East Penn School District
Curriculum and Instruction

Curriculum for: Physics 2, Advanced Placement

Course(s): AP Physics 2

Grades: 11-12

Department: Science

Length of Period (average minutes): 42

Periods per cycle: 8

Length of Course (yrs): 1

Type of offering: elective

Credit(s) awarded: 1.4 5.0/4.0

Developed by: The College Board

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Content Outline

Content Area 1: Fluids

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

Big Idea 3: *The interactions of an object with other objects can be described by forces.*

Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system.	**1.A.5.2:** The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**	**1.A.5:** Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an *object*.
1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	**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]** **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]**	**1.E.1:** Matter has a property called density. *Relevant Equation:* $\rho = \frac{m}{V}$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.	**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]**	**EK 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. **Boundary Statement:** *AP Physics 2 has learning objectives under Enduring Understanding* ***3.A*** *that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2 rather than the mechanical systems introduced in Physics 1.*
	3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]** **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]** **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]**	**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. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. (Continued)	**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]** **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]** **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]**	**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.
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.	**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]** **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]**	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ **Boundary Statement:** *AP Physics 2 contains learning objectives under Enduring Understanding **3.B** that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. (Continued)	**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]**	**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. c. 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.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.	**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]** **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]**	**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). *Relevant Equations:* $F_b = \rho V g$ $P = \frac{F}{A}$

Course Framework

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.B: The energy of a system is conserved.	**5.B.10.1:** The student is able to use Bernoulli's equation to make calculations related to a moving fluid. **[SP 2.2]** **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]** **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]** **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]**	**5.B.10:** Bernoulli's equation describes the conservation of energy in fluid flow. The absolute pressure (P) equals atmospheric pressure (P_0) plus the gauge pressure (ρgh). *Relevant Equations:* $P_1 + \rho g y_1 + \frac{1}{2}\rho v_1 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2$ $P = \frac{F}{A}$ $A_1 v_1 = A_2 v_2$ $P = P_0 + \rho g h$
5.F: Classically, the mass of a system is conserved.	**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]**	**5.F.1:** The continuity equation describes conservation of mass flow rate in fluids. Examples include volume rate of flow and mass flow rate. *Relevant Equation:* $A_1 v_1 = A_2 v_2$ **Boundary Statement:** *Fluid viscosity is not part of Physics 1.*

Content Area 2: Thermodynamics

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

Big Idea 3: *The interactions of an object with other objects can be described by forces.*

Big Idea 4: *Interactions between systems can result in changes in those systems.*

Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

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.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system.	**1.A.5.2:** The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**	**1.A.5:** Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an *object*.
1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	**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]**	**1.E.3:** Matter has a property called thermal conductivity. Thermal conductivity is the measure of a material's ability to transfer thermal energy. *Relevant Equation:* $\frac{Q}{\Delta t} = \frac{kA\Delta T}{\Delta L}$
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.	**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]**	**EK 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. **Boundary Statement:** *AP Physics 2 has learning objectives under Enduring Understanding* ***3.A*** *that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. (Continued)	**3.A.3.2:** The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]** **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]** **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]**	**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. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$
	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]** **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]** **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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.	**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]** **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]**	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ **Boundary Statement:** *AP Physics 2 contains learning objectives Enduring Understanding **3.B** that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*
	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]**	**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. c. 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.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.	**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]** **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]**	**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). *Relevant Equations:* $F_b = \rho V g$ $P = \frac{F}{A}$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
4.C: Interactions with other objects or systems can change the total energy of a system.	**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]**	**4.C.3:** Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process through which energy is transferred between systems at different temperatures is called heat. a. Conduction, convection, and radiation are mechanisms for this energy transfer. b. At a microscopic scale the mechanism of conduction is the transfer of kinetic energy between particles. c. During average collisions between molecules, kinetic energy is transferred from faster molecules to slower molecules.
5.B: The energy of a system is conserved.	**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]**	**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.] *Relevant Equation:* $\Delta U_E = q\Delta V$ **Boundary Statement:** *Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.*
	5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **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]**	**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.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.B: The energy of a system is conserved. (Continued)	**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]** **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]** **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]**	**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 energy transfer 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.] The work done on a system is defined as $W = -P\Delta V$ for constant pressure or an average pressure. *Relevant Equations:* $\Delta E = W = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$
	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]**	**5.B.6:** Energy can be transferred by thermal processes involving differences in temperature; this process of transfer is called heat.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.B: The energy of a system is conserved. (Continued)	**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]** **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]** **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]**	**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 include P-V diagrams — isovolumetric process, isothermal process, isobaric process, and adiabatic process. No calculations of thermal energy or internal energy from temperature change are required; in this course, examples of these relationships are qualitative and/or semiquantitative. *Relevant Equations:* $W = -P\Delta V$ $\Delta U = Q + W$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.D: The linear momentum of a system is conserved.	**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]** **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]**	**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 a closed system, the linear momentum is constant throughout the collision. b. In a closed system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision. *Relevant Equations:* $p = mv$ $K = \frac{1}{2}mv^2$ **Boundary Statement:** *Physics 1 includes a quantitative and qualitative treatment of conservation of momentum in one dimension and a semiquantitative treatment of conservation of momentum in two dimensions. Test items involving solution of simultaneous equations are not included in either the Physics 1 or Physics 2 exams, but items testing whether students can set up the equations properly and can reason about how changing a given mass, speed, or angle would affect other quantities are included. Physics 1 includes only conceptual understanding of center of mass motion of a system without the need for calculation of center of mass. Physics 2 includes full qualitative and quantitative two-dimensional treatment of conservation of momentum and velocity of the center of mass of the system. Physics 1 addresses Enduring Understanding* **5.D** *with topics in the context of mechanical systems. Physics 2 does so with content that involves interactions arising in the context of topics such as nuclear decay, other nuclear reactions, and interactions of subatomic particles with each other and with photons.*

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.D: The linear momentum of a system is conserved. (Continued)	**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]** **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]**	**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 a closed system, the linear momentum is constant throughout the collision. b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision. *Relevant Equations:* $p = mv$ $K = \frac{1}{2}mv^2$
7.A: The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure.	**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]** **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]**	**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 or 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. *Relevant Equations:* $P = \frac{F}{A}$ $\Delta p = F\Delta t$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
7.A: The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure. (Continued)	**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.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.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. *Relevant Equation:* $K = \frac{3}{2}k_B T$
	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]** **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]** **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]**	**7.A.3:** In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the ideal gas law $PV = nRT$. *Relevant Equation:* $PV = nRT = Nk_B T$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
7.B: The tendency of isolated systems to move toward states with higher disorder is described by probability.	**7.B.1.1:** The student is able to construct an explanation, based on atomic scale interactions and probability, of how a system approaches thermal equilibrium when energy is transferred to it or from it in a thermal process. **[SP 6.2]**	**7.B.1:** The approach to thermal equilibrium is a probability process. a. The amount of thermal energy needed to change the temperature of an object depends both on the mass of the object and on the temperature change. 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 objects have the same temperature.
	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.B.2:** The second law of thermodynamics describes the change in entropy for reversible and irreversible processes. Only a qualitative treatment is considered in this course. a. Entropy, like temperature, pressure, and internal energy, is a state function, the value of which depends only on the configuration of the system at a particular instant and not on how the system arrived at that configuration. b. Entropy can be described as a measure of the disorder of a system, or of the unavailability of some system energy to do work. c. The entropy of a closed system never decreases, i.e., it can stay the same or increase. d. The total entropy of the universe is always increasing.

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Content Area 3: Electric Force, Field, and Potential

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

Big Idea 2: *Fields existing in space can be used to explain interactions.*

Big Idea 3: *The interactions of an object with other objects can be described by forces.*

Big Idea 4: *Interactions between systems can result in changes in those systems.*

Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system.	**1.A.5.2:** The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**	**1.A.5:** Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an *object.*
1.B: Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge.	**1.B.1.1:** The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]** **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]**	**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. *Relevant Equation:* $I = \frac{\Delta Q}{\Delta t}$ **Boundary Statement:** *Full coverage of electrostatics occurs in Physics 2. A basic introduction to the concepts that there are positive and negative charges, and the electrostatic attraction and repulsion between these charges, is included in Physics 1 as well.*

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.B: Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge. (Continued)	**1.B.2.1:** The student is able to construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]** **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]** **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. **[SP 6.1]**	**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.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.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.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	*[While there is no specific learning objective for it, EK 1.E.4 serves as a foundation for other learning objectives in the course.]*	**1.E.4:** Matter has a property called electric permittivity. a. Free space has a constant value of the permittivity that appears in physical relationships. b. The permittivity of matter has a value different from that of free space.

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.	*[While there is no specific learning objective for it, EK 2.A.1 serves as a foundation for other learning objectives in the course.]*	**2.A.1**: A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector. a. Vector fields are represented by field vectors indicating direction and magnitude. b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition. c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.
	[While there is no specific learning objective for it, EK 2.A.2 serves as a foundation for other learning objectives in the course.]	**2.A.2**: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential. a. Scalar fields are represented by field values. b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition. c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources.
2.C: An electric field is caused by an object with electric charge.	**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]** **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.C.1:** The magnitude of the electric force F exerted on an object with electric charge q by an electric field 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.

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
2.C: An electric field is caused by an object with electric charge. (Continued)	**2.C.2.1:** The student is able to qualitatively and semiquantitatively apply the vector relationship between the electric field and the net electric charge creating that field. **[SP 2.2, 6.4]**	**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.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]**	**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 $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$. 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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
2.C: An electric field is caused by an object with electric charge. (Continued)	**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.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]**	**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. *Relevant Equation:* $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
2.C: An electric field is caused by an object with electric charge. (Continued)	**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]** **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.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]**	**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. *Relevant Equations:* $E = \frac{Q}{\varepsilon_0 A}$ $E = \frac{\Delta V}{\Delta r}$ $\Delta V = \frac{Q}{C}$ $U_C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
2.E: Physicists 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.	**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]**	**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.] *Relevant Equation:* $U_G = -\frac{Gm_1m_2}{r}$
	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]** **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]** **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]**	**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. *Relevant Equation:* $V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
2.E: Physicists 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. (Continued)	**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.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]**	**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. *Relevant Equation:* $E = \frac{\Delta V}{\Delta r}$
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.	**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]**	**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. **Boundary Statement:** *AP Physics 2 has learning objectives under Enduring Understanding* ***3.A*** *that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*
	3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]** **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]** **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]**	**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. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. (Continued)	**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]** **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]** **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]**	**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.
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.	**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]** **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]**	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ **Boundary Statement:** *AP Physics 2 contains learning objectives under Enduring Understanding **3.B** that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. (Continued)	**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]**	**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. c. 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.
3C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.	**3.C.2.1:** The student is able to use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. **[SP 2.2, 6.4]** **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]** **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]**	**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. *Relevant Equations:* $F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$ $F_G = \frac{Gm_1m_2}{r^2}$
3G: Certain types of forces are considered fundamental.	**3.G.1.2:** The student is able to connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces. **[SP 7.1]**	**3.G.1:** Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales. *Relevant Equation:* $F_G = \frac{Gm_1m_2}{r^2}$

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
3G: Certain types of forces are considered fundamental. Continued	**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]**	**3.G.2:** Electromagnetic forces are exerted at all scales and can dominate at the human scale. *Relevant Equation:* $F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
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.	**4.E.3.1:** The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction. **[SP 6.4]** **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]** **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]** **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]** **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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.B: The energy of a system is conserved.	**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]**	**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.] *Relevant Equation:* $\Delta U_E = q\Delta V$ **Boundary Statement:** *Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.*
	5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **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]**	**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. **Boundary Statement:** *Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.*

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.B: The energy of a system is conserved. (Continued)	**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]** **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]** **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]**	**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 energy transfer 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.] The work done on a system is defined as $W = -P\Delta V$ for constant pressure or an average pressure. *Relevant Equations:* $\Delta E = W = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$
5.C: The electric charge of a system is conserved.	**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]** **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]** **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]**	**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).

Content Area 4: Electric Circuits

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

Big Idea 4: *Interactions between systems can result in changes in those systems.*

Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.B: Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge.	**1.B.1.1:** The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]** **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]**	**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. *Relevant Equation:* $I = \frac{\Delta Q}{\Delta t}$ **Boundary Statement:** *Full coverage of electrostatics occurs in Physics 2. A basic introduction to the concepts that there are positive and negative charges, and the electrostatic attraction and repulsion between these charges, is included in Physics 1 as well.*
	1.B.2.1: The student is able to construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]** **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]** **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. **[SP 6.1]**	**EK 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.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up 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]**	**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. *Relevant Equation:* $R = \frac{\rho l}{A}$
4.E: The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects of systems.	**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]** **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.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]**	**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, κ, of the material between the plates and the electric permittivity, ε_0. 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. *Relevant Equations:* $R = \frac{\rho l}{A}$ $C = \kappa\varepsilon_0 \frac{A}{d}$ $I = \frac{\Delta V}{R}$ $\Delta V = \frac{Q}{C}$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
4.E: The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects of systems. (Continued)	**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]** **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]** **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]**	**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. *Relevant Equations:* $I = \frac{\Delta V}{R}$ $R_S = \sum_i R_i$ $\frac{1}{R_P} = \sum_i \frac{1}{R_i}$ $C_P = \sum_i \frac{1}{C_i}$ $\frac{1}{C_S} = \sum_i \frac{1}{C_i}$

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.B: The energy of a system is conserved.	**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. ($\Sigma \Delta V = 0$) **[SP 5.1]** **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]** **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]** **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]** **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]**	**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. *Relevant Equations:* $\Sigma \Delta V = 0$ $\Delta V = IR$ $P = I\Delta V$ **Boundary Statement:** *Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.*

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.C: The electric charge of a system is conserved.	**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]** **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]** **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]** **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]**	**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 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.] *Relevant Equations:* $I = \frac{\Delta V}{R}$ $R_S = \sum_i R_i$ $\frac{1}{R_P} = \sum_i \frac{1}{R_i}$ $C_P = \sum_i \frac{1}{C_i}$ $\frac{1}{C_S} = \sum_i \frac{1}{C_i}$ $I = \Delta Q / \Delta t$

Content Area 5: Magnetism and Electromagnetic Induction

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

Big Idea 2: *Fields existing in space can be used to explain interactions.*

Big Idea 3: *The interactions of an object with other objects can be described by forces.*

Big Idea 4: *Interactions between systems can result in changes in those systems.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system.	**1.A.5.2:** The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**	**1.A.5:** Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an *object*.
1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	*[While there is no specific learning objective for it, EK 1.E.5 serves as a foundation for other learning objectives in the course.]*	**1.E.5:** Matter has a property called magnetic permeability. a. Free space has a constant value of the permeability that appears in physical relationships. b. The permeability of matter has a value different from that of free space.
	[While there is no specific learning objective for it, EK 1.E.6 serves as a foundation for other learning objectives in the course.]	**1.E.6:** Matter has a property called magnetic dipole moment. a. Magnetic dipole moment is a fundamental source of magnetic behavior of matter and an intrinsic property of some fundamental particles such as the electron. b. Permanent magnetism or induced magnetism of matter is a system property resulting from the alignment of magnetic dipole moments within the system.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.	*[While there is no specific learning objective for it, EK 2.A.1 serves as a foundation for other learning objectives in the course.]*	**2.A.1:** A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector. a. Vector fields are represented by field vectors indicating direction and magnitude. b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition. c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.
	[While there is no specific learning objective for it, EK 2.A.2 serves as a foundation for other learning objectives in the course.]	**2.A.2**: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential. a. Scalar fields are represented by field values. b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition. c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources.
2.C: An electric field is caused by an object with electric charge.	**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.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.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
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 of by magnetic dipoles or combinations of dipoles and never by single poles.	**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.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°, and 180° and qualitative for other angles. *Relevant Equations:* $F_M = qv\ X\ B$ $F_M = qv\ sin\theta\ B$
	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]**	**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. c. Determining the force due to the magnetic field from a permanent magnet is a subset of determining the force due to the magnetic field of a current carrying wire. *Relevant Equation:* $B = \frac{\mu_o}{2\pi}\frac{I}{r}$
	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]**	**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 include magnetic field pattern of a bar magnet as detected by iron filings or small compasses. d. The Earth has a magnetic field.

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
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 of by magnetic dipoles or combinations of dipoles and never by single poles. (Continued)	**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]**	**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.
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.	**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]**	**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. **Boundary Statement:** *AP Physics 2 has learning objectives under Enduring Understanding **3.A** that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*
	3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]** **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]** **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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. (Continued)	**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]** **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]** **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]**	**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.
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.	**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]** **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]**	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ **Boundary Statement:** *AP Physics 2 contains learning objectives under Enduring Understanding* ***3.B*** *that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.*

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
3B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. (Continued)	**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]**	**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. c. 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.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.	**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]** **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]**	**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. a. Magnetic dipoles have "north" and "south" polarity. b. The magnetic dipole moment of an object has the tail of the magnetic dipole moment vector at the south end of the object and the head of the vector at the north end of the object. c. In the presence of an external magnetic field, the magnetic dipole moment vector will align with the external magnetic field. d. The force exerted on a moving charged object is perpendicular to both the magnetic field and the velocity of the charge and is described by a right-hand rule. *Relevant Equations:* $F_M = Il \ X \ B$ $F_M = Il \ sin\theta \ B$

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
3.G: Certain types of forces are considered fundamental.	**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]**	**3.G.2:** Electromagnetic forces are exerted at all scales and can dominate at the human scale. *Relevant Equation:* $F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
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.	**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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
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. (Continued)	**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]**	**4.E.2:** Changing magnetic 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. *Relevant Equations:* $\Phi_B = BA$ $\Phi_B = B \cos\theta \, A$ $\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$ $\varepsilon = Blv$

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Content Area 6: Geometric and Physical Optics

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.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
6.A: A wave is a traveling disturbance that transfers energy and momentum.	**6.A.1.2:** The student is able to describe representations of transverse and longitudinal waves. **[SP 1.2]** **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]**	**6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal. a. Mechanical waves can either be transverse or longitudinal. Examples include waves on stretched strings and sound waves. b. Electromagnetic waves are transverse waves. c. Transverse waves may be polarized. **Boundary Statement:** *Physics 1 treats mechanical waves only. Mathematical modeling of waves using sines or cosines is included in Physics 2. Superposition of no more than two wave pulses and properties of standing waves is evaluated in Physics 1. Interference is revisited in Physics 2, where two-source interference and diffraction may be demonstrated with mechanical waves, leading to the development of these concepts in the context of electromagnetic waves, the focus of Physics 2.*
	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.A.2:** For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples include light traveling through a vacuum and sound not traveling through a vacuum.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
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.	**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]**	**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. *Relevant Equation:* $x = A\cos(\omega t) = A\cos(2\pi\ ft)$
6.C: Only waves exhibit interference and diffraction.	**6.C.1.1:** The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]** **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]**	**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. Examples include interference resulting from diffraction through slits as well as thin film interference.
	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]**	**6.C.2:** When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed. *Relevant Equations:* $\Delta L = m\lambda$ $d\sin\theta = m\lambda$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
6.C: Only waves exhibit interference and diffraction. (Continued)	**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]**	**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 include monochromatic double-slit interference.
	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.C.4:** When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples include hearing around corners, but not seeing around them, and water waves bending around obstacles.
6E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.	**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.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.)

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
6E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media. (Continued)	**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.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. *Relevant Equations:* $\frac{1}{s_i}+\frac{1}{s_o}=\frac{1}{f}$ $\lvert M\rvert=\left\lvert\frac{h_i}{h_o}\right\rvert=\left\lvert\frac{s_i}{s_o}\right\rvert$
	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]** **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]** **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.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. *Relevant Equations:* $n=\frac{c}{v}$ $n_1\sin\theta_1=n_2\sin\theta_2$

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
6E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media. (Continued)	**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]** **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]**	**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. Examples include concave and convex mirrors. b. Ray diagrams 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. *Relevant Equations:* $\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$ $\lvert M \rvert = \left\lvert \frac{h_i}{h_o} \right\rvert = \left\lvert \frac{s_i}{s_o} \right\rvert$
	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]** **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]**	**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. Examples include converging and diverging lenses. *Relevant Equations:* $\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$ $\lvert M \rvert = \left\lvert \frac{h_i}{h_o} \right\rvert = \left\lvert \frac{s_i}{s_o} \right\rvert$

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.	**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.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. *Relevant Equation:* $\lambda = \frac{v}{f}$
	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]**	**6.F.2:** Electromagnetic waves can transmit energy through a medium and through a vacuum. a. Electromagnetic waves are transverse waves composed of mutually perpendicular electric and magnetic fields that can propagate through a vacuum. b. The planes of these transverse waves are both perpendicular to the direction of propagation.

Content Area 7: Quantum, Atomic, and Nuclear Physics

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

Big Idea 3: *The interactions of an object with other objects can be described by forces.*

Big Idea 4: *Interactions between systems can result in changes in those systems.*

Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

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.*

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.*

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system.	**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.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.
	[While there is no specific learning objective for it, EK 1.A.3 serves as a foundation for other learning objectives in the course.]	**1.A.3:** Nuclei have internal structures that determine their properties. a. The number of protons identifies the element. b. The number of neutrons together with the number of protons identifies the isotope. c. There are different types of radioactive emissions from the nucleus. d. The rate of decay of any radioactive isotope is specified by its half-life.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.A: The internal structure of a system determines many properties of the system. (Continued)	**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.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.C: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.	**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]**	**1.C.4:** In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.
1.D: Classical mechanics cannot describe all properties of objects.	**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]**	**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. *Relevant Equation:* $\lambda = \frac{h}{p}$
	[While there is no specific learning objective for it, EK 1.D.2 serves as a foundation for other learning objectives in the course.]	**1.D.2:** Certain phenomena classically thought of as waves can exhibit properties of particles. a. The classical models of waves do not describe the nature of a photon. b. Momentum and energy of a photon can be related to its frequency and wavelength.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
1.D: Classical mechanics cannot describe all properties of objects. (Continued)	**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]**	**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.) *Relevant Equation:* $E = mc^2$
3.G: Certain types of forces are considered fundamental.	**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]**	**3.G.3:** The strong force is exerted at nuclear scales and dominates the interactions of nucleons.
4.C: Interactions with other objects or systems can change the total energy of a system.	**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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.B: The energy of a system is conserved.	**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]**	**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.] *Relevant Equation:* $\Delta U_E = q\Delta V$ **Boundary Statement:** *Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.*
	5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **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]**	**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.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]**	**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 energy transfer 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.] The work done on a system is defined as $W = -P\Delta V$ for constant pressure or an average pressure. *Relevant Equations:* $\Delta E = W = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.B: The energy of a system is conserved. (Continued)	**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]**	**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.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]**	**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.C: The electric charge of a system is conserved.	**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]**	**5.C.1:** Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples include equations representing nuclear decay.

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
5.D: The linear momentum of a system is conserved.	**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]** **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]**	**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 a closed system, the linear momentum is constant throughout the collision. b. In a closed system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision. *Relevant Equations:* $p = mv$ $K = \frac{1}{2}mv^2$ **Boundary Statement:** *Physics 1 includes a quantitative and qualitative treatment of conservation of momentum in one dimension and a semiquantitative treatment of conservation of momentum in two dimensions. Test items involving solution of simultaneous equations are not included in either the Physics 1 or Physics 2 exams, but items testing whether students can set up the equations properly and can reason about how changing a given mass, speed, or angle would affect other quantities are included. Physics 1 includes only conceptual understanding of center of mass motion of a system without the need for calculation of center of mass. Physics 2 includes full qualitative and quantitative two-dimensional treatment of conservation of momentum and velocity of the center of mass of the system. Physics 1 addresses Enduring Understanding* ***5.D*** *with topics in the context of mechanical systems. Physics 2 does so with content that involves interactions arising in the context of topics such as nuclear decay, other nuclear reactions, and interactions of subatomic particles with each other and with photons.*

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Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.D: The linear momentum of a system is conserved. (Continued)	**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]** **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]**	**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 a closed system, the linear momentum is constant throughout the collision. b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision. *Relevant Equations:* $p = mv$ $K = \frac{1}{2}mv^2$
	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]** **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]**	**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. *Relevant Equation:* $x_{cm} = \frac{\Sigma m_i x_i}{\Sigma m_i}$

Enduring Understanding (Core concepts that students should retain)	**Learning Objectives** (What students must be able to do)	**Essential Knowledge** (What students need to know)
5.G: Nucleon number is conserved.	**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]**	**5.G.1:** The possible nuclear reactions are constrained by the law of conservation of nucleon number.
6.C: Only waves exhibit interference and diffraction.	**6.C.1.1:** The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]** **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]**	**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. Examples include interference resulting from diffraction through slits as well as thin film interference.
	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]**	**6.C.2:** When waves pass through an opening whose dimensions are comparable to the wavelength a diffraction pattern can be observed. *Relevant Equations:* $\Delta L = m\lambda$ $d\sin\theta = m\lambda$

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
6.C: Only waves exhibit interference and diffraction. (Continued)	**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]**	**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 include monochromatic double-slit interference.
	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.C.4:** When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples include hearing around corners, but not seeing around them, and water waves bending around obstacles.
6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.	**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.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, emission increases with the frequency and not the intensity of absorbed radiation. The photoelectric effect should be included as an example. *Relevant Equation:* $K_{max} = hf - \Phi$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles. (Continued)	**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.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.G: All matter can be modeled as waves or as particles.	**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.G.1:** Under certain regimes of energy or distance, matter can be modeled as a classical particle.
	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.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.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. *Relevant Equation:* $\lambda = \frac{h}{p}$

Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
7.C: At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.	**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]**	**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.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]**	**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. *Relevant Equation:* $\lambda = \frac{h}{p}$
	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]**	**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.

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Enduring Understanding (Core concepts that students should retain)	Learning Objectives (What students must be able to do)	Essential Knowledge (What students need to know)
7.C: At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world. (Continued)	**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]**	**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.

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