AP PHYSICS 2 FRAMEWORKS

Big Ideas	Enduring Knowledge
Essential Knowledge	Learning Objectives
Science Practices	

ELECTRIC FORCE, FIELD AND POTENTIAL

- **Static Electricity; Electric Charge and its Conservation**
- **Insulators and Conductors**
- **Charging Processes: Friction, Conduction and Induction**
- **Coulomb's Law**
- **Electric Field**
- **Electric Potential and Potential Difference**
- **Relation Between Electric Potential and Electric Field**
- **Equipotential Lines**
- **Electric Potential due to Point Charges**

CUTNELL (9e): Chapter 18 (18-1 through 18-8) and Chapter 19 (19-1 through 19-4)

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in
AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.B:

Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge.

Electric charge is the fundamental property of an object that determines how the object interacts with other electrically charged objects. The interaction of a charged object with a distribution of other charged objects is simplified by the field model, where a distribution of charged objects creates a field at every point and the charged object interacts with the field. There are two types of electric charge, positive and negative. Protons are examples of positively charged objects, and electrons are examples of negatively charged objects. Neutral objects and systems are ones whose net charge is zero. The magnitudes of the charge of a proton and of an electron are equal, and this is the smallest unit of charge that is found in an isolated object. Electric charge is conserved in all known processes and interactions.

Essential Knowledge 1.B.1:
Electric charge is conserved. The net charge of a system is equal to the sum of the charges of all the objects in the system.

a. An electrical current is a movement of charge through a conductor.
b. A circuit is a closed loop of electrical current.

1.B.1.1: The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

1.B.1.2: The student is able to make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 1.B.2:
There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge.

a. Like-charged objects and systems repel, and unlike- charged objects and systems attract.
b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system.

1.B.2.2: The student is able to make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

1.B.2.3: The student is able to challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object. **[SP6.1]**

6.1 The student can justify claims with evidence.

Essential Knowledge 1.B.3: The smallest observed unit of charge that can be isolated is the electron charge, also known as the elementary charge.

a. The magnitude of the elementary charge is equal to **1.6×10^{-19}** coulombs.
b. Electrons have a negative elementary charge; protons have a positive elementary charge of equal magnitude, although the mass of a proton is much larger than the mass of an electron.

1.B.3.1: The student is able to challenge the claim that an electric charge smaller than the elementary charge has been isolated. **[SP 1.5, 6.1, 7.2]**

1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
6.1 The student can justify claims with evidence.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

BIG IDEA 2: Fields existing in space can be used to explain interactions.

All of the fundamental forces, including the gravitational force and the electric and magnetic forces, are exerted "at a distance"; the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields, which associate a value of some quantity with every point in space. Forces are vectors and

so the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, for instance, temperature and pressure, vary with position. In general, a field created by an array of "sources" can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition. For a gravitational field the source is an object with mass. For an electric field the source is an object with electric charge. For a magnetic field the source is a magnet or a moving object with electric charge. Visual representations are extensively used by physicists in the analysis of many situations. A broadly used example across many applications involving fields is a map of isolines connecting points of equal value for some quantity related to a field, such as topographical maps that display lines of approximately equal gravitational potential.

Enduring Understanding 2.C:
An electric field is caused by an object with electric charge.

Coulomb's law of electric force describes the interaction at a distance between two electrically charged objects. By contrast, the electric field serves as the intermediary in the interaction of two objects or systems that have the property of electric charge. In the field view, charged source objects create an electric field. The magnitude and direction of the electric field at a given location are due to the vector sum of the fields created by each of the charged objects that are the source of the field. Another charged object placed at a given location in the field experiences an electric force. The force depends on the charge of the object and the magnitude and direction of the electric field at that location.

The concept of the electric field greatly facilitates the description of electrical interactions between multiple-point charges or continuous distributions of charge. In this course, students should be familiar with graphical and mathematical representations of the electric field due to one or more point charges including the field of an electric dipole, the field outside a spherically symmetric charged object, and the uniform field between the plates when far from the edges of oppositely charged parallel plates. Students should be able to use these representations to calculate the direction and magnitude of the force on a small charged object due to such electric fields. Electric field representations are to be vectors and not lines.

Essential Knowledge 2.C.1:

The magnitude of the electric force **F** exerted on an object with electric charge *q* by an electric field $\vec{E}$ is $\vec{F} = q\vec{E}$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

2.C.1.1: The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge *q* placed in an electric field *E* using the mathematical model of the relation between an electric force and an electric field: $\vec{F} = q\vec{E}$; a vector relation.**[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

2.C.1.2: The student is able to calculate any one of the variables — electric force, electric charge, and electric field — at a point given the values and sign or direction of the other two quantities.**[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 2.C.2:
The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

2.C.2.1: The student is able to qualitatively and semi-quantitatively apply the vector relationship between the electric field and the net electric charge creating that field. **[SP 2.2, 6.4**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Essential Knowledge 2.C.3:
The electric field outside a spherically symmetric charged object is radial and its magnitude varies as the inverse square of the radial distance from the center of that object. Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.

a. The inverse square relation known as Coulomb's law gives the magnitude of the electric field at a distance *r* from the center of a source object of electric charge *Q* as $|E| = \frac{1}{4\pi\varepsilon_o}\frac{|Q|}{r^2}$
b. This relation is based on a model of the space surrounding a charged source object by considering the radial dependence of the area of the surface of a sphere centered on the source object.

2.C.3.1: The student is able to explain the inverse square dependence of the electric field surrounding a spherically symmetric electrically charged object. **[SP 6.2**]

6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

Essential Knowledge 2.C.4:
The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

a. When an object is small compared to the distances involved in the problem, or when a larger object is being modeled as a large number of very small constituent particles, these can be modeled as charged objects of negligible size, or "point charges."
b. The expression for the electric field due to a point charge can be used to determine the electric field, either qualitatively or quantitatively, around a simple, highly symmetric distribution of point charges.

2.C.4.1: The student is able to distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semiquantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. **[SP 2.2, 6.4, 7.2**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

2.C.4.2: The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points. **[SP 1.4, 2.2**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 2.C.5:

Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.

2.C.5.1: The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates. **[SP 1.1, 2.2**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

2.C.5.2: The student is able to calculate the magnitude and determine the direction of the electric field between two electrically charged parallel plates, given the charge of each plate, or the electric potential difference and plate separation. **[SP 2.2**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

2.C.5.3: The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field. **[SP 1.1, 2.2, 7.1**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

7.1 The student can connect phenomena and models across spatial and temporal scales.

Enduring Understanding 2.E:

hysicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.

When visualizing a scalar field, it is useful to construct a set of contour lines connecting points at which the field has the same (constant) value. A good example is the set of contour lines (gravitational equipotentials) on which the gravitational potential energy per unit mass has a constant value. Such equipotential lines can be constructed using the electric potential and can also be associated with temperature and other scalar fields. When considering equipotential lines, the associated vector field (such as the electric field) is always perpendicular to the equipotential lines. When not provided with a diagram of field vectors, students will be expected to draw accurate equipotential lines ONLY for spherically symmetric sources and for sources that create approximately uniform fields.

Essential Knowledge 2.E.1:
Isolines on a topographic (elevation) map describe lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential). As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational and electrical potential and potential differences.]

2.E.1.1: The student is able to construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential. **[SP 1.4, 6.4, 7.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 2.E.2:
Isolines in a region where an electric field exists represent lines of equal electric potential referred to as equipotential lines.

a. An isoline map of electric potential can be constructed from an electric field vector map, using the fact that the isolines are perpendicular to the electric field vectors.
b. Since the electric potential has the same value along an isoline, there can be no component of the electric field along the isoline.

2.E.2.1: The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

2.E.2.2: The student is able to predict the structure of isolines of electric potential by constructing them in a given electric field and make connections between these isolines and those found in a gravitational field. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

2.E.2.3: The student is able to qualitatively use the concept of isolines to construct isolines of electric potential in an electric field and determine the effect of that field on electrically charged objects. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Essential Knowledge 2.E.3:
The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

2.E.3.1: The student is able to apply mathematical routines to calculate the average value of the magnitude of the electric field in a region from a description of the electric potential in that region using the displacement along the line on which the difference in potential is evaluated. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

2.E.3.2: The student is able to apply the concept of the isoline representation of electric potential for a given electric charge distribution to predict the average value of the electric field in the region. **[SP 1.4, 6.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

BIG IDEA 3: The interactions of an object with other objects can be described by forces.

An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

Enduring Understanding 3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.

The description of motion, including such quantities as position, velocity, or acceleration, depends on the observer, specifically on the reference frame. When the interactions of objects are considered, we only consider the observers in inertial reference frames. In such reference frames, an object that does not interact with any other objects moves at constant velocity. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force. If a component of the acceleration is observed to be zero, then the sum of the corresponding force components must be zero. If one object exerts a force on a second object, the second object always exerts a force of equal magnitude but opposite direction on the first object. These two forces are known as an action-reaction pair.

Essential Knowledge 3.A.2:

Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.
b. Forces have magnitude and direction.

3.A.2.1: The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 3.A.3:
A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.
b. Even though an object is at rest, there may be forces exerted on that object by other objects.
c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1**]

6.1 The student can justify claims with evidence.

3.A.3.3: The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

3.A.3.4: The student is able to make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge. **[SP 6.1, 6.4]**

6.1 The student can justify claims with evidence.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Essential Knowledge 3.A.4:
If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

3.A.4.1: The student is able to construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

3.A.4.2: The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.4.3: The student is able to analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Enduring Understanding 3.B:

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma\vec{F}}{m}$

Newton's second law describes the acceleration when one or more forces are exerted on an object. The object's acceleration also depends on its inertial mass. Newton's second law is easier to appreciate when the law is written as $\vec{a} = \frac{\Sigma\vec{F}}{m}$ which underscores the cause–effect relationship. In a free-body diagram, the choice of appropriate axes (usually one axis parallel to the direction in which the object will accelerate) and the resolution of forces into components along the chosen set of axes are essential parts of the process of analysis. The set of component forces along an axis corresponds to the list of forces that are combined to cause acceleration along that axis. Constant forces will yield a constant acceleration, but restoring forces, proportional to the displacement of an object, cause oscillatory motion. In this course, the oscillatory solution should be the result of an experiment, rather than the solution of the differential equation.

Essential Knowledge 3.B.1: If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

3.B.1.3: The student is able to reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. **[SP 1.5, 2.2]**

1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

3.B.1.4: The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 3.B.2: Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.

a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.
b. A force exerted on an object can be represented as an arrow whose length represents the magnitude of the force and whose direction shows the direction of the force.

A coordinate system with one axis parallel to the direction of the acceleration simplifies the translation from the free- body diagram to the algebraic representation.

3.B.2.1: The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. **[SP 1.1, 1.4, 2.2]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Enduring Understanding 3.C:
At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

In Big Idea 3, the behavior of an object is analyzed without reference to the internal structure of the object. Internal structure is included in Big Idea 4. There are a small number of forces that occur in nature, and the macroscopic ones are considered here. The identification of forces is a key step in the analysis of mechanical systems.

Gravitational forces, electric forces, and magnetic forces between objects are all evident on the macroscopic scale. The gravitational force is a weaker force than the electric or magnetic force. However, on the larger scale, the gravitational force dominates. Electric forces are dominant in determining the properties of the objects in our everyday experience. However, the many electrically charged particles that interact make the treatment of this everyday force very complex. Introducing new concepts such as the frictional force as averages over the many particles reduces the complexity. Contact forces (e.g., frictional force, buoyant force) result from the interaction of one object touching another object and are ultimately due to microscopic electric forces. The frictional force is due to the interaction between surfaces at rest or in relative motion. Buoyant force is caused by the difference in pressure, or force per unit area, exerted on the different surfaces of the object. It is important for students to study each of these forces and to use free-body diagrams to analyze the interactions between objects.

Essential Knowledge 3.C.2: Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.

a. Electric forces dominate the properties of the objects in our everyday experiences. However, the large number of particle interactions that occur make it more convenient to treat everyday forces in terms of nonfundamental forces called contact forces, such as normal force, friction, and tension.
b. Electric forces may be attractive or repulsive, depending upon the charges on the objects involved.

3.C.2.2: The student is able to connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.C.2.3: The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry). **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Enduring Understanding 3.G:
Certain types of forces are considered fundamental.

There are different types of fundamental forces, and these forces can be characterized by their actions at different scales. The fundamental forces discussed in these courses include the electroweak force, the gravitational force, and the strong (nuclear) force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. All other forces can be thought of as secondary forces and are ultimately derived from the fundamental forces.

On the scale appropriate to the secondary forces we deal with every day, the electromagnetic aspect of the electroweak force dominates. There are two kinds of electric charge that can produce both attractive and repulsive interactions. While there are two kinds of electric charge, there appears to be only a single type of mass. Consequently, gravitational forces are only attractive.

Since there are no repulsive contributions to the net force exerted at a very large distance, the gravitational force dominates at large scales. The weak aspect of the electroweak force is important at very large stellar scales and at very small nuclear scales, and the strong force dominates inside the nucleus. (Students will not be required to know interactions involving the weak force.)

Essential Knowledge 3.G.2: Electromagnetic forces are exerted at all scales and can dominate at the human scale.

3.G.2.1: The student is able to connect the strength of electromagnetic forces with the spatial scale of the situation, the magnitude of the electric charges, and the motion of the electrically charged objects involved. **[SP**

7.1]

7.1 The student can connect phenomena and models across spatial and temporal scales.

BIG IDEA 4: Interactions between systems can result in changes in those systems.

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton's second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other systems.

Enduring Understanding 4.E:
The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

Electric and magnetic forces may be exerted on objects that possess an electric charge. These forces affect the motion of electrically charged objects. If a charged object is part of a system, electric and magnetic forces and fields can affect the properties of the system. One such example involves the behavior
of moving charged objects (i.e., an electric current) in a circuit. The electric current in a circuit can be affected by an applied potential difference or by changing the magnetic flux through the circuit. The behavior of individual circuit elements, such as resistors and capacitors, can be understood in terms of how an applied electric or magnetic field affects charge motion within the circuit element.

Essential Knowledge 4.E.3: The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.

a. Charging can take place by friction or by contact.
b. An induced charge separation can cause a neutral object to become polarized.
c. Charging by induction can occur when a polarizing conducting object is touched by another.
d. In solid conductors, some electrons are mobile. When no current flows, mobile charges are in static equilibrium, excess charge resides at the surface, and the interior field is zero. In solid insulators, excess (fixed) charge may reside in the interior as well as at the surface.

4.E.3.2: The student is able to make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

4.E.3.3: The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors. **[SP 1.1, 1.4, 6.4]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.E.3.4: The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction. **[SP 1.1, 1.4, 6.4]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.E.3.5: The student is able to plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]**

3.2 The student can refine scientific questions.
4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

BIG IDEA 5: Changes that occur as a result of interactions are constrained by conservation laws.

Conservation laws constrain the possible behaviors of the objects in a system of any size or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Enduring Understanding 5.A:
Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems.

Conservation laws constrain the possible motions of the objects in a system of any size, or the outcome of an interaction or a process. For example, thinking about physical systems from the perspective of Newton's second law, each object changes its motion at any instant in response to external forces and torques, its response constrained only by its inertial mass and the distribution of that mass. However, with even a few objects in a system, tracking the motions becomes very complex. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, the conservation law constrains the possible configurations of a system. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Essential Knowledge 5.A.2: For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.

5.A.2.1: The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 5.B:
The energy of a system is conserved.

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff 's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

Essential Knowledge 5.B.2: A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. [Physics 1: includes mass-spring oscillators and simple pendulums. Physics 2: includes charged object in electric fields and examining changes in internal energy with changes in configuration.]

5.B.2.1: The student is able to calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. **[SP 1.4, 2.1]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.1 The student can justify the selection of a mathematical routine to solve problems.

Enduring Understanding 5.C:
The electric charge of a system is conserved.

Conservation of electric charge is a fundamental conservation principle in physics. All processes in nature conserve the net electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves around a circuit or from place to place within a circuit. Any increase or decrease in the net charge in one region is compensated for by a corresponding decrease or increase in the net charge in other regions. In electrostatics, it is common for electrons to move from one object to another, and the number of electrons that leave one object is always equal to the number of electrons that move onto other objects. In some reactions such as radioactive decay or interactions involving elementary particles, it is possible for the number of electrically charged particles after a reaction or decay to be different from the number before. However, the net charge before and after is always equal. So, if a process produces a "new" electron that was not present before the reaction, then a "new" positive charge must also be created so that the net charge is the same before and after the process.

Essential Knowledge 5.C.2: The exchange of electric charges among a set of objects in a system conserves electric charge.

a. Charging by conduction between objects in a system conserves the electric charge of the entire system.
b. Charge separation in a neutral system can be induced by an external charged object placed close to the neutral system.
c. Grounding involves the transfer of excess charge to another larger system (e.g., the Earth).

5.C.2.1: The student is able to predict electric charges on objects within a system by application of the principle of charge conservation within a system. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.C.2.2: The student is able to design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data. **[SP 4.2, 5.1]**

4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

5.C.2.3: The student is able to justify the selection of data relevant to an investigation of the electrical charging of objects and electric charge induction on neutral objects. **[SP 4.1]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.

ELECTRIC CIRCUITS

- **Electric Current**
- **Ohm's Law: Resistance and Resistors**
- **Resistivity**
- **Capacitance**
- **Storage of Electric Energy**
- **Electric Power**
- **Resistors in Series and Parallel**
- **Kirchhoff's Rules**
- **RC Circuits (steady state only)**

CUTNELL (9e): Chapter 19 (19-5); Chapter 20 (20-1 through 20-13)

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.E:
Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. Some of the most important fundamental characteristics of matter and space are identified here and employed in other big ideas.

Matter has properties called density, resistivity, and thermal conductivity that are used when discussing thermodynamics, fluids, electric current, and transfer of thermal energy. The values of these quantities depend upon the molecular and atomic structure of the material. Matter and space also have properties called electric permittivity and magnetic permeability. The permittivity and the permeability of free space are constants that appear in physical relationships and in the relationship for the speed of electromagnetic radiation in a vacuum. The electric permittivity and the magnetic permeability of a material both depend upon the material's structure at the atomic level.

Electric dipole moments (as treated in Enduring Understanding 2.C) and magnetic dipole moments are other properties of matter. A separated pair of positively and negatively charged objects is an example of an electric dipole. A current loop is an example of a magnetic dipole.

Essential Knowledge 1.E.2:
Matter has a property called resistivity.

a. The resistivity of a material depends on its molecular and atomic structure.
b. The resistivity depends on the temperature of the material.

1.E.2.1: The student is able to choose and justify the selection of data needed to determine resistivity for a given material. **[SP 4.1**]

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.

BIG IDEA 4: Interactions between systems can result in changes in those systems.

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton's second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other systems.

Enduring Understanding 4.E:
The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

Electric and magnetic forces may be exerted on objects that possess an electric charge. These forces affect the motion of electrically charged objects. If a charged object is part of a system, electric and magnetic forces and fields can affect the properties of the system. One such example involves the behavior of moving charged objects (i.e., an electric current) in a circuit. The electric current in a circuit can be affected by an applied potential difference or by changing the magnetic flux through the circuit. The behavior of individual circuit elements, such as resistors and capacitors, can be understood in terms of how an applied electric or magnetic field affects charge motion within the circuit element.

Essential Knowledge 4.E.4: The resistance of a resistor and the capacitance of a capacitor can be understood from the basic properties of electric fields and forces as well as the properties of materials and their geometry.

a. The resistance of a resistor is proportional to its length and inversely proportional to its cross-sectional area. The constant of proportionality is the resistivity of the material.
b. The capacitance of a parallel plate capacitor is proportional to the area of one of its plates and inversely proportional to the separation between its plates. The constant of proportionality is the product of the dielectric constant, k , of the material between the plates and the electric permittivity, ε_o.
c. The current through a resistor is equal to the potential difference across the resistor divided by its resistance.
d. The magnitude of charge of one of the plates of a parallel plate capacitor is directly proportional to the product of the potential difference across the capacitor and the capacitance. The plates have equal amounts of charge of opposite sign.

4.E.4.1: The student is able to make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships. **[SP 2.2, 6.4]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.E.4.2: The student is able to design a plan for the collection of data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. **[SP 4.1, 4.2]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
4.2 The student can design a plan for collecting data to answer a particular scientific question.

4.E.4.3: The student is able to analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. **[SP 5.1]**

5.1 The student can analyze data to identify patterns or relationships.

Essential Knowledge 4.E.5: The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors.

4.E.5.1: The student is able to make and justify a quantitative prediction of the effect of a change in values or arrangements of one or two circuit elements on the currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. **[SP 2.2, 6.4]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.E.5.2: The student is able to make and justify a qualitative prediction of the effect of a change in values or arrangements of one or two circuit elements on currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. **[SP 6.1, 6.4]**

6.1 The student can justify claims with evidence.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.E.5.3: The student is able to plan data collection strategies and perform data analysis to examine the values of currents and potential differences in an electric circuit that is modified by changing or rearranging circuit elements, including sources of emf, resistors, and capacitors. **[SP 2.2, 4.2, 5.1]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

4.2 The student can design a plan for collecting data to answer a particular scientific question.

5.1 The student can analyze data to identify patterns or relationships.

BIG IDEA 5: Changes that occur as a result of interactions are constrained by conservation laws.

Conservation laws constrain the possible behaviors of the objects in a system of any size or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Enduring Understanding 5.B:
The energy of a system is conserved.

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff 's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

Essential Knowledge 5.B.9: Kirchhoff 's loop rule describes conservation of energy in electrical circuits. [The application of Kirchhoff 's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.]

a. Energy changes in simple electrical circuits are conveniently represented in terms of energy change per charge moving through a battery and a resistor.
b. Since electric potential difference times charge is energy, and energy is conserved, the sum of the potential differences about any closed loop must add to zero.
c. The electric potential difference across a resistor is given by the product of the current and the resistance.
d. The rate at which energy is transferred from a resistor is equal to the product of the electric potential difference across the resistor and the current through the resistor.
e. Energy conservation can be applied to combinations of resistors and capacitors in series and parallel circuits.

5.B.9.4: The student is able to analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule.**[SP 5.1]**

5.1 The student can analyze data to identify patterns or relationships.

5.B.9.5: The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.B.9.6: The student is able to mathematically express the changes in electric potential energy of a loop in a multiloop electrical circuit and justify this expression using the principle of the conservation of energy. **[SP 2.1, 2.2]**

2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.9.7: The student is able to refine and analyze a scientific question for an experiment using Kirchhoff's Loop rule for circuits that includes determination of internal resistance of the battery and analysis of a non-ohmic resistor. **[SP 4.1, 4.2, 5.1, 5.3]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

5.B.9.8: The student is able to translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor. **[SP 1.5]**

Enduring Understanding 5.C:
The electric charge of a system is conserved.

Conservation of electric charge is a fundamental conservation principle in physics. All processes in nature conserve the net electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves around a circuit or from place to place within a circuit. Any increase or decrease in the net charge in one region is compensated for by a corresponding decrease or increase in
the net charge in other regions. In electrostatics, it is common for electrons to move from one object to another, and the number of electrons that leave one object is always equal to the number of electrons that move onto other objects. In some reactions such as radioactive decay or interactions involving elementary particles, it is possible for the number of electrically charged particles after a reaction or decay to be different from the number before. However, the net charge before and after is always equal. So, if a process produces a “new” electron that was not present before the reaction, then a “new” positive charge must also be created so that the net charge is the same before and after the process.

Essential Knowledge 5.C.3: Kirchhoff ’s junction rule describes the conservation of electric charge in electrical circuits. Since charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 1: covers circuits with resistors in series, with at most one parallel branch, one battery only. Physics 2: includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]

5.C.3.4: The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.C.3.5: The student is able to determine missing values and direction of electric current in branches of a circuit with resistors and NO capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.C.3.6: The student is able to determine missing values and direction of electric current in branches of a circuit with both resistors and capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.C.3.7: The student is able to determine missing values, direction of electric current, charge of capacitors at steady state, and potential differences within a circuit with resistors and capacitors from values and directions of current in other branches of the circuit. **[SP 1.4, 2.2**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

MAGNETISM AND ELECTROMAGNETIC INDUCTION

- **Magnets and Magnetic Fields**
- **Force on an Electric Current in a Magnetic Field**
- **Force on an Electric Charge Moving in a Magnetic Field**
- **Induced EMF**
- **Faraday's Law of Induction; Lenz's Law**
- **EMF Induced in a Moving Conductor**

GIANCOLI (7e): Chapter 20 (20-1 through 20-6 and 20-10 through 20-12 (hysteresis is not required); Chapter 21 (21-1 through 21-4)
ETKINA: Chapter 17 (17-1 through 17-8) Chapter 18 (18-1 through 18-8)
KNIGHT (3e): Chapter 24 (24-1 through 24-6 and 24-8); Chapter 25 (25-1 through 25-4)
CUTNELL (9e): Chapter 21 (21-1 through 21-5, 21-7 and 21-9); Chapter 22 (22-1 through 22-7)
SERWAY (10e): Chapter 19 (19-1 through 19-10); Chapter 20 (20-1 through 20-4)
WALKER (4e): Chapter 22 (22-1 through 22-4 and 22-8); Chapter 23 (23-1 through 23-6)

BIG IDEA 2: Fields existing in space can be used to explain interactions.

All of the fundamental forces, including the gravitational force and the electric and magnetic forces, are exerted "at a distance"; the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields, which associate a value of some quantity with every point in space. Forces are vectors and so the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, for instance, temperature and pressure, vary with position. In general, a field created by an array of "sources" can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition. For a gravitational field the source is an object with mass. For an electric field the source is an object with electric charge. For a magnetic field the source is a magnet or a moving object with electric charge. Visual representations are extensively used by physicists in the analysis of many situations. A broadly used example across many applications involving fields is a map of isolines connecting points of equal value for some quantity related to a field, such as topographical maps that display lines of approximately equal gravitational potential.

Enduring Understanding 2.C:
An electric field is caused by an object with electric charge.

Coulomb's law of electric force describes the interaction at a distance between two electrically charged objects. By contrast, the electric field serves as the intermediary in the interaction of two objects or systems that have the property of electric charge. In the field view, charged source objects create an electric field. The magnitude and direction of the electric field at a given location are due to the vector sum of the fields created by each of the charged objects that are the source of the field. Another charged object placed at a given location in the field experiences an electric force. The force depends on the charge of the object and the magnitude and direction of the electric field at that location.

The concept of the electric field greatly facilitates the description of electrical interactions between multiple-point charges or continuous distributions of charge. In this course, students should be familiar with graphical and mathematical representations of the electric field due to one or more point charges including the field of an electric dipole, the field outside a spherically symmetric charged object, and the uniform field between the plates when far from the edges of oppositely charged parallel plates. Students should be able to use these representations to calculate the direction and magnitude of the force on a small charged object due to such electric fields. Electric field representations are to be vectors and not lines.

Essential Knowledge 2.C.4:

The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

a. When an object is small compared to the distances involved in the problem, or when a larger object is being modeled as a large number of very small constituent particles, these can be modeled as charged objects of negligible size, or "point charges."
b. The expression for the electric field due to a point charge can be used to determine the electric field, either qualitatively or quantitatively, around a simple, highly symmetric distribution of point charges.

2.C.4.1: The student is able to distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semiquantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. **[SP 2.2, 6.4, 7.2**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 2.D:

A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

Knowledge of the properties and sources of magnetic fields is necessary in other big ideas dealing with magnetism. This knowledge is critical to student understanding of areas such as geophysical processes and medical applications. Students also should know that magnetic fields observed in nature always seem to be caused by dipoles or combinations of dipoles and never by single poles. A magnetic dipole can be modeled as a current in a loop. A single magnetic pole (a magnetic monopole like an isolated north pole of a magnet) has never been observed in nature. Representations of these fields are important to the skills that students need to develop in the course. The pattern of magnetic field vectors tangent to concentric circles around a current-carrying wire and the dipole pattern of field vectors around a bar magnet are needed representations.

Magnetic materials contain magnetic domains that are themselves little magnets. Representations can be drawn of the atomic-scale structure of ferromagnetic materials, such as arrows or smaller bar magnets, which indicate the directional nature of magnets even at these small scales. These magnetic moments lead to discussions of important modern applications such as magnetic storage media.

Essential Knowledge 2.D.1:

The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity, and the magnitude of the magnetic field. It also depends on the angle between the velocity and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles.

2.D.1.1: The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. **[SP 2.2**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 2.D.2:
The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.

a. The magnitude of the magnetic field is proportional to the magnitude of the current in a long straight wire.
b. The magnitude of the field varies inversely with distance from the wire, and the direction of the field can be determined by a right-hand rule.

2.D.2.1: The student is able to create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires. **[SP 1.1]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 2.D.3:
A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.

a. A simple magnetic dipole can be modeled by a current in a loop. The dipole is represented by a vector pointing through the loop in the direction of the field produced by the current as given by the right-hand rule.
b. A compass needle is a permanent magnetic dipole. Iron filings in a magnetic field become induced magnetic dipoles.
c. All magnets produce a magnetic field. Examples should include magnetic field pattern of a bar magnet as detected by iron filings or small compasses.
d. Earth has a magnetic field.

2.D.3.1: The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. **[SP 1.2]**

1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 2.D.4:
Ferromagnetic materials contain magnetic domains that are themselves magnets.

a. Magnetic domains can be aligned by external magnetic fields or can spontaneously align.
b. Each magnetic domain has its own internal magnetic field, so there is no beginning or end to the magnetic field — it is a continuous loop.
c. If a bar magnet is broken in half, both halves are magnetic dipoles in themselves; there is no magnetic north pole found isolated from a south pole.

2.D.4.1: The student is able to use the representation of magnetic domains to qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

BIG IDEA 3: The interactions of an object with other objects can be described by forces.

An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

Enduring Understanding 3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.

The description of motion, including such quantities as position, velocity, or acceleration, depends on the observer, specifically on the reference frame. When the interactions of objects are considered, we only consider the observers in inertial reference frames. In such reference frames, an object that does not interact with any other objects moves at constant velocity. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force. If a component of the acceleration is observed to be zero, then the sum of the corresponding force components must be zero. If one object exerts a force on a second object, the second object always exerts a force of equal magnitude but opposite direction on the first object. These two forces are known as an action-reaction pair.

Essential Knowledge 3.A.2: Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.
b. Forces have magnitude and direction.

3.A.2.1: The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 3.A.3: A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.
b. Even though an object is at rest, there may be forces exerted on that object by other objects.
c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP** 6.1]

6.1 The student can justify claims with evidence.

3.A.3.3: The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Essential Knowledge 3.A.4: If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

3.A.4.1: The student is able to construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.1 The student can justify claims with evidence.

3.A.4.2: The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.4.3: The student is able to analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Enduring Understanding 3.C:
At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

In Big Idea 3, the behavior of an object is analyzed without reference to the internal structure of the object. Internal structure is included in Big Idea 4. There are a small number of forces that occur in nature, and the macroscopic ones are considered here. The identification of forces is a key step in the analysis of mechanical systems.

Gravitational forces, electric forces, and magnetic forces between objects are all evident on the macroscopic scale. The gravitational force is a weaker force than the electric or magnetic force. However, on the larger scale, the gravitational force dominates. Electric forces are dominant in determining the properties of the objects in our everyday experience. However, the many electrically charged particles that interact make the treatment of this everyday force very complex. Introducing new concepts such as the frictional force as averages over the many particles reduces the complexity. Contact forces (e.g., frictional force, buoyant force) result from the interaction of one object touching another object and are ultimately due to microscopic electric forces. The frictional force is due to the interaction between surfaces at rest or in relative motion. Buoyant force is caused by the difference in pressure, or force per unit area, exerted on the different surfaces of the object. It is important for students to study each of these forces and to use free-body diagrams to analyze the interactions between objects.

Essential Knowledge 3.C.3: A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.

3.C.3.1: The student is able to use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

3.C.3.2: The student is able to plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion. **[SP 4.2, 5.1]**

4.2 The student can design a plan for collecting data to answer a particular scientific question.

5.1 The student can analyze data to identify patterns or relationships.

BIG IDEA 4: Interactions between systems can result in changes in those systems.

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton's second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other systems.

Enduring Understanding 4.E:

The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

Electric and magnetic forces may be exerted on objects that possess an electric charge. These forces affect the motion of electrically charged objects. If a charged object is part of a system, electric and magnetic forces and fields can affect the properties of the system. One such example involves the behavior

of moving charged objects (i.e., an electric current) in a circuit. The electric current in a circuit can be affected by an applied potential difference or by changing the magnetic flux through the circuit. The behavior of individual circuit elements, such as resistors and capacitors, can be understood in terms of how an applied electric or magnetic field affects charge motion within the circuit element.

Essential Knowledge 4.E.1: The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.

a. Ferromagnetic materials can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles.
b. Paramagnetic materials interact weakly with an external magnetic field in that the magnetic dipole moments of the material do not remain aligned after the external field is removed.
c. All materials have the property of diamagnetism in that their electronic structure creates a (usually) weak alignment of the dipole moments of the material opposite to the external magnetic field.

4.E.1.1: The student is able to use representations and models to qualitatively describe the magnetic properties of some materials that can be affected by magnetic properties of other objects in the system. **[SP 1.1, 1.4, 2.2**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Essential Knowledge 4.E.2: Changing magnet flux induces an electric field that can establish an induced emf in a system.

a. Changing magnetic flux induces an emf in a system, with the magnitude of the induced emf equal to the rate of change in magnetic flux.
b. When the area of the surface being considered is constant, the induced emf is the area multiplied by the rate of change in the component of the magnetic field perpendicular to the surface.
c. When the magnetic field is constant, the induced emf is the magnetic field multiplied by the rate of change in area perpendicular to the magnetic field.
d. The conservation of energy determines the direction of the induced emf relative to the change in the magnetic flux.

4.E.2.1: The student is able to construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

THERMODYNAMICS

- **Thermal Equilibrium and the Zeroth Law of Thermodynamics**
- **The Gas Laws and Absolute Temperature**
- **The Ideal Gas Law**
- **Energy Transfer: Conduction, Convection and Radiation**
- **The First Law of Thermodynamics**
- **Thermodynamic Processes and PV Diagrams**
- **The Second Law of Thermodynamics (qualitative)**
- **Entropy (qualitative)**

CUTNELL (9e): Chapter 12 (12-6); Chapter 13 (13-1 through 13-3); Chapter 14 (14-1 through 14-3); Chapter 15 (15-1 through 15-5, 15-7)

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or “properties” that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.E:

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. Some of the most important fundamental characteristics of matter and space are identified here and employed in other big ideas.

Matter has properties called density, resistivity, and thermal conductivity that are used when discussing thermodynamics, fluids, electric current, and transfer of thermal energy. The values of these quantities depend upon the molecular and atomic structure of the material. Matter and space also have properties called electric permittivity and magnetic permeability. The permittivity and the permeability of free space are constants that appear in physical relationships and in the relationship for the speed of electromagnetic radiation in a vacuum. The electric permittivity and the magnetic permeability of a material both depend upon the material’s structure at the atomic level.

Electric dipole moments (as treated in Enduring Understanding 2.C) and magnetic dipole moments are other properties of matter. A separated pair of positively and negatively charged objects is an example of an electric dipole. A current loop is an example of a magnetic dipole.

Essential Knowledge 1.E.3:

Matter has a property called thermal conductivity.

a. The thermal conductivity is the measure of a material’s ability to transfer thermal energy.

1.E.3.1: The student is able to design an experiment and analyze data from it to examine thermal conductivity. **[SP 4.1, 4.2, 5.1]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2 The student can design a plan for collecting data to answer a particular scientific question.

5.1 The student can analyze data to identify patterns or relationships.

BIG IDEA 4: Interactions between systems can result in changes in those systems.

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton's second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other systems.

Enduring Understanding 4.C:
Interactions with other objects or systems can change the total energy of a system.

A system of objects can be characterized by its total energy, a scalar that is the sum of the kinetic energy (due to large-scale relative motion of parts of the system), its potential energy (due to the relative position of interacting parts of the system), and its microscopic internal energy (due to relative motion and interactions at the molecular and atomic levels of the parts of the system). A single object does not possess potential energy. Rather, the system of which the object is a part has potential energy due to the interactions and relative positions of its constituent objects. In general, kinetic, potential, and internal energies can be changed by interactions with other objects or other systems that transfer energy into or out of the system under study. An external force exerted on an object parallel to the displacement of the object transfers energy into or out of the system. For a force that is constant in magnitude and direction, the product of the magnitude of the parallel force component and the magnitude of the displacement is called the work. For a constant or variable force, the work can be calculated by finding the area under the force versus displacement graph. The force component parallel to the displacement gives the rate of transfer of energy with respect to displacement. Work can result in a change in kinetic energy, potential energy, or internal energy of a system. Positive work transfers energy into the system, while negative work transfers energy out of the system. There are two mechanisms by which energy transfers into (or out of) a system. One is when the environment does work on the system (defined as positive work on the system), or the system does work on its environment (defined as negative work on the system). The other is when energy is exchanged between two systems at different temperatures, with no work involved. The amount of energy transferred through work done on or by a system is called work and the amount of energy transferred by heating a system is called heat. Work and heat are not "kinds" of energy (like potential or kinetic), rather they are the specific amount of energy transferred by each process. Summing work and heat gives the change in a system's energy.

Classically, mass conservation and energy conservation are separate laws; but in modern physics we recognize that the mass of a system changes when its energy changes so that a transfer of energy into a system entails an increase in the mass of that system as well, although in most processes the change in mass is small enough to be ignored. The relationship between the mass and energy of a system is described by Einstein's famous equation, $E == mc^2$. The large energies produced during nuclear fission and fusion processes correspond to small reductions in the mass of a system.

Essential Knowledge 4.C.3: Energy is transferred spontaneously from a higher temperature system to a lower temperature system. This process of transferring energy is called heating. The amount of energy transferred is called heat.

c. Conduction, convection, and radiation are mechanisms for this energy transfer.
d. At a microscopic scale the mechanism of conduction is the transfer of kinetic energy between particles.
e. During average collisions between molecules, kinetic energy is transferred from faster molecules to slower molecules.

4.C.3.1: The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

BIG IDEA 5: Changes that occur as a result of interactions are constrained by conservation laws.

Conservation laws constrain the possible behaviors of the objects in a system of any size or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Enduring Understanding 5.A:
Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems.

Conservation laws constrain the possible motions of the objects in a system of any size, or the outcome of an interaction or a process. For example, thinking about physical systems from the perspective of Newton's second law, each object changes its motion at any instant in response to external forces and torques, its response constrained only by its inertial mass and the distribution of that mass. However, with even a few objects in a system, tracking the motions becomes very complex. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, the conservation law constrains the possible configurations of a system. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Essential Knowledge 5.A.2: For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.

5.A.2.1: The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 5.B:
The energy of a system is conserved.

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff 's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

Essential Knowledge 5.B.4: The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.

a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy.
b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.

5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.4.2: The student is able to calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. **[SP 1.4, 2.1, 2.2**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.1 The student can justify the selection of a mathematical routine to solve problems.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 5.B.5: Energy can be transferred by an external force exerted on an object or system that moves the object or system through a distance. This process is called doing work on a system. The amount of energy transferred by this mechanical process is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system.

[A piston filled with gas getting compressed or expanded is treated in Physics 2 as a part of thermodynamics.]

5.B.5.4: The student is able to make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.5.5: The student is able to predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. **[SP 2.2, 6.4**]

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.B.5.6: The student is able to design an experiment and analyze graphical data in which interpretations of the area under a pressure-volume curve are needed to determine the work done on or by the object or system. **[SP 4.2, 5.1**]

4.2 The student can design a plan for collecting data to answer a particular scientific question.

5.1 The student can analyze data to identify patterns or relationships.

Essential Knowledge 5.B.6: Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.

5.B.6.1: The student is able to describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation. **[SP 1.2**]

1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 5.B.7: The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples should include P-V diagrams — isovolumetric processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of internal energy change from temperature change are required; in this course, examples of these relationships are qualitative and/or semiquantitative.

5.B.7.1: The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.7.2: The student is able to create a plot of pressure versus volume for a thermodynamic process from given data. **[SP 1.1**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

5.B.7.3: The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). **[SP 1.1, 1.4, 2.2**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

BIG IDEA 7: The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.

As developed by Newton, classical mechanics uses mathematics to deterministically calculate the motions of objects as a result of their interactions. Newton and his followers envisioned a universe in which the future could be calculated from the past. In practice, physicists soon found that only a small number of objects and interactions could be dealt with in such calculations. When a system includes many objects, such as the molecules in a gas, the mathematics of probability must be used to describe the system. Using probability, the properties of an ideal gas can be explained in terms of a small number of variables such as temperature and pressure. Furthermore, the evolution of isolated systems toward states of higher disorder can be explained using probability, giving one account of the “arrow of time.”

When the physical size of a system is scaled down to atomic size, the mathematics of probability can be used to interpret the meaning of the wave model of matter. At this scale, we find that interactions between objects are fundamentally not deterministic as Newton envisioned but can only be described by probabilities, which are calculated from a mathematical description of the wave called a wave function. This accounts for the observed wavelike properties. Although quantum physics is far from intuitive, the probabilistic description of matter at this scale has been fantastically successful in explaining the behavior of atoms and is now being applied at the frontiers of modern technology.

Enduring Understanding 7.A:

The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure.

In a gas, all of the molecules are in constant motion, and there is a distribution of speeds. Individual speeds may be influenced by collisions with other molecules and with the walls of the container. In an ideal gas, this complicated behavior can be characterized by just a few variables: pressure (P), the combined result of the impacts of molecules; temperature (T), the average kinetic energy of the molecules; and volume (V). Statistical methods are used to relate the state variables of pressure and temperature to the distribution of velocities of the molecules. For the ideal gas model the equation ***PV=nRT*** describes the relationship between the state variables.

In Maxwell’s description of the connection between thermodynamic properties and atomic-scale motion, the rate of change of momentum at any surface, including that of the container that holds the gas, increases as temperature increases. Newton’s second law expresses the rate of change of momentum as a force. Pressure is expressed as force per unit area.

The average kinetic energy of the gas molecules in the system is an average over a distribution of different speeds for individual molecules. The root mean square of the velocity is related to the temperature.

Essential Knowledge 7.A.1: The pressure of a system determines the force that the system exerts on the walls of its container and is a measure of the average change in the momentum, the impulse, of the molecules colliding with the walls of the container. The pressure also exists inside the system itself, not just at the walls of the container.

7.A.1.1: The student is able to make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container, and how changes in pressure affect the thermal equilibrium of the system. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

7.A.1.2: Treating a gas molecule as an object (i.e., ignoring its internal structure), the student is able to analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, to quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 7.A.2: The temperature of a system characterizes the average kinetic energy of its molecules.

a. The average kinetic energy of the system is an average over the many different speeds of the molecules in the system that can be described by a distribution curve.
b. The root mean square speed corresponding to the average kinetic energy for a specific gas at a given temperature can be obtained from this distribution.

7.A.2.1: The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. **[SP 7.1]**

7.1 The student can connect phenomena and models across spatial and temporal scales.

7.A.2.2: The student is able to connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and to relate this to thermodynamic processes. **[SP 7.1]**

7.1 The student can connect phenomena and models across spatial and temporal scales.

Essential Knowledge 7.A.3: In an ideal gas, the macroscopic (average) pressure *(P)*, temperature *(T)*, and volume *(V)* are related by the equation $PV=nRT$.

7.A.3.1: The student is able to extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

7.A.3.2: The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables. **[SP 3.2, 4.2]**

3.2 The student can refine scientific questions.

4.2 The student can design a plan for collecting data to answer a particular scientific question.

7.A.3.3: The student is able to analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$. **[SP 5.1]**

5.1 The student can analyze data to identify patterns or relationships.

Enduring Understanding 7.B:
The tendency of isolated systems to move toward states with higher disorder is described by probability.

The transfers of energy that occur in thermal processes depend on a very large number of very small-scale (molecular and atomic) interactions, and thus these energy transfers are best described by the mathematics of probability. When parts of an isolated system initially at different temperatures interact, higher momentum particles are more likely to be involved in more collisions. Consequently, conservation of momentum makes it more likely that kinetic energy will be transferred from higher energy to lower energy particles, reducing both the number of high energy particles and the number of low energy particles until, after many collisions, all interacting parts of a system will arrive at the same temperature. The amount of thermal energy needed to change the temperature of a given part
of a system will depend on the total mass of that part of the system and on the difference between its initial and final temperatures. Neither energy conservation nor momentum conservation laws have any preferred direction in time, yet large- scale processes always tend toward equilibrium and not toward disequilibrium. The second law of thermodynamics describes the tendency of large systems to move toward states with higher disorder. A new state function, entropy, can be defined, and it depends only on the configuration of the system and not on how the system arrived in that configuration. Unlike energy, entropy is not conserved but instead always increases for irreversible processes in closed systems.

Essential Knowledge 7.B.1: The approach to thermal equilibrium is a probability process.

a. The amount of thermal energy needed to change the temperature of a system of particles depends both on the mass of the system and on the temperature change of the system.
b. The details of the energy transfer depend upon interactions at the molecular level.
c. Since higher momentum particles will be involved in more collisions, energy is most likely to be transferred from higher to lower energy particles. The most likely state after many collisions is that both systems of particles have the same temperature.

7.B.1.1: The student is able to extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

7.B.2.1: The student is able to connect qualitatively the second law of thermodynamics in terms of the state function called entropy and how it (entropy) behaves in reversible and irreversible processes. **[SP 7.1]**

7.1 The student can connect phenomena and models across spatial and temporal scales.

FLUIDS

- **Density**
- **Static Fluids**
- **Fluids in Motion; Flow Rate, Continuity and Bernoulli's Principle**

CUTNELL (9e): Chapter 11 (11-1 through 11-10)

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.E:

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. Some of the most important fundamental characteristics of matter and space are identified here and employed in other big ideas.

Matter has properties called density, resistivity, and thermal conductivity that are used when discussing thermodynamics, fluids, electric current, and transfer of thermal energy. The values of these quantities depend upon the molecular and atomic structure of the material. Matter and space also have properties called electric permittivity and magnetic permeability. The permittivity and the permeability of free space are constants that appear in physical relationships and in the relationship for the speed of electromagnetic radiation in a vacuum. The electric permittivity and the magnetic permeability of a material both depend upon the material's structure at the atomic level.

Electric dipole moments (as treated in Enduring Understanding 2.C) and magnetic dipole moments are other properties of matter. A separated pair of positively and negatively charged objects is an example of an electric dipole. A current loop is an example of a magnetic dipole.

Essential Knowledge 1.E.1:

Matter has a property called density.

1.E.1.1: The student is able to predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction. **[SP 4.2, 6.4]**

4.2 The student can design a plan for collecting data to answer a particular scientific question.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

1.E.1.2: The student is able to select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects. **[SP 4.1, 6.4]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

BIG IDEA 3: The interactions of an object with other objects can be described by forces.

An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

Enduring Understanding 3.C:
At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

In Big Idea 3, the behavior of an object is analyzed without reference to the internal structure of the object. Internal structure is included in Big Idea 4. There are a small number of forces that occur in nature, and the macroscopic ones are considered here. The identification of forces is a key step in the analysis of mechanical systems.

Gravitational forces, electric forces, and magnetic forces between objects are all evident on the macroscopic scale. The gravitational force is a weaker force than the electric or magnetic force. However, on the larger scale, the gravitational force dominates. Electric forces are dominant in determining the properties of the objects in our everyday experience. However, the many electrically charged particles that interact make the treatment of this everyday force very complex. Introducing new concepts such as the frictional force as averages over the many particles reduces the complexity. Contact forces (e.g., frictional force, buoyant force) result from the interaction of one object touching another object and

are ultimately due to microscopic electric forces. The frictional force is due to the interaction between surfaces at rest or in relative motion. Buoyant force is caused by the difference in pressure, or force per unit area, exerted on the different surfaces of the object. It is important for students to study each of these forces and to use free-body diagrams to analyze the interactions between objects.

Essential Knowledge 3.C.4: Contact forces result from the interaction of one object touching another object, and they arise from interatomic electric forces. These forces include tension, friction, normal, spring (Physics 1), and buoyant (Physics 2).

3.C.4.1: The student is able to make claims about various contact forces between objects based on the microscopic cause of those forces. **[SP 6.1]**

6.1 The student can justify claims with evidence.

3.C.4.2: The student is able to explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. **[SP 6.2]**

6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

BIG IDEA 5: Changes that occur as a result of interactions are constrained by conservation laws.
Conservation laws constrain the possible behaviors of the objects in a system of any size or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Enduring Understanding 5.B:
The energy of a system is conserved.
Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff 's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

Essential Knowledge 5.B.10:
Bernoulli's equation describes the conservation of energy in fluid flow.

5.B.10.1: The student is able to use Bernoulli's equation to make calculations related to a moving fluid. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.10.2: The student is able to use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.10.3: The student is able to use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.10.4: The student is able to construct an explanation of Bernoulli's equation in terms of the conservation of energy. **[SP 6.2]**

6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

Enduring Understanding 5.F:
Classically, the mass of a system is conserved.

The conservation of mass is an important principle that holds up to a certain energy scale where the concepts of mass and energy need to be combined. In this course, conservation of mass is assumed in most problems. Thus, when using $\vec{a} = \frac{\Sigma \vec{F}}{m}$ etc., conservation of mass is assumed. An ideal example of this conservation law is found in the continuity equation, which describes conservation of mass flow rate in fluids. If no mass is entering or leaving a system, then the mass must be constant. If an enclosed fluid flow is uniform and the fluid is also incompressible, then the mass entering an area must be equal to the mass leaving an area. Fluid flow in engineering and in biological systems can be modeled starting with this enduring understanding but requires the addition of fluid viscosity for a complete treatment, which is not a part of this course.

Essential Knowledge 5.F.1: The continuity equation describes conservation of mass flow rate in fluids. Examples should include volume rate of flow and mass flow rate.

5.F.1.1: The student is able to make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). **[SP 2.1, 2.2, 7.2]**

2.1 The student can justify the selection of a mathematical routine to solve problems.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

GEOMETRIC AND PHYSICAL OPTICS

- **Electromagnetic Waves**
- **Polarization, Reflection and Refraction**
- **Formation of Images by Spherical Mirrors**
- **Formation of Images by Thin Lenses**
- **Interference - Young's Double Slit Experiment**
- **Diffraction**
- **Interference by Thin Films**

CUTNELL (9e): Chapter 16 (16-1 through 16-3); Chapter 24 (24-1 through 24-4 and 24-6); Chapter 25 (25-1 through 25-7); Chapter 26 (26-1 through 26-4); Chapter 27 (27-1 through27-3 and 27-7)

BIG IDEA 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.
Classically, waves are a "disturbance" that propagates through space. Mechanical waves are a disturbance of a mechanical medium such as a string, a solid, or a gas, and they carry energy and momentum from one place to another without any net motion of the medium. Electromagnetic waves are a different type of wave; in this case, the disturbance is in the electromagnetic field itself, and therefore requires no medium. Electromagnetic waves also carry energy and momentum. In most cases, multiple waves can propagate through a medium independently of each other. Two waves do not "collide" as would objects traveling through the same region of space. Waves "pass through" each other, according to the principle of superposition and a phenomenon called interference. Important examples of wave motion are sound (a mechanical wave that can propagate in gases, liquids, and solids), and light (which can be modeled as electromagnetic waves to which our eyes are sensitive). In the quantum regime, all particles can be modeled as waves, although the wavelike behavior is only observable under certain conditions — for example, an electron in an atom behaves in some ways like a classical particle and in other ways like a classical wave.

Enduring Understanding 6.A:
A wave is a traveling disturbance that transfers energy and momentum.
When an object moves as a projectile from one place to another, it possesses kinetic energy and momentum. Such a process thus transfers energy and momentum, and also mass, from place to place. A wave is a disturbance that carries energy and momentum from one place to another without the transfer of mass. Some waves are mechanical in nature — this means that they are a disturbance of a mechanical system such as a solid, a liquid, or a gas; this system is called the medium through which the wave travels. Mechanical waves are then described in terms of the way they disturb or displace their medium. The propagation properties of the mechanical wave, such as the wave speed, also depend on the properties of the medium. Electromagnetic waves do not require a mechanical medium. They are instead associated with oscillating electric and magnetic fields. Electromagnetic waves can travel through a mechanical medium, such as a solid, but they can also travel through a vacuum.

Essential Knowledge 6.A.1: Waves can propagate via different oscillation modes such as transverse and longitudinal.

a. Mechanical waves can be either transverse or longitudinal. Examples should include waves on a stretched string and sound waves.
b. Electromagnetic waves are transverse waves.
c. Transverse waves may be polarized.

6.A.1.2: The student is able to describe representations of transverse and longitudinal waves. **[SP 1.2]**

1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

6.A.1.3: The student is able to analyze data (or a visual representation) to identify patterns that indicate that a particular mechanical wave is polarized and construct an explanation of the fact that the wave must have a vibration perpendicular to the direction of energy propagation. **[SP 5.1, 6.2]**

5.1 The student can analyze data to identify patterns or relationships.

6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

Essential Knowledge 6.A.2: For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples should include light traveling through a vacuum and sound not traveling through a vacuum.

6.A.2.2: The student is able to contrast mechanical and electromagnetic waves in terms of the need for a medium in wave propagation. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 6.B:
A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.

The properties of periodic waves are important to understanding wave phenomena in the world around us. These properties are amplitude, frequency, period, speed of the wave in a particular medium, wavelength, and energy. A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave. Wave speeds depend upon the properties of the medium, but the speed of a wave is generally independent of the frequency and wavelength of the wave. The speed of an electromagnetic wave in a vacuum is a constant, usually referred to as *c*. In other materials, the apparent speed of an electromagnetic wave depends on properties of the material.

The frequency of a wave, as perceived by observers, depends upon the relative motion of the source and the observer. If the relative motions of the source and observer are away from each other, the perceived frequency decreases. If the relative motions of the source and observer are toward each other, the perceived frequency increases. This change in observed frequency or wavelength is known as the Doppler effect and finds uses from astronomy to medicine to radar speed traps.

Essential Knowledge 6.B.3: A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave.

6.B.3.1: The student is able to construct an equation relating the wavelength and amplitude of a wave from a graphical representation of the electric or magnetic field value as a function of position at a given time instant and vice versa, or construct an equation relating the frequency or period and amplitude of a wave from a graphical representation of the electric or magnetic field value at a given position as a function of time and vice versa. **[SP 1.5**]

1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.

Enduring Understanding 6.C:
Only waves exhibit interference and diffraction.

When two or more waves move through the same space, the displacement at a particular point is a result of the superposition or sum of the displacements due to each of the waves. Depending on the direction of propagation of the waves from the various sources and their phase or time relationship to each other, this principle explains a large variety of phenomena, including standing waves in a musical instrument, rogue waves at sea, and the colors seen in soap bubbles. Where the crest of one wave coincides with the crest of another wave, constructive interference occurs, producing large amplitude oscillations. Where crest meets trough, cancellation or destructive interference occurs. Since the oscillation at a particular point can be treated as a source of waves spreading from that point (Huygens' principle), as waves pass through openings or around objects that are of sizes comparable to the wavelength, we observe that waves can spread or diffract out into the space beyond the edge or obstacle, which accounts, among other things, for our ability to hear around corners, but not see around them.

Essential Knowledge 6.C.1: When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called superposition.

6.C.1.1: The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples should include standing waves. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

6.C.1.2: The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Essential Knowledge 6.C.2: When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.

6.C.2.1: The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening, and to qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave. **[SP 1.4, 6.4, 7.2**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 6.C.3: When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples should include monochromatic double-slit interference.

6.C.3.1: The student is able to qualitatively apply the wave model to quantities that describe the generation of interference patterns to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small compared to the wavelength of the waves. **[SP 1.4, 6.4**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Essential Knowledge 6.C.4: When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples should include hearing around corners, but not seeing around them, and water waves bending around obstacles.

6.C.4.1: The student is able to predict and explain, using representations and models, the ability or inability of waves to transfer energy around corners and behind obstacles in terms of the diffraction property of waves in situations involving various kinds of wave phenomena, including sound and light. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 6.E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.

The propagation of a wave depends on the properties of the medium or region through which the wave travels. The speed of a wave, including electromagnetic waves such as light, depends on the material through which it travels. When light (or any other type of wave) travels from one material to another, the frequency remains the same, but the change in wave speed causes a change in the propagation direction, described by Snell's law. This change in direction is termed refraction when light passes through an interface. Reflection occurs when part or all of a wave bounces back from the interface. Both reflection and refraction can be used to form images. The study of image formation with light is called geometrical optics and involves the properties of images formed with mirrors and lenses.

Essential Knowledge 6.E.1: When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed. (Qualitative understanding only.)

6.E.1.1: The student is able to make claims using connections across concepts about the behavior of light as the wave travels from one medium into another, as some is transmitted, some is reflected, and some is absorbed. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 6.E.2: When light hits a smooth reflecting surface at an angle, it reflects at the same angle on the other side of the line perpendicular to the surface (specular reflection); this law of reflection accounts for the size and location of images seen in mirrors.

6.E.2.1: The student is able to make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface. **[SP 6.4, 7.2]**

> *6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.*
>
> *7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*

Essential Knowledge 6.E.3: When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.

a. Snell's law relates the angles of incidence and refraction to the indices of refraction, with the ratio of the indices of refraction inversely proportional to the ratio of the speeds of propagation in the two media.
b. When light travels from an optically slower substance into an optically faster substance, it bends away from the perpendicular.
c. At the critical angle, the light bends far enough away from the perpendicular that it skims the surface of the material.
d. Beyond the critical angle, all of the light is internally reflected.

6.E.3.1: The student is able to describe models of light traveling across a boundary from one transparent material to another when the speed of propagation changes, causing a change in the path of the light ray at the boundary of the two media. **[SP 1.1, 1.4]**

> *1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.*
>
> *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*

6.E.3.2: The student is able to plan data collection strategies as well as perform data analysis and evaluation of the evidence for finding the relationship between the angle of incidence and the angle of refraction for light crossing boundaries from one transparent material to another (Snell's law). **[SP 4.1, 5.1, 5.2, 5.3]**

> *4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.*
>
> *5.1 The student can analyze data to identify patterns or relationships.*
>
> *5.2 The student can refine observations and measurements based on data analysis.*
>
> *5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.*

6.E.3.3: The student is able to make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation. **[SP 6.4, 7.2]**

> *6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.*
>
> *7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*

Essential Knowledge 6.E.4: The reflection of light from surfaces can be used to form images.

a. Ray diagrams are very useful for showing how and where images of objects are formed for different mirrors and how this depends upon the placement of the object. Concave and convex mirror examples should be included.
b. They are also useful for determining the size of the resulting image compared to the size of the object.
c. Plane mirrors, convex spherical mirrors, and concave spherical mirrors are part of this course. The construction of these ray diagrams and comparison with direct experiences are necessary.

6.E.4.1: The student is able to plan data collection strategies, and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**

3.2 The student can refine scientific questions.
4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.
5.2 The student can refine observations and measurements based on data analysis.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

6.E.4.2: The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 6.E.5: The refraction of light as it travels from one transparent medium to another can be used to form images.

a. Ray diagrams are used to determine the relative size of object and image, the location of object and image relative to the lens, the focal length, and the real or virtual nature of the image. Converging and diverging lenses should be included as examples.

6.E.5.1: The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses. **[SSP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

6.E.5.2: The student is able to plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**

3.2 The student can refine scientific questions.
4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.
5.2 The student can refine observations and measurements based on data analysis.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Enduring Understanding 6.F:
Electromagnetic radiation can be modeled as waves or as fundamental particles.

One of the great discoveries of modern physics is that electromagnetic radiation, modeled in the 19th century as a classical wave, also has particle- like properties that are best captured by a hybrid model in which light is neither waves nor particles. In this hybrid, quantum model of electromagnetic spectra, photons are individual energy packets of electromagnetic waves. The discrete spectra of atoms are evidence that supports the quantum model of electromagnetic spectra. The nature of light requires that a different model of light is most appropriate at different scales. Interference is a property of waves, and radio waves traveling different paths can interfere with each other causing "dead spots" — areas of limited reception. The behavior of waves through a slit or set of slits is discussed in Enduring Understanding 6.C. Wavelengths of electromagnetic radiation range from extremely small to extremely large.

Essential Knowledge 6.F.1: Types of electromagnetic radiation are characterized by their wavelengths, and certain ranges of wavelength have been given specific names. These include (in order of increasing wavelength spanning a range from picometers to kilometers) gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.

6.F.1.1: The student is able to make qualitative comparisons of the wavelengths of types of electromagnetic radiation. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

6.F.2.1: The student is able to describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present. **[SP 1.1**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

QUANTUM PHYSICS, ATOMIC AND NUCLEAR PHYSICS

- **Reasons that Classical Mechanics must be replaced by Special Relativity (see 1.3.D.1)**
- **Planck's Quantum Hypothesis**
- **Photon Theory of Light and the Photoelectric Effect**
- **Wave Nature of Matter**
- **Atomic Energy Levels: Emission and Absorption Spectra**
- **Nuclear Reactions and Decays: fission, fusion, alpha decay, beta decay, or gamma decay.**
- **Conservation Laws: Charge, Nucleon and Mass-Energy**

CUTNELL (9e): Chapter 28 (28-2); Chapter 29 (29-1 through 29-5); Chapter 30 (30-1 through 30-4 and 27-6); Chapter 31 (31-1 through 31-4)

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.A:

The internal structure of a system determines many properties of the system.

In a problem of interest, this enduring understanding distinguishes *systems,* where internal structure exists and may need to be taken into account, from *objects,* where internal structure is not present or can be ignored.

Matter builds from fundamental particles, which are objects that have no internal structure, up to systems such as nuclei, atoms, molecules, and macroscopic objects that do have internal structure. The number and arrangements of atomic constituents cause substances to have different properties. There is much contact with chemistry in this enduring understanding in terms of atomic structure, chemical properties of elements, and the incorporation of concepts leading to the quantum model of the atom: energy states, quantized parameters, and transitions.

Essential Knowledge 1.A.2: Fundamental particles have no internal structure.

a. Electrons, neutrinos, photons, and quarks are examples of fundamental particles.
b. Neutrons and protons are composed of quarks.
c. All quarks have electric charges, which are fractions of the elementary charge of the electron. Students will not be expected to know specifics of quark charge or quark composition of nucleons.

1.A.2.1: The student is able to construct representations of the differences between a fundamental particle and a system composed of fundamental particles and to relate this to the properties and scales of the systems being investigated. **[SP 1.1, 7.1]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
7.1 The student can connect phenomena and models across spatial and temporal scales.

Essential Knowledge 1.A.4:
Atoms have internal structures that determine their properties.

a. The number of protons in the nucleus determines the number of electrons in a neutral atom.
b. The number and arrangements of electrons cause elements to have different properties.
c. The Bohr model based on classical foundations was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states (represented in energy diagrams by discrete energy levels).
d. Discrete energy state transitions lead to spectra.

1.A.4.1: The student is able to construct representations of the energy-level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated. **[SP 1.1, 7.1]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
7.1 The student can connect phenomena and models across spatial and temporal scales.

1.C.4.1: The student is able to articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass-energy. **[SP 6.3]**

6.3 The student can articulate the reasons that scientific explanations and theories are refined or replaced.

Enduring Understanding 1.D:
Classical mechanics cannot describe all properties of objects.

Physicists developed classical mechanics from the intuitive partition of behavior of nature at the human scale into objects that behaved like particles (e.g., rocks) and systems that behaved like waves (e.g., sound waves). Similarly, in classical mechanics they recognized from experience that the motion of objects would appear differently to observers moving relative to each other but assumed that measurements of elapsed time would not be affected by motion. As physicists in the late 19th and early 20th centuries probed the structure of matter at smaller and smaller scales, they discovered that models of atomic and subatomic behavior based on classical intuitions could not explain the experimental results. Ultimately, new mathematical theories were developed that could predict the outcome of experiments but lacked the intuitive underpinning of the classical view. The mathematics gives unambiguous results, but has no single intuitive reference or analogy that can be described in ordinary language. As a result, the best we can do is to describe certain results of experiments as analogous to classical particle behavior and others as analogous to classical wavelike behavior while recognizing that the underlying nature of the object has no precise analogy in human-scale experience. During the same period, experimental results and theoretical predictions of results in the study of electromagnetic radiation came into conflict with the classical assumption of a common time for all observers. At relative velocities that are large compared with common experience, the special theory of relativity correctly predicts changes in the observed momentum, length, and elapsed time for objects in relative motion. Because humans have no experience of relative motion at such velocities, we have no intuitive underpinnings to explain this behavior. The physics of large relative velocities will only be treated qualitatively in this course.

Essential Knowledge 1.D.1:
Objects classically thought of as particles can exhibit properties of waves.

a. This wavelike behavior of particles has been observed, e.g., in a double-slit experiment using elementary particles.
b. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.

1.D.1.1: The student is able to explain why classical mechanics cannot describe all properties of objects by articulating the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties. **[SP 6.3]**

6.3 The student can articulate the reasons that scientific explanations and theories are refined or replaced.

Essential Knowledge 1.D.3:
Properties of space and time cannot always be treated as absolute.

a. Relativistic mass–energy equivalence is a reconceptualization of matter and energy as two manifestations of the same underlying entity, fully interconvertible, thereby rendering invalid the classically separate laws of conservation of mass and conservation of energy. Students will not be expected to know apparent mass or rest mass.
b. Measurements of length and time depend on speed. (Qualitative treatment only.)

1.D.3.1: The student is able to articulate the reasons that classical mechanics must be replaced by special relativity to describe the experimental results and theoretical predictions that show that the properties of space and time are not absolute. [Students will be expected to recognize situations in which nonrelativistic classical physics breaks down and to explain how relativity addresses that breakdown, but students will not be expected to know in which of two reference frames a given series of events corresponds to a greater or lesser time interval, or a greater or lesser spatial distance; they will just need to know that observers in the two reference frames can "disagree" about some time and distance intervals.] **[SP 6.3, 7.1]**

6.3 The student can articulate the reasons that scientific explanations and theories are refined or replaced.
7.1 The student can connect phenomena and models across spatial and temporal scales.

BIG IDEA 3: The interactions of an object with other objects can be described by forces.

An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

Enduring Understanding 3.G: Certain types of forces are considered fundamental.

There are different types of fundamental forces, and these forces can be characterized by their actions at different scales. The fundamental forces discussed in these courses include the electroweak force, the gravitational force, and the strong (nuclear) force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. All other forces can be thought of as secondary forces and are ultimately derived from the fundamental forces.

On the scale appropriate to the secondary forces we deal with every day, the electromagnetic aspect of the electroweak force dominates. There are two kinds of electric charge that can produce both attractive and repulsive interactions. While there are two kinds of electric charge, there appears to be only a single type of mass. Consequently, gravitational forces are only attractive.

Since there are no repulsive contributions to the net force exerted at a very large distance, the gravitational force dominates at large scales. The weak aspect of the electroweak force is important at very large stellar scales and at very small nuclear scales, and the strong force dominates inside the nucleus. (Students will not be required to know interactions involving the weak force.)

Essential Knowledge 3.G.3: The strong force is exerted at nuclear scales and dominates the interactions of nucleons.

3.G.3.1: The student is able to identify the strong force as the force that is responsible for holding the nucleus together. **[SP 7.2**]

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

BIG IDEA 4: Interactions between systems can result in changes in those systems.

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton’s second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other systems.

Enduring Understanding 4.C:
Interactions with other objects or systems can change the total energy of a system.

A system of objects can be characterized by its total energy, a scalar that is the sum of the kinetic energy (due to large-scale relative motion of parts of the system), its potential energy (due to the relative position of interacting parts of the system), and its microscopic internal energy (due to relative motion and interactions at the molecular and atomic levels of the parts of the system). A single object does not possess potential energy. Rather, the system of which the object is a part has potential energy due to the interactions and relative positions of its constituent objects. In general, kinetic, potential, and internal energies can be changed by interactions with other objects or other systems that transfer energy into or out of the system under study. An external force exerted on an object parallel to the displacement of the object transfers energy into or out of the system. For a force that is constant in magnitude and direction, the product of the magnitude of the parallel force component and the magnitude of the displacement is called the work. For a constant or variable force, the work can be calculated by finding the area under the force versus displacement graph. The force component parallel to the displacement gives the rate of transfer of energy with respect to displacement. Work can result in a change in kinetic energy, potential energy, or internal energy of a system. Positive work transfers energy into the system, while negative work transfers energy out of the system. There are two mechanisms by which energy transfers into (or out of) a system. One is when the environment does work on the system (defined as positive work on the system), or the system does work on its environment (defined as negative work on the system). The other is when energy is exchanged between two systems at different temperatures, with no work involved. The amount of energy transferred through work done on or by a system is called work and the amount of energy transferred by heating a system is called heat. Work and heat are not "kinds" of energy (like potential or kinetic), rather they are the specific amount of energy transferred by each process. Summing work and heat gives the change in a system's energy.

Classically, mass conservation and energy conservation are separate laws; but in modern physics we recognize that the mass of a system changes when its energy changes so that a transfer of energy into a system entails an increase in the mass of that system as well, although in most processes the change in mass is small enough to be ignored. The relationship between the mass and energy of a system is described by Einstein's famous equation, $E = mc^2$. The large energies produced during nuclear fission and fusion processes correspond to small reductions in the mass of a system.

Essential Knowledge 4.C.4: Mass can be converted into energy, and energy can be converted into mass.

a. Mass and energy are interrelated by $E = mc^2$.
b. Significant amounts of energy can be released in nuclear processes.

4.C.4.1: The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale. **[SP 2.2, 2.3, 7.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
2.3 The student can estimate numerically, quantities that describe natural phenomena.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

BIG IDEA 5: Changes that occur as a result of interactions are constrained by conservation laws.

Conservation laws constrain the possible behaviors of the objects in a system of any size or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed and isolated system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

Enduring Understanding 5.B:
The energy of a system is conserved.

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff 's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

Essential Knowledge 5.B.8: Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei.

a. Transitions between two given energy states of an atom correspond to the absorption or emission of a photon of a given frequency (and hence, a given wavelength).
b. An emission spectrum can be used to determine the elements in a source of light.

5.B.8.1: The student is able to describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed. **[SP 1.2, 7.2]**

1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 5.B.11: Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.

a. $E = mc^2$ can be used to calculate the mass equivalent for a given amount of energy transfer or an energy equivalent for a given amount of mass change (e.g., fission and fusion reactions).

5.B.11.1: The student is able to apply conservation of mass and conservation of energy concepts to a natural phenomenon and use the equation $E = mc^2$ to make a related calculation. **[SP 2.2, 7.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 5.C:
The electric charge of a system is conserved.

Conservation of electric charge is a fundamental conservation principle in physics. All processes in nature conserve the net electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves around a circuit or from place to place within a circuit. Any increase or decrease in the net charge in one region is compensated for by a corresponding decrease or increase in
the net charge in other regions. In electrostatics, it is common for electrons to move from one object to another, and the number of electrons that leave one object is always equal to the number of electrons that move onto other objects. In some reactions such as radioactive decay or interactions involving elementary particles, it is possible for the number of electrically charged particles after a reaction or decay to be different from the number before. However, the net charge before and after is always equal. So, if a process produces a “new” electron that was not present before the reaction, then a “new” positive charge must also be created so that the net charge is the same before and after the process.

Essential Knowledge 5.C.1: Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples should include equations representing nuclear decay.

5.C.1.1: The student is able to analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge. **[SP 6.4, 7.2**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 5.D:
The linear momentum of a system is conserved.

Conservation of linear momentum is another of the important conservation laws. This law holds at all scales from the subatomic scale to the galactic scale. Linear momentum in a system isolated from external forces is constant. Interactions with other objects or systems can change the total linear momentum of a system. Such changes are discussed in Enduring Understandings 3.D and 4.B.

When objects collide, the collisions can be elastic or inelastic. In both types of collisions linear momentum is conserved. The elastic collision of nonrotating objects describes those cases in which the linear momentum stays constant and the kinetic and internal energies of the system are the same before and after the collision. The inelastic collision of objects describes those cases in which the linear momentum stays constant and the kinetic and internal energies of the objects are different before and after the collision.

The velocity of the center of mass of the system cannot be changed by an interaction within the system. In an isolated system that is initially stationary, the location of the center of mass is fixed. When two objects collide, the velocity of their center of mass will not change.

Essential Knowledge 5.D.1: In a collision between objects, linear momentum is conserved. In an elastic collision, kinetic energy is the same before and after.

a. In an isolated system, the linear momentum is constant throughout the collision.
b. In an isolated system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision.

5.D.1.6: The student is able to make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models..

5.D.1.7: The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**

2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

Essential Knowledge 5.D.2: In a collision between objects, linear momentum is conserved. In an inelastic collision, kinetic energy is not the same before and after the collision.

a. In an isolated system, the linear momentum is constant throughout the collision.
b. In an isolated system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.

5.D.2.5: The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum as the appropriate solution method for an inelastic collision, recognize that there is a common final velocity for the colliding objects in the totally inelastic case, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**

2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.D.2.6: The student is able to apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 5.D.3: The velocity of the center of mass of the system cannot be changed by an interaction within the system. [Physics 1: includes no calculations of centers of mass; the equation is not provided until Physics 2. However, without doing calculations, Physics 1 students are expected to be able to locate the center of mass of highly symmetric mass distributions, such as a uniform rod or cube of uniform density, or two spheres of equal mass.]

a. The center of mass of a system depends upon the masses and positions of the objects in the system. In an isolated system (a system with no external forces), the velocity of the center of mass does not change.
b. When objects in a system collide, the velocity of the center of mass of the system will not change unless an external force is exerted on the system.

5.D.3.2: The student is able to make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.D.3.3: The student is able to make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Enduring Understanding 5.G:
Nucleon number is conserved.

The conservation of nucleon number, according to which the number of nucleons (protons and neutrons) doesn't change, applies to nuclear reactions and decays including fission, fusion, alpha decay, beta decay, and gamma decay. This conservation law, along with conservation of electric charge, is the basis for balancing nuclear equations.

Essential Knowledge 5.G.1: The possible nuclear reactions are constrained by the law of conservation of nucleon number.

5.G.1.1: The student is able to apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

BIG IDEA 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Classically, waves are a "disturbance" that propagates through space. Mechanical waves are a disturbance of a mechanical medium such as a string, a solid, or a gas, and they carry energy and momentum from one place to another without any net motion of the medium. Electromagnetic waves are a different type of wave; in this case, the disturbance is in the electromagnetic field itself, and therefore requires no medium. Electromagnetic waves also carry energy and momentum. In most cases, multiple waves can propagate through a medium independently of each other. Two waves do not "collide" as would objects traveling through the same region of space. Waves "pass through" each other, according to the principle of superposition and a phenomenon called interference. Important examples of wave motion are sound (a mechanical wave that can propagate in gases, liquids, and solids), and light (which can be modeled as electromagnetic waves to which our eyes are sensitive). In the quantum regime, all particles can be modeled as waves, although the wavelike behavior is only observable under certain conditions — for example, an electron in an atom behaves in some ways like a classical particle and in other ways like a classical wave.

Enduring Understanding 6.F:
Electromagnetic radiation can be modeled as waves or as fundamental particles.

One of the great discoveries of modern physics is that electromagnetic radiation, modeled in the 19th century as a classical wave, also has particle- like properties that are best captured by a hybrid model in which light is neither waves nor particles. In this hybrid, quantum model of electromagnetic spectra, photons are individual energy packets of electromagnetic waves. The discrete spectra of atoms are evidence that supports the quantum model of electromagnetic spectra. The nature of light requires that a different model of light is most appropriate at different scales. Interference is a property of waves, and radio waves traveling different paths can interfere with each other causing “dead spots” — areas of limited reception. The behavior of waves through a slit or set of slits is discussed in Enduring Understanding 6.C. Wavelengths of electromagnetic radiation range from extremely small to extremely large.

Essential Knowledge 6.F.3: Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck’s constant and f is the frequency of the associated light wave.

a. In the quantum model of electromagnetic radiation, the energy is emitted or absorbed in discrete energy packets called photons. Discrete spectral lines should be included as an example.
b. For the short-wavelength portion of the electromagnetic spectrum, the energy per photon can be observed by direct measurement when electron emissions from matter result from the absorption of radiant energy.
c. Evidence for discrete energy packets is provided by a frequency threshold for electron emission. Above the threshold, maximum kinetic energy of the emitted electrons increases with the frequency and not the intensity of absorbed radiation. The photoelectric effect should be included as an example.

6.F.3.1: The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Essential Knowledge 6.F.4: The nature of light requires that different models of light are most appropriate at different scales.

a. The particle-like properties of electromagnetic radiation are more readily observed when the energy transported during the time of the measurement is comparable to E_{photon}
b. The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects it interacts with is comparable to or larger than the wavelength of the radiation.

6.F.4.1: The student is able to select a model of radiant energy that is appropriate to the spatial or temporal scale of an interaction with matter. **[SP 6.4, 7.1]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.1 The student can connect phenomena and models across spatial and temporal scales.

Enduring Understanding 6.G:
All matter can be modeled as waves or as particles.

At the human scale, a thrown rock moves through space on a well-defined path. The moving object carries momentum and energy that are transferred on impact to another object or system. A splash in a pond creates a disturbance in the water, spreading in all directions and transferring energy and momentum without transferring mass. These two different forms of interaction have historically served as the metaphors that we attempt to use to explain the physical phenomena we observe. Abstracted into sophisticated mathematical models, they give highly precise predictions at the human scale. However, at other vastly different scales of size and energy, we find that neither model is an exact fit for the phenomena. Instead, we find that each of the metaphors works well to model some aspects of a situation while failing to model other aspects. The successful mathematical treatment of quantum mechanics combining mathematics derived from both metaphors goes beyond either to accurately describe phenomena at the quantum scale but leaves us without any simple visual metaphor from our everyday experience. The wave representing a particle indicates the probability of locating that particle at a particular place in space and time. This course treats these wave representations in a qualitative fashion.

Essential Knowledge 6.G.1: Under certain regimes of energy or distance, matter can be modeled as a classical particle.

6.G.1.1: The student is able to make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate. **[SP 6.4, 7.1]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.1 The student can connect phenomena and models across spatial and temporal scales.

Essential Knowledge 6.G.2: Under certain regimes of energy or distance, matter can be modeled as a wave. The behavior in these regimes is described by quantum mechanics.

a. A wave model of matter is quantified by the de Broglie wavelength that increases as the momentum of the particle decreases.
b. The wave property of matter was experimentally confirmed by the diffraction of electrons in the experiments of Clinton Joseph Davisson, Lester Germer, and George Paget Thomson.

6.G.2.1: The student is able to articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal. **[SP 6.1]**

6.1 The student can justify claims with evidence.

6.G.2.2: The student is able to predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (de Broglie wavelength need not be given, so students may need to obtain it.) **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

BIG IDEA 7: The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.

As developed by Newton, classical mechanics uses mathematics to deterministically calculate the motions of objects as a result of their interactions. Newton and his followers envisioned a universe in which the future could be calculated from the past. In practice, physicists soon found that only a small number of objects and interactions could be dealt with in such calculations. When a system includes many objects, such as the molecules in a gas, the mathematics of probability must be used to describe the system. Using probability, the properties of an ideal gas can be explained in terms of a small number of variables such as temperature and pressure. Furthermore, the evolution of isolated systems toward states of higher disorder can be explained using probability, giving one account of the "arrow of time."

When the physical size of a system is scaled down to atomic size, the mathematics of probability can be used to interpret the meaning of the wave model of matter. At this scale, we find that interactions between objects are fundamentally not deterministic as Newton envisioned but can only be described by probabilities, which are calculated from a mathematical description of the wave called a wave function. This accounts for the observed wavelike properties. Although quantum physics is far from intuitive, the probabilistic description of matter at this scale has been fantastically successful in explaining the behavior of atoms and is now being applied at the frontiers of modern technology.

Enduring Understanding 7.C:

At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.

This enduring understanding follows on the heels of Enduring Understandings 1.D and 6.G. Students need to be aware that classical physics cannot describe everything and that there are new, nonclassical ideas that must be addressed for a more complete understanding of the physical world.

The dynamic properties of quantum mechanical systems are expressed in terms of probability distributions. At this scale, we find that interactions between objects are fundamentally not deterministic as Newton envisioned but can only be described by probabilities, which are calculated from the wave function. This gives rise to observed wave properties of matter. One such property is that an electron in an atom has a discrete set of possible energy states. The energy states of the atom can be described in terms of allowable energy transitions due to emission or absorption of photons, processes that are determined by probability. These phenomena are the basis of lasers. The spontaneous radioactive decay of an individual nucleus is described by probability as well. Balancing of mass and charge in nuclear equations can be used to determine missing species in the equation and to explain pair production and annihilation. These ideas can also be used to understand fission and fusion, one current and one possible future source of energy.

Essential Knowledge 7.C.1: The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region. (Qualitative treatment only, using graphical analysis.)

7.C.1.1: The student is able to use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region. **[SP 1.4]**

> *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*

Essential Knowledge 7.C.2: The allowed states for an electron in an atom can be calculated from the wave model of an electron.

a. The allowed electron energy states of an atom are modeled as standing waves. Transitions between these levels, due to emission or absorption of photons, are observable as discrete spectral lines.
b. The de Broglie wavelength of an electron can be calculated from its momentum, and a wave representation can be used to model discrete transitions between energy states as transitions between standing waves.

7.C.2.1: The student is able to use a standing wave model in which an electron orbit circumference is an integer multiple of the de Broglie wavelength to give a qualitative explanation that accounts for the existence of specific allowed energy states of an electron in an atom. **[SP 1.4**]

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Essential Knowledge 7.C.3: The spontaneous radioactive decay of an individual nucleus is described by probability.

a. In radioactive decay processes, we cannot predict when any one nucleus will undergo a change; we can only predict what happens on the average to a large number of identical nuclei.
b. In radioactive decay, mass and energy are interrelated, and energy is released in nuclear processes as kinetic energy of the products or as electromagnetic energy.
c. The time for half of a given number of radioactive nuclei to decay is called the half-life.
d. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years.

7.C.3.1: The student is able to predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay. **[SP 6.4**]

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Essential Knowledge 7.C.4: Photon emission and absorption processes are described by probability.

a. An atom in a given energy state may absorb a photon of the right energy and move to a higher energy state (stimulated absorption).
b. An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon (spontaneous emission).
c. Spontaneous transitions to higher energy states have a very low probability but can be stimulated to occur. Spontaneous transitions to lower energy states are highly probable.
d. When a photon of the right energy interacts with an atom in an excited energy state, it may stimulate the atom to make a transition to a lower energy state with the emission of a photon (stimulated emission). In this case, both photons have the same energy and are in phase and moving in the same direction.

7.C.4.1: The student is able to construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that since the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.] **[SP 1.1, 1.2**]

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.