acting on it; if the total force on the object is not zero, its motion will change. The greater the mass of the object, the greater the force needed to achieve the same change in motion. For any given object, a larger force causes a larger change in motion. Forces on an object can also change its shape or orientation. All positions of objects and the directions of forces and motions must be described in an arbitrarily chosen reference frame

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and arbitrarily chosen units of size. In order to share information with other people, these choices must also be shared.

By the end of grade 12. Newton's second law accurately predicts changes in the motion of macroscopic objects, but it requires revision for subatomic scales or for speeds close to the speed of light. (Boundary: No details of quantum physics or relativity are included at this grade level.)

Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. In any system, total momentum is always conserved. If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system.

PS2.B: TYPES OF INTERACTIONS

What underlying forces explain the variety of interactions observed?

All forces between objects arise from a few types of interactions: gravity, electromagnetism, and strong and weak nuclear interactions. Collisions between objects involve forces between them that can change their motion. Any two objects in contact also exert forces on each other that are electromagnetic in origin. These forces result from deformations of the objects' substructures and the electric charges of the particles that form those substructures (e.g., a table supporting a book, friction forces).

Gravitational, electric, and magnetic forces between a pair of objects do not require that they be in contact. These forces are explained by force fields that contain energy and can transfer energy through space. These fields can be mapped by their effect on a test object (mass, charge, or magnet, respectively).

Objects with mass are sources of gravitational fields and are affected by the gravitational fields of all other objects with mass. Gravitational forces are always attractive. For two human-scale objects, these forces are too small to observe without sensitive instrumentation. Gravitational interactions are nonnegligible, however, when very massive objects are involved. Thus the gravitational force due to Earth, acting on an object near Earth's surface, pulls that object toward the planet's center. Newton's law of universal gravitation provides the mathematical model to describe and predict the effects of gravitational forces between distant objects. These long-range gravitational interactions govern the evolution and

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maintenance of large-scale structures in the universe (e.g., the solar system, galaxies) and the patterns of motion within them.

Electric forces and magnetic forces are different aspects of a single electromagnetic interaction. Such forces can be attractive or repulsive, depending on the relative sign of the electric charges involved, the direction of current flow, and the orientation of magnets. The forces' magnitudes depend on the magnitudes of the charges, currents, and magnetic strengths as well as on the distances between the interacting objects. All objects with electrical charge or magnetization are sources of electric or magnetic fields and can be affected by the electric or magnetic fields of other such objects. Attraction and repulsion of electric charges at the atomic scale explain the structure, properties, and transformations of matter and the contact forces between material objects (link to PS1.A and PS1.B). Coulomb's law provides the mathematical model to describe and predict the effects of electrostatic forces (relating to stationary electric charges or fields) between distant objects.

The strong and weak nuclear interactions are important inside atomic nuclei. These short-range interactions determine nuclear sizes, stability, and rates of radioactive decay (see PS1.C).

Grade Band Endpoints for PS2.B

By the end of grade 2. When objects touch or collide, they push on one another and can change motion or shape.

By the end of grade 5. Objects in contact exert forces on each other (friction, elastic pushes and pulls). Electric, magnetic, and gravitational forces between a pair of objects do not require that the objects be in contact—for example, magnets push or pull at a distance. The sizes of the forces in each situation depend on the properties of the objects and their distances apart and, for forces between two magnets, on their orientation relative to each other. The gravitational force of Earth acting on an object near Earth's surface pulls that object toward the planet's center.

By the end of grade 8. Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the

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distances between the interacting objects. Gravitational forces are always attractive. There is a gravitational force between any two masses, but it is very small except when one or both of the objects have large mass—for example, Earth and the sun. Long-range gravitational interactions govern the evolution and maintenance of large-scale systems in space, such as galaxies or the solar system, and determine the patterns of motion within those structures.

Forces that act at a distance (gravitational, electric, and magnetic) can be explained by force fields that extend through space and can be mapped by their effect on a test object (a ball, a charged object, or a magnet, respectively).

By the end of grade 12. Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects.

Forces at a distance are explained by fields permeating space that can transfer energy through space. Magnets or changing electric fields cause magnetic fields; electric charges or changing magnetic fields cause electric fields. Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. The strong and weak nuclear interactions are important inside atomic nuclei—for example, they determine the patterns of which nuclear isotopes are stable and what kind of decays occur for unstable ones.

PS2.C: STABILITY AND INSTABILITY IN PHYSICAL SYSTEMS

Why are some physical systems more stable than others?

Events and processes in a system typically involve multiple interactions occurring simultaneously or in sequence. The system's stability or instability and its rate of evolution depend on the balance or imbalance among these multiple effects.

A stable system is one in which the internal and external forces are such that any small change results in forces that return the system to its prior state (e.g., a weight hanging from a string). A system can be static but unstable, with any small change leading to forces that tend to increase that change (e.g., a ball at the top of a hill). A system can be changing but have a stable repeating cycle of changes, with regular patterns of change that allow predictions about the system's future (e.g., Earth orbiting the sun). And a stable system can appear to be unchanging when flows or processes within it are going on at opposite but equal rates (e.g., water in a dam at a constant height but with water flowing in that offsets the

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water flowing out; a person maintaining steady weight but eating food, burning calories, and excreting waste).

Stability and instability in any system depend on the balance of competing effects. A steady state of a complex system can be maintained through a set of feedback mechanisms, but changes in conditions can move the system out of its range of stability (e.g., homeostasis breaks down at too high or too low a temperature). With no energy inputs, a system starting out in an unstable state will continue to change until it reaches a stable configuration (e.g., the temperatures of hot and cold objects in contact). Viewed at a given scale, stable systems may appear static or dynamic. Conditions and properties of the objects within a system affect the rates of energy transfer and thus how fast or slowly a process occurs (e.g., heat conduction, the diffusion of particles in a fluid).

When a system has a great number of component pieces, one may not be able to predict much about its precise future. For such systems (e.g., with very many colliding molecules), one can often predict average but not detailed properties and behaviors (e.g., average temperature, motion, and rates of chemical change but not the trajectories of particular molecules).

Grade Band Endpoints for PS2.C

By the end of grade 2. Whether an object stays still or moves often depends on the effects of multiple pushes and pulls on it (e.g., multiple players trying to pull an object in different directions). It is useful to investigate what pushes and pulls keep something in place (e.g., a ball on a slope, a ladder leaning on a wall) as well as what makes something change or move.

By the end of grade 5. A system can change as it moves in one direction (e.g., a ball rolling down a hill), shifts back and forth (e.g., a swinging pendulum), or goes through cyclical patterns (e.g., day and night). Examining how the forces on and within the system change as it moves can help to explain the system's patterns of change.

A system can appear to be unchanging when processes within the system are occurring at opposite but equal rates (e.g., water behind a dam is at a constant height because water is flowing in at the same rate that water is flowing out). Changes can happen very quickly or very slowly and are sometimes hard to see (e.g., plant growth). Conditions and properties of the objects within a system affect how fast or slowly a process occurs (e.g., heat conduction rates).

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By the end of grade 8. A stable system is one in which any small change results in forces that return the system to its prior state (e.g., a weight hanging from a string). A system can be static but unstable (e.g., a pencil standing on end). A system can be changing but have a stable repeating cycle of changes; such observed regular patterns allow predictions about the system's future (e.g., Earth orbiting the sun). Many systems, both natural and engineered, rely on feedback mechanisms to maintain stability, but they can function only within a limited range of conditions. With no energy inputs, a system starting out in an unstable state will continue to change until it reaches a stable configuration (e.g., sand in an hourglass).

By the end of grade 12. Systems often change in predictable ways; understanding the forces that drive the transformations and cycles within a system, as well as the forces imposed on the system from the outside, helps predict its behavior under a variety of conditions.

When a system has a great number of component pieces, one may not be able to predict much about its precise future. For such systems (e.g., with very many colliding molecules), one can often predict average but not detailed properties and behaviors (e.g., average temperature, motion, and rates of chemical change but not the trajectories or other changes of particular molecules). Systems may evolve in unpredictable ways when the outcome depends sensitively on the starting condition and the starting condition cannot be specified precisely enough to distinguish between different possible outcomes.

Core Idea PS3 Energy

How is energy transferred and conserved?

Interactions of objects can be explained and predicted using the concept of transfer of energy from one object or system of objects to another. The total energy within a defined system changes only by the transfer of energy into or out of the system.

PS3.A: DEFINITIONS OF ENERGY

What is energy?

That there is a single quantity called energy is due to the remarkable fact that a system's *total* energy is conserved. Regardless of the quantities of energy transferred

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between subsystems and stored in various ways within the system, the total energy of a system changes only by the amount of energy transferred into and out of the system.

At the macroscopic scale, energy manifests itself in multiple phenomena, such as motion, light, sound, electrical and magnetic fields, and thermal energy. Historically, different units were introduced for the energy present in these different phenomena, and it took some time before the relationships among them were recognized. Energy is best understood at the microscopic scale, at which it can be modeled as either motions of particles or as stored in force fields (electric, magnetic, gravitational) that mediate interactions between particles. This last concept includes electromagnetic radiation, a phenomenon in which energy stored in fields moves across space (light, radio waves) with no supporting matter medium.

Motion energy is also called kinetic energy; defined in a given reference frame, it is proportional to the mass of the moving object and grows with the square of its speed. Matter at any temperature above absolute zero contains thermal energy. Thermal energy is the random motion of particles (whether vibrations in solid matter or molecules or free motion in a gas), this energy is distributed among all the particles in a system through collisions and interactions at a distance. In contrast, a sound wave is a moving pattern of particle vibrations that transmits energy through a medium.

Electric and magnetic fields also contain energy; any change in the relative positions of charged objects (or in the positions or orientations of magnets) changes the fields between them and thus the amount of energy stored in those fields. When a particle in a molecule of solid matter vibrates, energy is continually being transformed back and forth between the energy of motion and the energy stored in the electric and magnetic fields within the matter. Matter in a stable form minimizes the stored energy in the electric and magnetic fields within it; this defines the equilibrium positions and spacing of the atomic nuclei in a molecule or an extended solid and the form of their combined electron charge distributions (e.g., chemical bonds, metals).

Energy stored in fields within a system can also be described as potential energy. For any system where the stored energy depends only on the spatial configuration of the system and not on its history, potential energy is a useful concept (e.g., a massive object above Earth's surface, a compressed or stretched spring). It is defined as a difference in energy compared to some arbitrary reference configuration of a system. For example, lifting an object increases the stored energy in the gravitational field between that object and Earth (gravitational potential energy)

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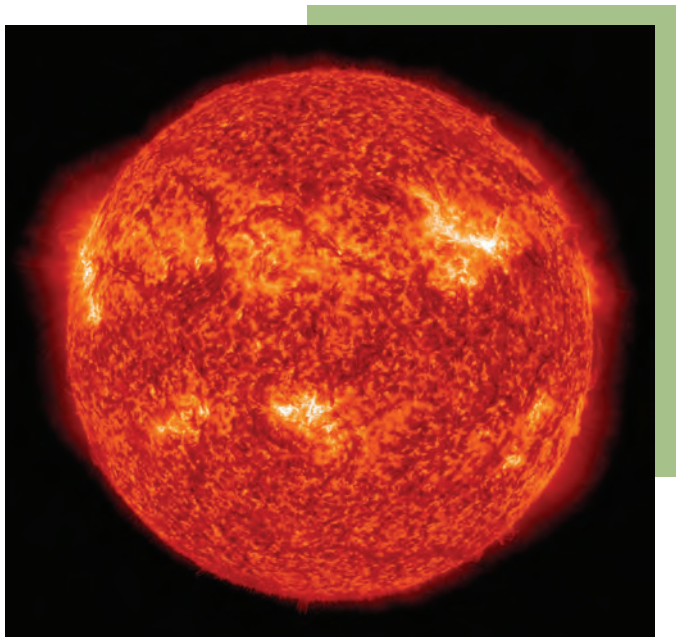
compared to that for the object at Earth's surface; when the object falls, the stored energy decreases and the object's kinetic energy increases. When a pendulum swings, some stored energy is transformed into kinetic energy and back again into stored energy during each swing. (In both examples energy is transferred out of the system due to collisions with air and for the pendulum also by friction in its support.) Any change in potential energy is accompanied by changes in other forms of energy within the system, or by energy transfers into or out of the system.



Electromagnetic radiation (such as light and X-rays) can be modeled as a wave of changing electric and magnetic fields. At the subatomic scale (i.e., in quantum theory), many phenomena involving electromagnetic radiation (e.g., photoelectric effect) are best modeled as a stream of particles called photons. Electromagnetic radiation from the sun is a major source of energy for life on Earth.

The idea that there are different forms of energy, such as thermal energy, mechanical energy, and chemical energy, is misleading, as it implies that the nature of the energy in each of these manifestations is distinct when in fact they all are ultimately, at the atomic scale, some mixture of kinetic energy, stored energy, and radiation. It is likewise misleading to call sound or light a form of energy; they are phenomena that, among their other properties, transfer energy from place to place and between objects.

Grade Band Endpoints for PS3.A

By the end of grade 2. [Intentionally left blank.]

By the end of grade 5. The faster a given object is moving, the more energy it possesses. Energy can be moved from place to place by moving objects or through sound, light, or electric currents. (Boundary: At this grade level, no attempt is made to give a precise or complete definition of energy.)

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At the macroscopic scale, energy manifests itself in multiple phenomena, such as motion, light, sound, electrical and magnetic fields, and thermal energy.

By the end of grade 8. Motion energy is properly called kinetic energy; it is proportional to the mass of the moving object and grows with the square of its speed. A system of objects may also contain stored (potential) energy, depending on their relative positions. For example, energy is stored—in gravitational interaction with Earth—when an object is raised, and energy is released when the object falls or is lowered. Energy is also stored in the electric fields between charged particles and the magnetic fields between magnets, and it changes when these objects are moved relative to one another. Stored energy is decreased in some chemical reactions and increased in others.

The term "heat" as used in everyday language refers both to thermal energy (the motion of atoms or molecules within a substance) and energy transfers by convection, conduction, and radiation (particularly infrared and light). In science, heat is used only for this second meaning; it refers to energy transferred when two objects or systems are at different temperatures. Temperature is a measure of the average kinetic energy of particles of matter. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter present.

By the end of grade 12. Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. That there is a single quantity called energy is due to the fact that a system's *total* energy is conserved, even as, within the system, energy is continually transferred from one object to another and between its various possible forms. At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. "Mechanical energy" generally refers to some combination of motion and stored energy in an operating machine. "Chemical energy" generally is used to mean the energy that can be released or stored in chemical processes, and "electrical energy" may mean energy stored in a battery or energy transmitted by electric currents. Historically, different units and names were used for the energy present in these different phenomena, and it took some time before the relationships between them were recognized. These relationships are better understood at

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the microscopic scale, at which all of the different manifestations of energy can be modeled as either motions of particles or energy stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space.

PS3.B: CONSERVATION OF ENERGY AND ENERGY TRANSFER

What is meant by conservation of energy?
How is energy transferred between objects or systems?

The total change of energy in any system is always equal to the total energy transferred into or out of the system. This is called conservation of energy. Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. Many different types of phenomena can be explained in terms of energy transfers. Mathematical expressions, which quantify changes in the forms of energy within a system and transfers of energy into or out of the system, allow the concept of conservation of energy to be used to predict and describe the behavior of a system.

When objects collide or otherwise come in contact, the motion energy of one object can be transferred to change the motion or stored energy (e.g., change in shape or temperature) of the other objects. For macroscopic objects, any such process (e.g., collisions, sliding contact) also transfers some of the energy to the surrounding air by sound or heat. For molecules, collisions can also result in energy transfers through chemical processes, which increase or decrease the total amount of stored energy within a system of atoms; the change in stored energy is always balanced by a change in total kinetic energy—that of the molecules present after the process compared with the kinetic energy of the molecules present before it.

Energy can also be transferred from place to place by electric currents. Heating is another process for transferring energy. Heat transfer occurs when two objects or systems are at different temperatures. Energy moves out of higher temperature objects and into lower temperature ones, cooling the former and heating the latter. This transfer happens in three different ways—by conduction within solids, by the flow of liquid or gas (convection), and by radiation, which can travel across space. Even when a system is isolated (such as Earth in space), energy is continually being transferred into and out of it by radiation. The processes underlying convection and conduction can be understood in terms of models of the possible motions of particles in matter.

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Radiation can be emitted or absorbed by matter. When matter absorbs light or infrared radiation, the energy of that radiation is transformed to thermal motion of particles in the matter, or, for shorter wavelengths (ultraviolet, X-ray), the radiation's energy is absorbed within the atoms or molecules and may possibly ionize them by knocking out an electron.

Uncontrolled systems always evolve toward more stable states—that is, toward more uniform energy distribution within the system or between the system and its environment (e.g., water flows downhill, objects that are hotter than their surrounding environment cool down). Any object or system that can degrade with no added energy is unstable. Eventually it will change or fall apart, although in some cases it may remain in the unstable state for a long time before decaying (e.g., long-lived radioactive isotopes).

Grade-Level Endpoints for PS3.B

By the end of grade 2. Sunlight warms Earth's surface.

By the end of grade 5. Energy is present whenever there are moving objects, sound, light, or heat. When objects collide, energy can be transferred from one object to another, thereby changing their motion. In such collisions, some energy is typically also transferred to the surrounding air; as a result, the air gets heated and sound is produced.

Light also transfers energy from place to place. For example, energy radiated from the sun is transferred to Earth by light. When this light is absorbed, it warms Earth's land, air, and water and facilitates plant growth.

Energy can also be transferred from place to place by electric currents, which can then be used locally to produce motion, sound, heat, or light. The currents may have been produced to begin with by transforming the energy of motion into electrical energy (e.g., moving water driving a spinning turbine which generates electric currents).

By the end of grade 8. When the motion energy of an object changes, there is inevitably some other change in energy at the same time. For example, the friction that causes a moving object to stop also results in an increase in the thermal energy in both surfaces; eventually heat energy is transferred to the surrounding environment as the surfaces cool. Similarly, to make an object start moving or to keep it moving when friction forces transfer energy away from it,

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energy must be provided from, say, chemical (e.g., burning fuel) or electrical (e.g., an electric motor and a battery) processes.

The amount of energy transfer needed to change the temperature of a matter sample by a given amount depends on the nature of the matter, the size of the sample, and the environment. Energy is transferred out of hotter regions or objects and into colder ones by the processes of conduction, convection, and radiation.

By the end of grade 12. Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems.

Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g., relative positions of charged particles, compression of a spring) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. The availability of energy limits what can occur in any system.

Uncontrolled systems always evolve toward more stable states—that is, toward more uniform energy distribution (e.g., water flows downhill, objects hotter than their surrounding environment cool down). Any object or system that can degrade with no added energy is unstable. Eventually it will do so, but if the energy releases throughout the transition are small, the process duration can be very long (e.g., long-lived radioactive isotopes).

PS3.C RELATIONSHIP BETWEEN ENERGY AND FORCES

How are forces related to energy?

When two objects interact, each one exerts a force on the other. These forces can transfer energy between the objects. Forces between two objects at a distance are explained by force fields (gravitational, electric, or magnetic) between them. Contact forces between colliding objects can be modeled at the microscopic level as due to electromagnetic force fields between the surface particles. When two objects interacting via a force field change their relative position, the energy in the

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force field between them changes. For any such pair of objects the force on each object acts in the direction such that motion of that object in that direction would reduce the energy in the force field between the two objects. However, prior motion and other forces also affect the actual direction of motion.

Patterns of motion, such as a weight bobbing on a spring or a swinging pendulum, can be understood in terms of forces at each instant or in terms of transformation of energy between the motion and one or more forms of stored energy. Elastic collisions between two objects can be modeled at the macroscopic scale using conservation of energy without having to examine the detailed microscopic forces.

Grade Band Endpoints for PS3.C

By the end of grade 2. A bigger push or pull makes things go faster. Faster speeds during a collision can cause a bigger change in shape of the colliding objects.

By the end of grade 5. When objects collide, the contact forces transfer energy so as to change the objects' motions. Magnets can exert forces on other magnets or on magnetizable materials, causing energy transfer between them (e.g., leading to changes in motion) even when the objects are not touching.

By the end of grade 8. When two objects interact, each one exerts a force on the other that can cause energy to be transferred to or from the object. For example, when energy is transferred to an Earth-object system as an object is raised, the gravitational field energy of the system increases. This energy is released as the object falls; the mechanism of this release is the gravitational force. Likewise, two magnetic and electrically charged objects interacting at a distance exert forces on each other that can transfer energy between the interacting objects.

By the end of grade 12. Force fields (gravitational, electric, and magnetic) contain energy and can transmit energy across space from one object to another.

When two objects interacting through a force field change relative position, the energy stored in the force field is changed. Each force between the two interacting objects acts in the direction such that motion in that direction would reduce the energy in the force field between the objects. However, prior motion and other forces also affect the actual direction of motion.

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PS3.D: ENERGY IN CHEMICAL PROCESSES AND EVERYDAY LIFE

How do food and fuel provide energy?
If energy is conserved, why do people say it is produced or used?

In ordinary language, people speak of "producing" or "using" energy. This refers to the fact that energy in concentrated form is useful for generating electricity, moving or heating objects, and producing light, whereas diffuse energy in the environment is not readily captured for practical use. Therefore, to produce energy typically means to convert some stored energy into a desired form—for example, the stored energy of water behind a dam is released as the water flows downhill and drives a turbine generator to produce electricity, which is then delivered to users through distribution systems. Food, fuel, and batteries are especially convenient energy resources because they can be moved from place to place to provide processes that release energy where needed. A system does not destroy energy when carrying out any process. However, the process cannot occur without energy being available. The energy is also not destroyed by the end of the process. Most often some or all of it has been transferred to heat the surrounding environment; in the same sense that paper is not destroyed when it is written on, it still exists but is not readily available for further use.

Naturally occurring food and fuel contain complex carbon-based molecules, chiefly derived from plant matter that has been formed by photosynthesis. The chemical reaction of these molecules with oxygen releases energy; such reactions provide energy for most animal life and for residential, commercial, and industrial activities.

Electric power generation is based on fossil fuels (i.e., coal, oil, and natural gas), nuclear fission, or renewable resources (e.g., solar, wind, tidal, geothermal, and hydro power). Transportation today chiefly depends on fossil fuels, but the use of electric and alternative fuel (e.g., hydrogen, biofuel) vehicles is increasing. All forms of electricity generation and transportation fuels have associated economic, social, and environmental costs and benefits, both short and long term. Technological advances and regulatory decisions can change the balance of those costs and benefits.

Although energy cannot be destroyed, it can be converted to less useful forms. In designing a system for energy storage, for energy distribution, or to perform some practical task (e.g., to power an airplane), it is important to design for maximum efficiency—thereby ensuring that the largest possible fraction of the energy is used for the desired purpose rather than being transferred out of the

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system in unwanted ways (e.g., through friction, which eventually results in heat energy transfer to the surrounding environment). Improving efficiency reduces costs, waste materials, and many unintended environmental impacts.

Grade Band Endpoints for PS3.D

By the end of grade 2. When two objects rub against each other, this interaction is called friction. Friction between two surfaces can warm of both of them (e.g., rubbing hands together). There are ways to reduce the friction between two objects.

By the end of grade 5. The expression "produce energy" typically refers to the conversion of stored energy into a desired form for practical use—for example, the stored energy of water behind a dam is released so that it flows downhill and drives a turbine generator to produce electricity. Food and fuel also release energy when they are digested or burned. When machines or animals "use" energy (e.g., to move around), most often the energy is transferred to heat the surrounding environment.

The energy released by burning fuel or digesting food was once energy from the sun that was captured by plants in the chemical process that forms plant matter (from air and water). (Boundary: The fact that plants capture energy from sunlight is introduced at this grade level, but details of photosynthesis are not.)

It is important to be able to concentrate energy so that it is available for use where and when it is needed. For example, batteries are physically transportable energy storage devices, whereas electricity generated by power plants is transferred from place to place through distribution systems.

By the end of grade 8. The chemical reaction by which plants produce complex food molecules (sugars) requires an energy input (i.e., from sunlight) to occur. In this reaction, carbon dioxide and water combine to form carbon-based organic molecules and release oxygen. (Boundary: Further details of the photosynthesis process are not taught at this grade level.)

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Both the burning of fuel and cellular digestion in plants and animals involve chemical reactions with oxygen that release stored energy. In these processes, complex molecules containing carbon react with oxygen to produce carbon dioxide and other materials.

Machines can be made more efficient, that is, require less fuel input to perform a given task, by reducing friction between their moving parts and through aerodynamic design. Friction increases energy transfer to the surrounding environment by heating the affected materials.

By the end of grade 12. Nuclear fusion processes in the center of the sun release the energy that ultimately reaches Earth as radiation. The main way in which that solar energy is captured and stored on Earth is through the complex chemical process known as photosynthesis. Solar cells are human-made devices that likewise capture the sun's energy and produce electrical energy.

A variety of multistage physical and chemical processes in living organisms, particularly within their cells, account for the transport and transfer (release or uptake) of energy needed for life functions.

All forms of electricity generation and transportation fuels have associated economic, social, and environmental costs and benefits, both short and long term.

Although energy cannot be destroyed, it can be converted to less useful forms—for example, to thermal energy in the surrounding environment. Machines are judged as efficient or inefficient based on the amount of energy input needed to perform a particular useful task. Inefficient machines are those that produce more waste heat while performing a task and thus require more energy input. It is therefore important to design for high efficiency so as to reduce costs, waste materials, and many environmental impacts.

Core Idea PS4 Waves and Their Applications in Technologies for Information Transfer

How are waves used to transfer energy and information?

Waves are a repeating pattern of motion that transfers energy from place to place without overall displacement of matter. Light and sound are wavelike phenomena. By understanding wave properties and the interactions of electromagnetic radiation with matter, scientists and engineers can design systems for transferring information across long distances, storing information, and investigating nature on many scales—some of them far beyond direct human perception.

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PS4.A: WAVE PROPERTIES

What are the characteristic properties and behaviors of waves?

Whether a wave in water, a sound wave, or a light wave, all waves have some features in common. A simple wave has a repeating pattern of specific wavelength, frequency, and amplitude. The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which, for each type of wave, depends on the medium in which the wave is traveling. Waves can be combined with other waves of the same type to produce complex information-containing patterns that can be decoded at the receiving end. Waves, which transfer energy and any encoded information without the bulk motion of matter, can travel unchanged over long distances, pass through other waves undisturbed, and be detected and decoded far from where they were produced. Information can be digitized (converted into a numerical representation), sent over long distances as a series of wave pulses, and reliably stored in computer memory.

Sound is a pressure wave in air or any other material medium. The human ear and brain working together are very good at detecting and decoding patterns of information in sound (e.g., speech and music) and distinguishing them from random noise.

Resonance is a phenomenon in which waves add up in phase (i.e., matched peaks and valleys), thus growing in amplitude. Structures have particular frequencies at which they resonate when some time-varying force acting on them transfers energy to them. This phenomenon (e.g., waves in a stretched string, vibrating air in a pipe) is used in the design of all musical instruments and in the production of sound by the human voice.

When a wave passes an object that is small compared with its wavelength, the wave is not much affected; for this reason, some things are too small to see with visible light, which is a wave phenomenon with a limited range of wavelengths

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corresponding to each color. When a wave meets the surface between two different materials or conditions (e.g., air to water), part of the wave is reflected at that surface and another part continues on, but at a different speed. The change of speed of the wave when passing from one medium to another can cause the wave to change direction or refract. These wave properties are used in many applications (e.g., lenses, seismic probing of Earth).

Grade Band Endpoints for PS4.A

By the end of grade 2. Waves, which are regular patterns of motion, can be made in water by disturbing the surface. When waves move across the surface of deep water, the water goes up and down in place; it does not move in the direction of the wave—observe, for example, a bobbing cork or seabird—except when the water meets the beach.

Sound can make matter vibrate, and vibrating matter can make sound.

By the end of grade 5. Waves of the same type can differ in amplitude (height of the wave) and wavelength (spacing between wave peaks). Waves can add or cancel one another as they cross, depending on their relative phase (i.e., relative position of peaks and troughs of the waves), but they emerge unaffected by each other. (Boundary: The discussion at this grade level is qualitative only; it can be based on the fact that two different sounds can pass a location in different directions without getting mixed up.)

Earthquakes cause seismic waves, which are waves of motion in Earth's crust.

By the end of grade 8. A simple wave has a repeating pattern with a specific wavelength, frequency, and amplitude. A sound wave needs a medium through which it is transmitted.

Geologists use seismic waves and their reflection at interfaces between layers to probe structures deep in the planet.

By the end of grade 12. The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing. The reflection, refraction, and transmission of waves at an interface between two media can be modeled on the basis of these properties.

Combining waves of different frequencies can make a wide variety of patterns and thereby encode and transmit information. Information can be digitized

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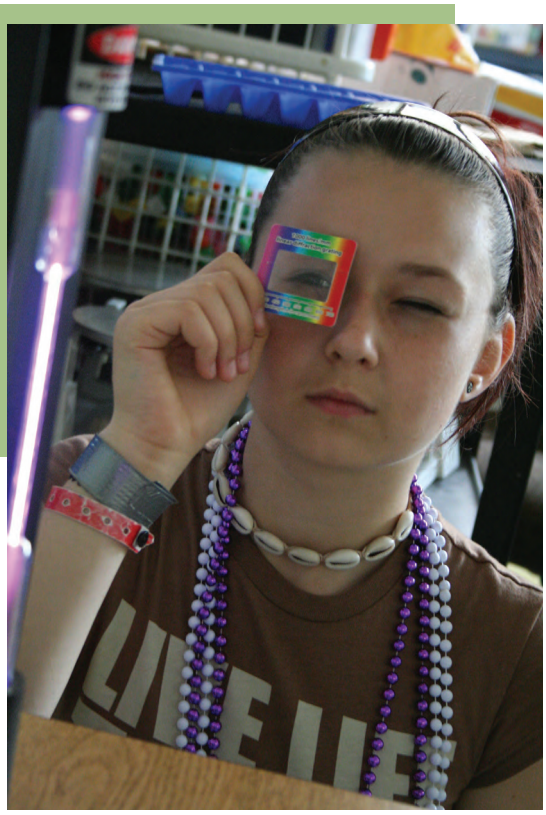
(e.g., a picture stored as the values of an array of pixels); in this form, it can be stored reliably in computer memory and sent over long distances as a series of wave pulses.

Resonance is a phenomenon in which waves add up in phase in a structure, growing in amplitude due to energy input near the natural vibration frequency. Structures have particular frequencies at which they resonate. This phenomenon (e.g., waves in a stretched string, vibrating air in a pipe) is used in speech and in the design of all musical instruments.



PS4.B: ELECTROMAGNETIC RADIATION

What is light?
How can one explain the varied effects that involve light?
What other forms of electromagnetic radiation are there?

Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave pattern of changing electric and magnetic fields or, alternatively, as particles. Each model is useful for understanding aspects of the phenomenon and its interactions with matter, and quantum theory relates the two models. Electromagnetic

By understanding wave properties and the interactions of electromagnetic radiation with matter, scientists and engineers can design systems for transferring information across long distances, storing information, and investigating nature on many scales—some of them far beyond direct human perception.

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waves can be detected over a wide range of frequencies, of which the visible spectrum of colors detectable by human eyes is just a small part. Many modern technologies are based on the manipulation of electromagnetic waves.

All electromagnetic radiation travels through a vacuum at the same speed, called the speed of light. Its speed in any given medium depends on its wavelength and the properties of that medium. At the surface between two media, like any wave, light can be reflected, refracted (its path bent), or absorbed. What occurs depends on properties of the surface and the wavelength of the light. When shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) is absorbed in matter, it can ionize atoms and cause damage to living cells. However, because X-rays can travel through soft body matter for some distance but are more rapidly absorbed by denser matter, particularly bone, they are useful for medical imaging. Photovoltaic materials emit electrons when they absorb light of a high-enough frequency. This phenomenon is used in barcode scanners and "electric eye" systems, as well as in solar cells. It is best explained using a particle model of light.

Any object emits a spectrum of electromagnetic radiation that depends on its temperature. In addition, atoms of each element emit and preferentially absorb characteristic frequencies of light. These spectral lines allow identification of the presence of the element, even in microscopic quantities or for remote objects, such as a star. Nuclear transitions that emit or absorb gamma radiation also have distinctive gamma ray wavelengths, a phenomenon that can be used to identify and trace specific radioactive isotopes.

Grade Band Endpoints for PS4.B

By the end of grade 2. Objects can be seen only when light is available to illuminate them. Very hot objects give off light (e.g., a fire, the sun).

Some materials allow light to pass through them, others allow only some light through, and others block all the light and create a dark shadow on any

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surface beyond them (i.e., on the other side from the light source), where the light cannot reach. Mirrors and prisms can be used to redirect a light beam. (Boundary: The idea that light travels from place to place is developed through experiences with light sources, mirrors, and shadows, but no attempt is made to discuss the speed of light.)

By the end of grade 5. A great deal of light travels through space to Earth from the sun and from distant stars.

An object can be seen when light reflected from its surface enters the eyes; the color people see depends on the color of the available light sources as well as the properties of the surface. (Boundary: This phenomenon is observed, but no attempt is made to discuss what confers the color reflection and absorption properties on a surface. The stress is on understanding that light traveling from the object to the eye determines what is seen.)

Because lenses bend light beams, they can be used, singly or in combination, to provide magnified images of objects too small or too far away to be seen with the naked eye.

By the end of grade 8. When light shines on an object, it is reflected, absorbed, or transmitted through the object, depending on the object's material and the frequency (color) of the light.

The path that light travels can be traced as straight lines, except at surfaces between different transparent materials (e.g., air and water, air and glass) where the light path bends. Lenses and prisms are applications of this effect.

A wave model of light is useful for explaining brightness, color, and the frequency-dependent bending of light at a surface between media (prisms). However, because light can travel through space, it cannot be a matter wave, like sound or water waves.

By the end of grade 12. Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features. Quantum theory relates the two models. (Boundary: Quantum theory is not explained further at this grade level.)

Because a wave is not much disturbed by objects that are small compared with its wavelength, visible light cannot be used to see such objects as individual

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atoms. All electromagnetic radiation travels through a vacuum at the same speed, called the speed of light. Its speed in any other given medium depends on its wavelength and the properties of that medium.

When light or longer wavelength electromagnetic radiation is absorbed in matter, it is generally converted into thermal energy (heat). Shorter wavelength electromagnetic radiation (ultraviolet, X-rays, gamma rays) can ionize atoms and cause damage to living cells. Photovoltaic materials emit electrons when they absorb light of a high-enough frequency.

Atoms of each element emit and absorb characteristic frequencies of light, and nuclear transitions have distinctive gamma ray wavelengths. These characteristics allow identification of the presence of an element, even in microscopic quantities.

PS4.C: INFORMATION TECHNOLOGIES AND INSTRUMENTATION

How are instruments that transmit and detect waves used to extend human senses?

Understanding of waves and their interactions with matter has been used to design technologies and instruments that greatly extend the range of phenomena that can be investigated by science (e.g., telescopes, microscopes) and have many useful applications in the modern world.

Light waves, radio waves, microwaves, and infrared waves are applied to communications systems, many of which use digitized signals (i.e., sent as wave pulses) as a more reliable way to convey information. Signals that humans cannot sense directly can be detected by appropriately designed devices (e.g., telescopes, cell phones, wired or wireless computer networks). When in digitized form, information can be recorded, stored for future recovery, and transmitted over long distances without significant degradation.

Medical imaging devices collect and interpret signals from waves that can travel through the body and are affected by, and thus gather information about, structures and motion within it (e.g., ultrasound, X-rays). Sonar (based on sound pulses) can be used to measure the depth of the sea, and a system based on laser pulses can measure the distance to objects in space, because it is

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known how fast sound travels in water and light travels in a vacuum. The better the interaction of the wave with the medium is understood, the more detailed the information that can be extracted (e.g., medical imaging or astronomical observations at multiple frequencies).

Grade Band Endpoints for PS4.C

By the end of grade 2. People use their senses to learn about the world around them. Their eyes detect light, their ears detect sound, and they can feel vibrations by touch.

People also use a variety of devices to communicate (send and receive information) over long distances.

By the end of grade 5. Lenses can be used to make eyeglasses, telescopes, or microscopes in order to extend what can be seen. The design of such instruments is based on understanding how the path of light bends at the surface of a lens.

Digitized information (e.g., the pixels of a picture) can be stored for future recovery or transmitted over long distances without significant degradation. High-tech devices, such as computers or cell phones, can receive and decode information—convert it from digitized form to voice—and vice versa.

By the end of grade 8. Appropriately designed technologies (e.g., radio, television, cell phones, wired and wireless computer networks) make it possible to detect and interpret many types of signals that cannot be sensed directly. Designers of such devices must understand both the signal and its interactions with matter.

Many modern communication devices use digitized signals (sent as wave pulses) as a more reliable way to encode and transmit information.

By the end of grade 12. Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them.

Knowledge of quantum physics enabled the development of semiconductors, computer chips, and lasers, all of which are now essential components of modern imaging, communications, and information technologies. (Boundary: Details of quantum physics are not formally taught at this grade level.)

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