Correlation with the 2019 Updated AP® Physics Curriculum Framework

College Physics,
AP® Edition

ELEVENTH EDITION

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Unit 1: Kinematics

Suggested Length: Twenty-five 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 1.1: Position, Velocity, and Acceleration	**3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. **3.A.1.1:** Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]** **3.A.1.2:** Design an experimental investigation of the motion of an object. **[SP 4.2]** **3.A.1.3:** Analyze experimental data describing the motion of an object and be able to express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**.	**3.A.1:** An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed and acceleration. a. Displacement, velocity and acceleration are all vector quantities b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values. $\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$ c. A choice of reference frame determines the direction and the magnitude of each of these quantities d. There are three fundamental interactions or forces in nature; the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects. e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force. f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both	2.1, pp. 31–41 2.3, pp. 42–52 3.1–3.2, pp. 59–68 4.1–4.7, pp. 80–110 7.2, pp. 194–195 7.3–7.4, pp. 198–206 30.3, pp. 939–940

		included. Circular motion is further covered in Unit 3. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are: $v_x = v_{x0} + a_x t$ $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ g. For rotational motion there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are: $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$ $\omega = \omega_0 + \alpha t$ $\omega^2 = \omega_0^2 + 2\alpha_x(\theta - \theta_0)$	
Topic 1.2: Representations of Motion	**4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **4.A.1.1:** Use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semi-quantitatively. **[SP 1.2, 1.4, 2.3, 6.4]** *Tested in Unit 2.*	**SP4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. a. The variables x, v, and a all refer to the center-of-mass quantities. $v = v + at$ $x = x_0 + v_0 t + \frac{1}{2}at^2$ $v^2 = v_0^2 + 2a\Delta x$	3.2, p. 66 5.7, pp. 147–148 8.2, pp. 228–233
	4.A: The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **4.A.2.1:** Make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. **[SP 6.4]**	**4.A.2**: The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time. a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system. b. Force and acceleration are both vectors, with acceleration in the same direction as the net force. c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of	2.1–2.4, pp. 31–53 3.1–3.3, pp. 59–73 4.1–4.2, pp. 80–86

	4.A.2.3: Create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system. **[SP 1.4, 2.2]** *This is more about the center of mass being representative of an object and not about the focus of center of mass, i.e., momentum ideas.*	change of position of the center of mass with time. d. The variables *x*, *v*, and a all refer to the center-of-mass quantities. $\vec{a} = \frac{\Sigma \vec{F}}{m_{system}}$ $\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$	

Unit 2: Dynamics

Suggested Length: Twenty 45-minute classes

- **Big Idea 1:** Objects and systems have properties such as mass and charge.
- **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

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 2.1: Systems	**1.A:** The internal structure of a system determines many properties of the system. *[While there is no specific learning objective for it, EK1.A.1 serves as a foundation for other learning objectives in the course.]*	**1.A.1:** A system is an object or a collection of objects. Objects are treated as having no internal structure. a. A collection of particles in which internal interactions change little or not at all, or in which changes in these interactions are irrelevant to the question addressed, can be treated as an object. b. Some elementary particles are fundamental particles, (e.g., electrons). Protons and neutrons are composed of fundamental particles (i.e., quarks) and might be treated as either systems or objects, depending on the question being addressed. c. The electric charges on neutrons and protons result from their quark compositions.	1.2, pp. 3–4 2.1, pp. 32, 40 3.2, pp. 65–66 4.3–4.7, pp. 92–110 5.3, p. 129 5.6, pp. 142–144
	1.A: The internal structure of a system determines many properties of the system. **1.A.5.1:** Model verbally or visually the properties of a system based on its substructure and relate this to changes in the system properties over time as external variables are changed. **[SP 1.1, 7.1]**	**1.A.5:** Systems have properties that are 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.	2.1, pp. 32, 40 3.2, pp. 65–66 4.3–4.7, pp. 92–110 5.3, p. 129 5.6, pp. 142–144

Topic 2.2: The Gravitational Field	**2.B:** A gravitational field is caused by an object with mass. **2.B.1.1:** Apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass *m* in a gravitational field of strength *g* in the context of the effects of a net force on objects and systems. **[SP: 2.2, 7.2]**	**2.B.1:** A gravitational field $\vec{g}$ at the location of an object with mass *m* causes a gravitational force of magnitude *mg* to be exerted on the object in the direction of the field. a. On Earth, this gravitational force is called weight. b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force. c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location. $\vec{g} = \frac{\vec{F}_g}{m}$	4.1, p. 81 4.2–4.3, pp. 86–94 4.6-4.7, pp. 102–110 5.1, p. 124 5.3, pp. 130–131
Topic 2.3: Contact Forces	**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:** Make claims about various contact forces between objects based on the microscopic cause of these forces. **[SP 6.1]** **3.C.4.2:** 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). $\left\|\vec{F}_f\right\| \le \mu\left\|\vec{F}_n\right\|$ $\left\|\vec{F}_s\right\| = k\left\|\vec{x}\right\|$	4.1, pp. 80–81
Topic 2.4: Newton's First Law	**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.1.1:** Design an experiment for collecting data to determine the relationship between the	**1.C.1:** Inertial mass is the property of an object or system that determines how its motion changes when it interacts with other objects or systems. a. $\vec{a} = \frac{\Sigma\vec{F}}{m}$	4.2, p. 83 26.8, p. 856

	net force exerted on an object, its inertial mass, and its acceleration. **[SP 4.2]**		
	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.3.1:** Design a plan for collecting data to measure gravitational mass and inertial mass and to distinguish between the two experiments. **[SP 4.2]**	**1.C.3:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.	4.2, p. 83 26.8, p. 856
Topic 2.5: Newton's Third Law and Free Body Diagrams	**3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. **3.A.2.1:** 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.	1.9–1.10 pp. 16–23 4.2, p. 83
	3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. **3.A.3.1:** Analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]** **3.A.3.2:** Challenge a claim that an object can exert a force on itself. **[SP 6.1]** **3.A.3.3:** Describe a force as an interaction between two objects, and identify both objects for any force. **[SP 1.4]**	**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.	4.1–4.2, pp. 80–92

	3.A: All forces share certain common characteristics when considered by observers in inertial reference frames. **3.A.4.1:** 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:** 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:** 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.	4.2, pp. 89–92
Topic 2.6: Newton's Second Law	**3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma \vec{F}}{m}$. **3.B.1.1:** 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, with acceleration in one dimension. **[SP 6.4, 7.2]** **3.B.1.2:** Design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurement and carry out an analysis to determine the relationship between the net force and the vector sum of the	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. Projectile motion and circular motion are both included in AP Physics 1. $\vec{a} = \frac{\Sigma \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ **Boundary Statement:** *AP Physics 2 contains learning objectives for Enduring Understanding **3.B.** that focuses 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.*	4.2, pp. 83–86

	individual forces. **[SP 4.2, 5.1]** **3.B.1.3:** Reexpress a free-body diagram into a mathematical representation and solve the mathematical representation for the acceleration of the object. **[SP 1.5, 2.2]**		
	3.B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **3.B.2.1:** 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 were extracted from its environment and the interactions with the environment were 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. d. Free-body or force diagrams may be depicted in one of two ways: one in which the forces exerted on an object are represented as arrows pointing outward from a dot, and the other in which the forces are specifically drawn at the point on the object at which each force is exerted.	4.2, pp. 91–94 4.5–4.6, pp. 98–101, 104 4.7, pp. 107–109
Topic 2.7: Applications of Newton's Second Law	**4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **4.A.1.1:** Use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semi-quantitatively. **[SP 1.2, 1.4, 2.3, 6.4]**	**4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities. $v = v + at$ $x = x_0 + v_0 t + \frac{1}{2}at^2$ $v^2 = v_0^2 + 2a\Delta x$	3.2, p. 66 5.5, pp. 140–141 5.8, p. 148 8.2, pp. 228–233

	4.A: The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **4.A.2.2:** Evaluate, using given data, whether all the forces on a system or all the parts of a system have been identified. **[SP 5.3]**	**4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time. a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system. $\vec{a} = \frac{\Sigma\vec{F}}{m_{system}}$ b. Force and acceleration are both vectors, with acceleration in the same direction as the net force. $\vec{v}_{avg} = \frac{\Delta\vec{x}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta\vec{v}}{\Delta t}$ c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of the position of the center of mass with time. *[Subsection c of the Essential Knowledge is not directly addressed in this edition of* College Physics*.]* d. The variables a, v, and a all refer to the center of mass quantities. $\vec{a} = \frac{\Sigma\vec{F}}{m_{system}} = \frac{\vec{F}_{net}}{m}$	2.1–2.4, pp. 31–53 3.1–3.2, pp. 59–68 4.2, p. 84 8.2, pp. 228–233
	4.A: The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma\vec{F}}{m}$. **4.A.3.1:** Apply Newton's second law to systems to calculate the change in the center-of-mass velocity	**4.A.3:** Forces that the systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system. $\vec{a} = \frac{\Sigma\vec{F}}{m_{system}} = \frac{\vec{F}_{net}}{m}$	8.2, pp. 232–233

	when an external force is exerted on the system. **[SP 2.2]** **4.A.3.2:** Use visual or mathematical representations of the forces between objects in a system to predict whether or not there will be a change in the center-of-mass velocity of that system. **[SP 1.4]**		

Unit 3: Circular Motion and Gravitation

Suggested Length: Thirteen 45-minute classes

- **Big Idea 1:** Objects and systems have properties such as mass and charge.
- **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

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 3.1: Vector Fields	**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 locations of sources. **Boundary Statement:** *Physics 1 treats gravitational fields; Physics 2 treats electric and magnetic fields.*	1.9, pp. 16–23 4.1, pp. 81–82
Topic 3.2: Fundamental Forces	**3.G:** Certain types of forces are considered fundamental. **3.G.1.1:** Articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. **[SP 7.1]**	**3.G.1:** Gravitational forces are exerted at all scales and dominate at the largest distances and mass scales	7.5, pp. 206–215
Topic 3.3: Gravitational and Electric Forces	**3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. **3.C.1.1:** Use Newton's law of gravitation to calculate the gravitational force that two objects exert on each other and use that force in contexts other than orbital motion. **[SP 2.2]**	**3.C.1:** Gravitational force describes the interaction of one object with mass with another object with mass. a. The gravitational force is always attractive. b. The magnitude of force between two spherically symmetric objects of mass m_1 and m_2 is $\frac{Gm_1m_2}{r^2}$ where r is the center-to-center distance between the objects.	4.2, pp. 86–87

	3.C.1.2: Use Newton's law of gravitation to calculate the gravitational force between two objects and use that force in contexts involving orbital motion (for circular orbital motion only in Physics 1). **[SP 2.2]** **3.C.2.2:** Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**	c. In a narrow range of heights above the Earth's surface, the local gravitational field, *g*, is approximately constant. $\lvert F_g \rvert = \frac{Gm_1m_2}{r^2}$ $\vec{g} = \frac{\vec{F}_g}{m}$	
Topic 3.4: Gravitational Field and Acceleration Due to Gravity on Different Planets	**2.B:** A gravitational field is caused by an object with mass. **2.B.1.1:** Apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass *m* in a gravitational field of strength *g* in the context of the effects of a net force on objects and systems. **[SP 2.2 7.2]**	**2.B.1:** A gravitational field $\vec{g}$ at the location of an object with mass *m* causes a gravitational force of magnitude *mg* to be exerted on the object in the direction of the field. a. On Earth, this gravitational force is called weight. b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force. c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location. $\vec{g} = \frac{\vec{F}_g}{m}$	4.1, p. 81 4.2, pp. 86–96 4.6–4.7, pp. 102–112 5.3, pp. 130–131
	2.B: A gravitational field is caused by an object with mass. **2.B.2.1:** Apply $g = \frac{GM}{r^2}$ to calculate the gravitational field due to an object with mass *M*, where the field is a vector directed toward the center of the object of mass *M*. **[SP 2.2]** **2.B.2.2:** Approximate a numerical value of the	**2.B.2:** The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object. a. The gravitational field cause by a spherically symmetric object is a vector whose magnitude outside the object is equal to $\frac{GM}{r^2}$ b. Only spherically symmetric objects will be	4.2, pp. 86–88

	gravitational field (g) near the surface of an object from its radius and mass relative to those of the Earth or other reference objects. **[SP 2.2]**	considered as sources of the gravitational field. $\vec{a} = \frac{\Sigma \vec{F}}{m_{system}} = \frac{\vec{F}_{net}}{m}$	
Topic 3.5: Inertial vs. Gravitational Mass	**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. *[While there is no specific learning objective for it, EK 1.C.2 serves as a foundation for other learning objectives in the course.]*	1.C.2: Gravitational mass is the property of an object or a system that determines the strength of the gravitational interaction with other objects, systems, or gravitational fields. a. The gravitational mass of an object determines the amount of force exerted on the object by a gravitational field. b. Near the Earth's surface, all objects fall (in a vacuum) with the same acceleration, regardless of their inertial mass.	26.8, pp. 856–857
	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.3.1:** Design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]**	**1.C.3:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.	26.8, pp. 856–857
Topic 3.6: Centripetal Acceleration and Centripetal Force	**4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\Sigma \vec{F}}{m}$. **4.A.2.2:** Evaluate, using given data, whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]**	**4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time. a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system. b. Force and acceleration are both vectors, with acceleration in the same direction as the net force. $\vec{a} = \frac{\Sigma \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$	2.1–2.4, pp. 31–53 3.1–3.2, pp. 59–68 4.2, p. 84

Topic 3.7: Free-Body Diagrams for Objects in Uniform Circular Motion	**3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma \vec{F}}{m}$. **3.B.1.2:** Design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]** **3.B.1.3:** Reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. **[SP1.5, 2.2]**	**3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. **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.*	4.2, pp. 84–86
	3.B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma \vec{F}}{m}$. **3.B.2.1:** 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 were extracted from its environment and the interactions with the environment were 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.	4.2, pp. 91–94 4.5–4.6, pp. 98–101, 104 4.7, pp. 107–109
Topic 3.8: Applications of Circular Motion and Gravitation	**3.A:** All forces share common characteristics when considered by observers in inertial reference frames **3.A.1.1:** Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1,**	**3.A.1:** An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed and acceleration. a. Displacement, velocity and acceleration are all vector quantities b. Displacement is change in position. Velocity is the rate of change of position with time.	2.1, pp. 31–41 2.3, pp. 42–52 3.1–3.2, pp. 59–68 4.1–4.7, pp. 80–110

	2.2] **3.A.1.2:** Design an experimental investigation of the motion of an object. **[SP 4.2]** **3.A.1.3:** Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**	Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values. $\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$ c. A choice of reference frame determines the direction and the magnitude of each of these quantities d. There are three fundamental interactions or forces in nature; the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects. e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So, force, like velocity is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force. f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are: $v_x = v_{x0} + a_x t$ $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ g. For rotational motion there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are: $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$ $\omega = \omega_0 + \alpha t$ $\omega^2 = \omega_0^2 + 2\alpha_x(\theta - \theta_0)$	 7.2, pp. 194–195 7.3–7.4, pp. 198–206 30.3, pp. 939–940

	3.A: All forces share common characteristics when considered by observers in inertial reference frames **3.A.2.1:** Represent forces in diagrams or mathematically, using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP1.1]**	**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.	4.2, p. 83
	3.A: All forces share common characteristics when considered by observers in inertial reference frames **3.A.3.1:** Analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]** **3.A.3.3:** Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**	**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.	4.1–4.2, pp. 80–92
	3.A: All forces share common characteristics when considered by observers in inertial reference frames **3.A.4.1:** 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:** 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:** Analyze situations involving interactions among	**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.	4.2, pp. 89–92

	several objects by using free-body diagrams that include the application of Newton's third law to identify forces. [**SP 1.4**]		
Topic 3.9: Introduction to Topic Energy	**4.C:** Interactions with other objects or systems can change the total energy of a system. **4.C.1.1:** Calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]** **4.C.1.2:** Predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. **[SP 6.4]**	**4.C.1:** The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples include gravitational potential energy, elastic potential energy, and kinetic energy. a. A rotating, rigid body may be considered to be a system and may have both translational and rotational kinetic energy. b. Although thermodynamics is not part of Physics 1, included is the idea that, during an inelastic collision, some of the mechanical energy dissipates as (converts to) thermal energy. $K = \frac{1}{2}mv^2$ $K = \frac{1}{2}I\omega^2$ $\Delta U_g = mg\Delta y$ $U_G = -\frac{Gm_1m_2}{r}$ $U_s = \frac{1}{2}kx^2$	5.2, pp. 126–135 5.5, pp. 137–142 7.5, p. 209 8.5, pp. 246–247
	4.C: Interactions with other objects or systems can change the total energy of a system. **4.C.2.1:** Make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. **[SP 6.4]** **4.C.2.2:** Apply the concepts of conservation of energy and the work-energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. **[SP 1.4, 2.2, 7.2]**	**4.C.2:** Mechanical energy (the sum of kinetic and potential energy) is transferred into or out of a system when an external force is exerted on a system such that a component of the force is parallel to its displacement. The process through which the energy is transferred is called work. a. If the force is constant during a given displacement, then the work done is the product of the displacement and the component of the force parallel or antiparallel to the displacement. $W = F_{\parallel}d$ b. Work (change in energy) can be found from the area under a graph of the magnitude of the force component parallel to the displacement versus displacement. $\Delta E = W = F_{\parallel}d = Fd\cos\theta$	5.1, pp. 121–122 5.8, pp. 149–151

Unit 4: Energy

Suggested Length: Thirteen 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 4.1: Open and Closed Systems – Energy	**5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. *[While there is no specific learning objective for it, EK 5.A.1 serves as a foundation for other learning objectives in the course.]*	**5.A.1:** A system is an object or a collection of objects. The objects are treated as having no internal structure.	4.2, pp. 82–92 4.6, pp. 100–110 5.3, pp. 29–135 5.6, pp. 142–144
	5.A: Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. **5.A.2.1:** Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**	**5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.	5.6, pp. 142–144 6.2, pp. 166–169 8.6, pp. 249–252 18.4, pp. 599–602
	5.A: Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. *[While there is no specific learning objective for it, EK 5.A.3 serves as a foundation*	**5.A.3:** An interaction can be either a force exerted by objects outside the system or the transfer of some quantity with objects outside the system.	4.1, pp. 80–82 5.1, pp. 121–124

	for other learning objectives in the course.]		
	5.A: Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. *[While there is no specific learning objective for it, EK 5.A.4 serves as a foundation for other learning objectives in the course.]*	**5.A.4:** The placement of a boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis.	4.3, pp. 92–110

Topic 4.2: Work and Mechanical Energy	**3.E:** A force exerted on an object can change the kinetic energy of the object
	
	3.E.1.1: Make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. **[SP 6.4, 7.2]**
	
	3.E.1.2: Use net force and velocity vectors to determine qualitatively whether the kinetic energy of an object would increase, decrease, or remain unchanged. **[SP 1.4]**
	
	3.E.1.3: Use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether the kinetic energy of that object would increase, decrease, or remain unchanged. **[SP 1.4, 2.2]**
	
	3.E.1.4: Apply mathematical routines to determine the change in kinetic energy of an object given the forces on the object and the displacement of the object. **[SP 2.2]**
		3.E.1: The change in the kinetic energy of an object depends on the force exerted on the object and on the displacement of the object during the interval that the force is exerted.
		
		a. Only the component of the net force exerted on an object parallel or antiparallel to the displacement of the object will increase (parallel) or decrease (antiparallel) the kinetic energy of the object.
		b. The magnitude of the change in the kinetic energy is the product of the magnitude of the displacement and of the magnitude of the component of force parallel or antiparallel to the displacement.
		
		$\Delta E = W = F_{//}d$
		
		c. The component of the net force exerted on an object perpendicular to the direction of the displacement of the object can change the direction of the motion of the object without changing the kinetic energy of the object. This should include uniform circular motion and projectile motion.
		d. The kinetic energy of a rigid system may be translational, rotational, or a combination of both. The change in the rotational kinetic energy of a rigid system is the product of the angular displacement and the net torque.
		
		$K = \frac{1}{2}mv^2$
		$\Delta E = W = F_{//}d = Fd\cos\theta$
			5.2, pp. 126–135
			
			8.5, pp. 246–248

	4.C: Interactions with other objects or systems can change the total energy of a system. **4.C.1.1:** Calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]** **4.C.1.2:** Predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. **[SP 6.4]**	**4.C.1:** The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples include gravitational potential energy, elastic potential energy, and kinetic energy. a. A rotating, rigid body may be considered to be a system and may have both translational and rotational kinetic energy. b. Although thermodynamics is not part of Physics 1, included is the idea that, during an inelastic collision, some of the mechanical energy dissipates as (converts to) thermal energy. $K = \frac{1}{2}mv^2$ $K = \frac{1}{2}I\omega^2$ $\Delta U_g = mg\Delta y$ $U_G = -\frac{Gm_1m_2}{r}$ $U_s = \frac{1}{2}kx^2$	5.2, pp. 126–135 5.5, pp. 137–142 7.5, pp. 209–211 8.5, pp. 246–247
	4.C: Interactions with other objects or systems can change the total energy of a system. **4.C.2.1:** Make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. **[SP 6.4]** **4.C.2.2:** Apply the concepts of conservation of energy and the work-energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. **[SP 1.4, 2.2, 7.2]**	**4.C.2:** Mechanical energy (the sum of kinetic and potential energy) is transferred into or out of a system when an external force is exerted on a system such that a component of the forces is parallel to its displacement. The process through which the energy is transferred is called work. a. If the force is constant during a given displacement, then the work done is the product of the displacement and the component of the force parallel or antiparallel to the displacement. $W = F_{\parallel}d$ b. Work (change in energy) can be found from the area under a graph of the magnitude of the force component parallel to the displacement versus displacement. $\Delta E = W = F_{\parallel}d = Fd\cos\theta$	5.1, pp. 121–122 5.8, pp. 149–151

Topic 4.3: Conservation of Energy The Work-Energy Principle Power	**5.B:** The energy of a system is conserved. **5.B.1.1:** Create a representation or model showing that a single object can only have kinetic energy and use information about that object to calculate its kinetic energy. **[SP 1.4, 2.2]** **5.B.1.2:** Translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. **[SP 1.5]**	**5.B.1:** Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects. $K = \frac{1}{2}mv^2$ **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.*	5.2, pp. 126–129
	5.B: The energy of a system is conserved. **5.B.2.1:** 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 objects in electric fields and examining changes in internal energy with changes in configuration.]	13.1–13.5, pp. 424–440
	5.B: The energy of a system is conserved. **5.B.3.1:** Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]** **5.B.3.2:** Make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]** **5.B.3.3:** Apply mathematical	**5.B.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces. a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system. b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators and objects falling in a gravitational field. c. The change in electric potential in a circuit is the change in potential energy per unit	5.3–5.6, pp. 129–144 7.5, p. 211 16.1, pp. 527–529

	reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**	charge. *[In Physics 1 only in the context of circuits.]* $\Delta U_g = mg\Delta y$ $U_s = \frac{1}{2}kx^2$	
	5.B: The energy of a system is conserved. **5.B.4.1:** Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **5.B.4.2:** 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.	5.2–5.3, pp. 126–135 5.5, pp. 137–142
	5.B: The energy of a system is conserved. **5.B.5.1:** Design an experiment and analyze data to determine how a force exerted on an object or system does work on the object or system as it moves through a distance. **[SP 4.2, 5.1]** **5.B.5.2:** Design an experiment and analyze graphical data in which interpretations of the area under a force-distance curve are needed to determine the work done on or by the object or system. **[SP 4.2, 5.1]** **5.B.5.3:** Predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance. **[SP 1.4, 2.2, 6.4]**	**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 part of thermodynamics.]* $\Delta E = W = F_{\parallel}d = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$	5.1–5.8, pp. 121–152

	5.B.5.4: 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:** 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]**		
Topic 4.4: Kinetic Energy in Elastic and Inelastic Collisions	**5.D:** The linear momentum of a system is conserved. **5.D.1.1:** Make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]** **5.D.1.2:** Apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]** **5.D.1.3:** Apply mathematical routines appropriately to problems involving elastic	**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. $\vec{p} = m\vec{v}$ $K = \frac{1}{2}mv^2$	5.3, pp. 132–133 6.2–6.3, pp. 166–176

	collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]** **5.D.1.4:** Design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]** **5.D.1.5:** 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: The linear momentum of a system is conserved. **5.D.2.1:** Qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]** **5.D.2.3:** 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. $\vec{p} = m\vec{v}$ $K = \frac{1}{2}mv^2$	6.1–6.2, pp. 166–176

Unit 5: Momentum

Suggested Length: Thirteen 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 5.1: Momentum and Impulse	**3.D:** A force exerted on an object can change the momentum of the object. **3.D.1.1:** Justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. **[SP 4.1]**	**3.D.1:** The change in momentum of an object is a vector in the direction of the net force exerted on the object. $\vec{p} = m\vec{v}$	6.1, pp. 161–163
	3.D: A force exerted on an object can change the momentum of the object. **3.D.2.1:** Justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. **[SP 2.1]** **3.D.2.2:** Predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 6.4]** **3.D.2.3:** Analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 5.1]** **3.D.2.4:** Design a plan for	**3.D.2:** The change in momentum of an object occurs over a time interval. a. The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object). b. The change in momentum of that object depends on the impulse, which is the product of the average force and the time interval during which the interaction occurred. $\vec{p} = m\vec{v}$	6.1, pp. 161–166

	collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. **[SP 4.2]**		
Topic 5.2: Representations of Changes in Momentum	**4.B:** Interactions with other objects or systems can change the total linear momentum of a system. **4.B.1.1:** Calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). **[SP 1.4, 2.2]** **4.B.1.2:** Analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. **[SP 5.1]**	**4.B.1:** The change in linear momentum for a constant-mass system is the product of the mass of the system and the change in velocity of the center of mass. $\vec{p} = m\vec{v}$	6.1, pp. 161–162
	4.B: Interactions with other objects or systems can change the total linear momentum of a system. **4.B.2.1:** Apply mathematical routines to calculate the change in momentum of a system by analyzing the average force exerted over a certain time on the system. **[SP 2.2]** **4.B.2.2:** Perform an analysis on data presented as a force-time graph and predict the change in momentum of a system. [**SP 5.1]**	**4.B.2:** The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted. a. The units for momentum are the same as the units of the area under the curve of a force versus time graph. b. The change in linear momentum and force are both vectors in the same direction. $\vec{p} = m\vec{v}$ $\vec{p} = \vec{F}\Delta t$	6.1, pp. 161–166
Topic 5.3: Open and Closed Systems – Momentum	**5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. **5.A.2.1:** Define open and closed	**5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.	5.6, pp. 142–144 6.2, pp. 166–169 8.6, pp. 249–252 18.4, pp. 599–

	systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**		602
Topic 5.4: Conservation of Linear Momentum	**5.D:** The linear momentum of a system is conserved. **5.D.1.1:** Make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]** **5.D.1.2** Apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]** **5.D.1.3:** Apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]** **5.D.1.4:** Design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data	**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. $\vec{p} = m\vec{v}$ $K = \frac{1}{2}mv^2$ **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 Physics 1, 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 the center of mass motion of a system without the need for calculation of center of mass.* *The Physics 1 course includes topics from Enduring Understanding 5.D in the context of mechanical systems.*	5.3, p. 132 6.2–6.3, pp. 166–176

	generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]** **5.D.1.5:** 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: The linear momentum of a system is conserved. **5.D.2.1:** Qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]** **5.D.2.2:** Plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. **[SP 4.1, 4.2, 5.1]** **5.D.2.3:** 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.2.4:** Analyze data that verify conservation of momentum in collisions with and without an external frictional force. **[SP 4.1, 4.2, 4.4, 5.1, 5.3]** **5.D.2.5:** Classify a given collision	**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. $\vec{p} = m\vec{v}$ $K = \frac{1}{2}mv^2$	6.2–6.3, pp. 166–176

	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: The linear momentum of a system is conserved. **5.D.3.1:** Predict the velocity of the center of mass of a system when there is no interaction outside of the system but there is an interaction within the system (i.e., the student simply recognizes that interactions within a system do not affect the center-of-mass motion of the system and is able to determine that there is no external force). **[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 on 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. c. Included in Physics 1 is the idea that, where there is both a heavier and lighter mass, the center of mass is closer to the heavier mass. Only a qualitative understanding of this concept is required.	8.2, pp. 228–233

Unit 6: Simple Harmonic Motion

Suggested Length: Eight 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 6.1: Period of Simple Harmonic Motion	**3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma \vec{F}}{m}$. **3.B.3.1:** Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. **[SP 6.4, 7.2]** **3.B.3.2:** Design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. **[SP 4.2]** **3.B.3.3:** Analyze data to identify qualitative and quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion and use those data to determine the value of an unknown. **[SP 2.2, 5.1]** **3.B.3.4:** Construct a qualitative and/or quantitative explanation of oscillatory behavior given evidence of a restoring force. **[SP 2.2, 6.2]**	**3.B.3:** Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object with undergo a special type of motion called simple harmonic motion. Examples included gravitational force exerted by the Earth on a simple pendulum and mass-spring oscillator. a. For a spring that exerts a linear restoring force, the period of a mass-spring oscillator increases with mass and decreases with spring stiffness. b. For a simple pendulum, the period increases with the length of the pendulum and decreases with the magnitude of the gravitational field. c. Minima, maxima, and zeros of position, velocity, and acceleration are features of harmonic motion. Students should be able to calculate force and acceleration for any given displacement for an object oscillating on a spring. $T_p = 2\pi\sqrt{\frac{l}{g}}$ $T_s = 2\pi\sqrt{\frac{m}{k}}$	13.2–13.6, pp. 429–439

Topic 6.2: Energy of a simple harmonic oscillator	**5.B:** The energy of a system is conserved. **5.B.2.1:** 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 objects in electric fields and examining changes in internal energy with changes in configuration.]*	13.1, pp. 423–440
	5.B: The energy of a system is conserved. **5.B.3.1:** Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]** **5.B.3.2:** Make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]** **5.B.3.3:** Apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**	**5.B.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces. a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system. b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators, objects falling in a gravitational field. c. The change in electric potential in a circuit is the change in potential energy per unit charge. [Physics 1: only in the context of circuits.] $T_p = 2\pi\sqrt{\frac{l}{g}}$ $T_s = 2\pi\sqrt{\frac{m}{k}}$ $U_s = \frac{1}{2}kx^2$ $\Delta U_g = mg\Delta y$	5.3–5.6, pp. 130–144 13.2, pp. 426–429 16.1, pp. 527–529
	5.B: The energy of a system is conserved. **5.B.4.1:** Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**	**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,	5.2–5.3, pp. 126–135 5.5, pp. 137–142

	5.B.4.2: 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]**	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.	

Unit 7: Torque and Rotational Motion

Suggested Length: Fourteen 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 7.1: Rotational Kinematics	**3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. **3.A.1.1:** Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**	**3.A.1:** An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed and acceleration a. Displacement, velocity and acceleration are all vector quantities b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values. $\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$ c. A choice of reference frame determines the direction and the magnitude of each of these quantities d. There are three fundamental interactions or forces in nature; the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects. e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force.	2.1, pp. 31–41 2.3, pp. 42–52 3.1-3.2, pp. 59-68 4.1–4.7, pp. 80–110 7.2, pp. 194–195 7.3–7.4, pp. 198-206 30.3, pp. 939–940

		f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are: $v_x = v_{x0} + a_x t$ $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ g. For rotational motion there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are: $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$ $\omega = \omega_0 + \alpha t$ $\omega^2 = \omega_0^2 + 2\alpha_x(\theta - \theta_0)$ h. This also includes situations where there is both a radial and tangential acceleration for an object moving in a circular path. $a_c = \frac{v^2}{r}$ For uniform circular motion of radius r, v is proportional to omega (for a given r) and proportional to r (for a given omega). Given a radius r and a period of rotation T, students derive and apply v = (2πr)/T. **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.*	
Topic 7.2: Torque and Angular Acceleration	**3.F:** A force exerted on an object can cause a torque on that object. **3.F.1.1:** Use representations of the relationship between force and torque. **[SP 1.4]** **3.F.1.2:** Compare the torques on an object caused by various forces. **[SP 1.4]** **3.F.1.3:** Estimate the torque on	**3.F.1:** Only the force component perpendicular to the line connecting the axis of rotation and the point of application of the force results in a torque about that axis. a. The lever arm is the perpendicular distance from the axis of rotation or revolution to the line of application of the force. b. The magnitude of the torque is the product of the magnitude of the lever arm and the magnitude of the force. c. The net torque on a balanced system is zero.	8.1, pp. 225–228

	an object caused by various forces in comparison with other situations. **[SP 2.3]** **3.F.1.4:** Design an experiment and analyze data testing a question about torques in a balanced rigid system. **[SP 4.1, 4.2, 5.1]** **3.F.1.5:** Calculate torques on a two-dimensional system in static equilibrium by examining a representation or model (such as a diagram or physical construction). **[SP 1.4, 2.2]**	$\tau = r_{\perp}F = rF\sin\theta$ **Boundary Statement:** *Quantities such as angular acceleration, velocity, and momentum are defined as vector quantities, but in Physics 1 the determination of "direction" is limited to clockwise and counterclockwise with respect to a given axis of rotation.*	
	3.F: A force exerted on an object can cause a torque on that object. **3.F.2.1:** Make predictions about the change in the angular velocity about an axis for an object when forces exerted on the object cause a torque about that axis. **[SP 6.4]** **3.F.2.2:** Plan data collection and analysis strategies designed to test the relationship between a torque exerted on an object and the change in angular velocity of that object about an axis. **[SP 4.1, 4.2, 5.1]**	**3.F.2:** The presence of a net torque along any axis will cause a rigid system to change its rotational motion or an object to change its rotational motion about that axis. a. Rotational motion can be described in terms of angular displacement, angular velocity, and angular acceleration about a fixed axis. b. Rotational motion of a point can be related to linear motion of the point using the distance of the point from the axis of rotation. c. The angular acceleration of an object or rigid system can be calculated from the net torque and the rotational inertia of the object or rigid system. $\tau = r_{\perp}F = rF\sin\theta$ $\alpha = \frac{\Sigma\tau}{I}$ $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$ $\omega = \omega_0 + \alpha t$ $\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$	7.1–7.4, pp. 190–201 8.1, pp. 224–228

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<td></td>
<td>3.F: A force exerted on an object can cause a torque on that object.

3.F.3.1: Predict the behavior of rotational collision situations by the same processes that are used to analyze linear collision situations using an analogy between impulse and change of linear momentum and angular impulse and change of angular momentum. [SP 6.4, 7.2]

3.F.3.2: In an unfamiliar context or using representations beyond equations, justify the selection of a mathematical routine to solve for the change in angular momentum of an object caused by torques exerted on the object. [SP 2.1]

3.F.3.3: Plan data collection and analysis strategies designed to test the relationship between torques exerted on an object and the change in angular momentum of that object. [SP 4.1, 4.2, 5.1, 5.3]</td>
<td>3.F.3: A torque exerted on an object can change the angular momentum of an object.

a. Angular momentum is a vector quantity, with its direction determined by a right-hand rule.
b. The magnitude of angular momentum of a point object about an axis can be calculated by multiplying the perpendicular distance from the axis of rotation to the line of motion by the magnitude of linear momentum.
c. The magnitude of angular momentum of an extended object can also be found by multiplying the rotational inertia by the angular velocity. Students do not need to know the equation for an object’s rotational inertia, as it will be provided at the exam. They should have a qualitative sense of what factors affect rotational inertia—for example, why a hoop has more rotational inertia than a puck of the same mass and radius.
d. The change in angular momentum of an object is given by the product of the average torque and the time the torque is exerted.

$L = I\omega$
$\Delta L = \tau\Delta t$
$L = mvr$</td>
<td>8.4, pp. 242–246

8.6, pp. 249–253</td>
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<td>Topic 7.3: Angular Momentum and Torque</td>
<td>4.D: A net torque exerted on a system by other objects or systems will change the angular momentum of the system.

4.D.1.1: Describe a representation and use it to analyze a situation in which several forces exerted on a rotating system of rigidly connected objects change the angular velocity and angular momentum of the system. [SP 1.2, 1.4]

4.D.1.2: Plan data collection strategies designed to establish that torque, angular velocity, angular acceleration, and angular momentum can be predicted accurately when the</td>
<td>4.D.1: Torque, angular velocity, angular acceleration, and angular momentum are vectors and can be characterized as positive or negative depending on whether they give rise to or correspond to counterclockwise or clockwise rotation with respect to an axis.

$\tau = r_{\perp}F = rF\sin\theta$
$\alpha = \frac{\Sigma\tau}{I}$
$L = I\omega$
$\Delta L = \tau\Delta t$
$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$
$\omega = \omega_0 + \alpha t$
$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$

Boundary Statement:
Students do not need to know the right-hand rule. A full dynamic treatment of rolling without slipping—for instance, using forces and torques to</td>
<td>8.1, pp. 224–228

8.4, pp. 238–240

8.6, pp. 249–253</td>
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	variables are treated as being clockwise or counterclockwise with respect to a well-defined axis of rotation, and refine the research question based on the examination of data. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]**	*find the linear and angular acceleration of a cylinder rolling down a ramp—is not included in Physics 1.*	
	4.D: A net torque exerted on a system by other objects or systems will change the angular momentum of the system. **4.D.2.1:** Describe a model of a rotational system and use that model to analyze a situation in which angular momentum changes due to interaction with other objects or systems. **[SP 1.2, 1.4]** **4.D.2.2:** Plan a data collection and analysis strategy to determine the change in angular momentum of a system and relate it to interactions with other objects and systems. **[SP 4.2]**	**4.D.2:** The angular momentum of a system may change due to interactions with other objects or systems. a. The angular momentum of a system with respect to an axis of rotation is the sum of the angular momenta, with respect to that axis, of the objects that make up the system. b. The angular momentum of an object about a fixed axis can be found by multiplying the momentum of the particle by the perpendicular distance from the axis to the line of motion of the object. c. Alternatively, the angular momentum of a system can be found from the product of the system's rotational inertia and its angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation. $L = I\omega$ $\Delta L = \tau \Delta t$ $\tau = r_{\perp} F = rF \sin\theta$	8.1, pp. 226–228 8.6, pp. 249–253
	4.D: A net torque exerted on a system by other objects or systems will change the angular momentum of the system. **4.D.3.1:** Use appropriate mathematical routines to calculate values for initial or final angular momentum, or change in angular momentum of a system, or average torque or time during which the torque is exerted in analyzing a situation involving torque and angular momentum. **[SP 2.2]**	**4.D.3:** The change in angular momentum is given by the product of the average torque and the time interval during which the torque is exerted. $L = I\omega$ $\Delta L = \tau \Delta t$ $\tau = r_{\perp} F = rF \sin\theta$	8.1, pp. 226–228

	4.D.3.2: Plan a data collection strategy designed to test the relationship between the change in angular momentum of a system and the product of the average torque applied to the system and the time interval during which the torque is exerted. **[SP 4.1, 4.2]**		
Topic 7.4: Conservation of Angular Momentum	**5.E:** The angular momentum of a system is conserved. **5.E.1.1:** Make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. **[SP 6.4, 7.2]** **5.E.1.2:** Make calculations of quantities related to the angular momentum of a system when the net external torque on the system is zero. **[SP 2.1, 2.2]**	**5.E.1:** If the net external torque exerted on the system is zero, the angular momentum of the system does not change. $L = I\omega$ $\Delta L = \tau \Delta t$ $\tau = r_{\perp} F = rF \sin\theta$	8.1, pp. 226–228
	5.E: The angular momentum of a system is conserved. **5.E.2.1:** Describe or calculate the angular momentum and rotational inertia of a system in terms of the locations and velocities of objects that make up the system. Use qualitative reasoning with compound objects and perform calculations with a fixed set of extended objects and point masses. **[SP 2.2]**	**5.E.2:** The angular momentum of a system is determined by the locations and velocities of the objects that make up the system. The rotational inertia of an object or system depends on the distribution of mass within the object or system. Changes in the radius of a system or in the distribution of mass within the system result in changes in the system's rotational inertia, and hence in its angular velocity and linear speed for a given angular momentum. Examples include elliptical orbits in an Earth-satellite system. Mathematical expressions for the moments of inertia will be provided where needed. Students will not be expected to know the parallel axis theorem. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation. $I = mr^2$	8.4, p. 242 8.5, p. 248 8.6, p. 252

Unit 8: Electric Charge and Electric Force

Suggested Length: Six 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 8.1: Conservation of Charge	**5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. **5.A.2.1:** Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**	**5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings**.**	5.6, pp. 142–144 6.2, pp. 166–169 8.6, pp. 249–252 18.6, pp. 599–602
Topic 8.2: Electric Charge	**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:** Make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]** **1.B.1.2:** 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. $I \equiv \frac{\Delta q}{\Delta t}$ **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. Physics 1 treats gravitational fields only; Physics 2 treats electric and magnetic fields.*	15.5, p. 510 17.1, pp. 566–569 17.6, p. 578

	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.2.1:** Construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**	**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. $\lvert F_E \rvert = k\left\lvert \frac{q_1 q_2}{r^2} \right\rvert$	15.1, pp. 495–496 15.2, p. 499
	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.3.1:** 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.	15.1, pp. 496–497
Topic 8.3: Electric Force	**3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. **3.C.2.1:** Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges (interactions between collections of electric point charges are not covered in Physics 1 and instead are restricted to Physics 2). **[SP 2.2, 6.4]** **3.C.2.2**: Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**	**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 on the charges on the objects involved. $\lvert \vec{F}_g \rvert = G\frac{m_1 m_2}{r^2}$	4.1, pp. 80–81 4.2, p. 87 7.5, p. 206 15.2, pp. 498–503 16.2, p. 535

Unit 9: DC Circuits

Suggested Length: Thirteen 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 9.1: Definition of a Circuit	**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:** Make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]** **1.B.1.2:** 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. $I \equiv \frac{\Delta q}{\Delta t}$	15.5, p. 510 17.1, pp. 566–569 17.6, p. 578 18.1–18.5, pp. 590–606
Topic 9.2: Resistivity	**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:** 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. Resistivity changes with temperature. $R = \frac{\rho l}{A}$ **Boundary Statement:** *Knowledge of what causes temperature to affect resistivity is not a part of Physics 1.*	17.4, pp. 574–575

Topic 9.3: Ohm's Law, Kirchoff's Loop Rule [Resistors in Series and Parallel]	**5.B:** The energy of a system is conserved. **5.B.9.1:** Construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule). **[SP 1.1, 1.4]** **5.B.9.2:** Apply conservation of energy concepts to the design of an experiment that will demonstrate the validity of Kirchhoff's loop rule ($\sum \Delta V = 0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches. **[SP 4.2, 6.4, 7.2]** **5.B.9.3:** Apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. **[SP 2.2, 6.4, 7.2]**	**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.]* The potential difference across an ideal battery is also referred to as the emf of the battery, represented as: $\varepsilon = \frac{E}{Q}$ *[Non-ideal batteries are not covered in Physics 1.]* 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. $I = \frac{\Delta V}{R}$ $P = I\Delta V$	18.1–18.4, pp. 590–602 17.4, pp. 572–573 17.6, pp. 577–580 18.2, pp. 593–594
Topic 9.4: Kirchoff's Junction Rule, Ohm's Law [Resistors in Series and Parallel]	**5.C:** The electric charge of a system is conserved. **5.C.3.1:** Apply conservation of electric charge (Kirchhoff's junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if configurations of the circuit are changed. **[SP 6.4, 7.2]**	**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.]*	17.6, pp. 577–580 18.2, pp. 591–594 18.4, pp. 599–602

	5.C.3.2: Design an investigation of an electrical circuit with one or more resistors in which evidence of conservation of electric charge can be collected and analyzed. **[SP 4.1, 4.2, 5.1]** **5.C.3.3:** Use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or branches of the circuit. **[SP 1.4, 2.2]**	$I \equiv \frac{\Delta q}{\Delta t}$ $I = \frac{\Delta V}{R}$ $P = I\Delta V$ $R_s = \sum_i R_i$ $R_p = \sum_i \frac{1}{R_i}$	

Unit 10: Mechanical Waves and Sound

Suggested Length: Thirteen 45-minute classes

- **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.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 10.1: Properties of Waves	**6.A:** A wave is a traveling disturbance that transfers energy and momentum. **6.A.1.1:** Use a visual representation to construct an explanation of the distinction between transverse and longitudinal waves by focusing on the vibration that generates the wave. **[SP 6.2]** **6.A.1.2:** Describe representations of transverse and longitudinal waves. **[SP 1.2]**	**6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal. a. Mechanical waves can be either transverse or longitudinal. Examples include waves on a stretched string and sound waves. b. This includes, as part of the mechanism of "propagation," the idea that the speed of a wave depends only on properties of the medium. c. The propagation of sound waves included in this EK includes the idea that the traveling disturbance consists of pressure variations coupled to displacement variations. d. This applies to both periodic waves and to wave pulses. **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.*	13.7, pp. 441–443 14.1, pp. 457–458
	6.A: A wave is a traveling disturbance that transfers energy and momentum. **6.A.2.1:** Describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. **[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. **Boundary Statement:** *Electromagnetic waves are not tested in Physics 1. This applies to both periodic waves and wave pulses.*	13.7, pp. 441–443 14.1, pp. 457–458

	6.A: A wave is a traveling disturbance that transfers energy and momentum. **6.A.3.1:** Use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. **[SP 1.4]**	**6.A.3:** The amplitude is the maximum displacement of a wave from its equilibrium value. a. The amplitude is the maximum displacement from equilibrium of the wave. A sound wave may be represented by either the pressure or the displacement of atoms or molecules. This covers both periodic waves and wave pulses. b. The pressure amplitude of a sound wave is the maximum difference between local pressure and atmospheric pressure.	13.1, p. 424 13.8, pp. 444–445 14.1–14.11, pp. 457–483
	6.A: A wave is a traveling disturbance that transfers energy and momentum. **6.A.4.1:** Explain and/or predict qualitatively how the energy carried by a sound wave relates to the amplitude of the wave and/or apply this concept to a real-world example. **[SP 6.4]**	**6.A.4:** Classically, the energy carried by a wave depends on and increases with amplitude. Examples include sound waves. a. Higher amplitude refers to both greater pressure variations and greater displacement variations. *[The subsection of the essential knowledge is not directly addressed in this edition of* College Physics.*]* b. Examples include both periodic waves and wave pulses.	13.8, pp. 444–447 14.7, pp. 471–472
Topic 10.2: Periodic Waves	**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.1.1:** Use a graphical representation of a periodic mechanical wave (position versus time) to determine the period and frequency of the wave and describe how a change in the frequency would modify features of the representation. **[SP 1.4, 2.2]**	**6.B.1:** For a periodic wave, the period is the repeat time of the wave. The frequency is the number of repetitions of the wave per unit time. a. In a periodic sound wave, pressure variations and displacement variations are both present and with the same frequency. $T = \frac{1}{f}$	13.1, p. 424 13.8, pp. 444–447
	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.2.1:** Use a visual representation of a periodic mechanical wave to determine	**6.B.2:** For a periodic wave, the wavelength is the repeat distance of the wave.	13.8, pp. 444–447

	wavelength of the wave. **[SP 1.4]**		
	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.4.1:** Design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. **[SP 4.2, 5.1, 7.2]**	**6.B.4:** For a periodic wave, wavelength is the ratio of speed over frequency. $\lambda = \frac{v}{f}$	13.8, pp. 444–447 14.10, p. 478–481
	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.5.1:** Create or use a wave front diagram to demonstrate or interpret qualitatively the observed frequency of a wave, dependent on relative motions of source and observer. **[SP 1.4]**	**6.B.5:** The observed frequency of a wave depends on the relative motion of source and observer. This is a qualitative treatment only.	14.5–14.6, pp. 464–467
Topic 10.3: Interference and Superposition [Waves in Tubes and on Strings]	**6.D:** Interference and superposition lead to standing waves and beats. **6.D.1.1:** Use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. **[SP 1.1, 1.4]** **6.D.1.2:** Design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for wave pulses or standing waves). **[SP 4.2, 5.1]** **6.D.1.3:** Design a plan for collecting data to quantify the	**6.D.1:** Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition.	13.10, p. 447–448 14.7, pp. 471–472

	amplitude variations when two or more traveling waves or wave pulses interact in a given medium. **[SP 4.2]**		
	6.D: Interference and superposition lead to standing waves and beats. **6.D.2.1:** Analyze data or observations or evaluate evidence of the interaction of two or more traveling waves in one or two dimensions (i.e., circular wave fronts) to evaluate the variations in resultant amplitudes. **[SP 5.1]**	**6.D.2:** Two or more traveling waves can interact in such a way as to produce amplitude variations in the resultant wave**.**	13.10, p. 447–448 14.7, pp. 471–472
	6.D: Interference and superposition lead to standing waves and beats. **6.D.3.1:** Refine a scientific question related to standing waves and design a detailed plan for the experiment that can be conducted to examine the phenomenon qualitatively or quantitatively. **[SP 2.1, 3.2, 4.2]** **6.D.3.2:** Predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. **[SP 6.4]** **6.D.3.3:** Plan data collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared with the prediction, explain any discrepancy, and, if necessary, revise the relationship among variables responsible for establishing standing waves on a string or in a column of air. **[SP 3.2, 4.1,5.1, 5.2, 5.3]** **6.D.3.4:** Describe representations and models of	**6.D.3:** Standing waves are the result of the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. Examples include waves on a fixed length of string and sound waves in both closed and open tubes. a. Reflection of waves and wave pulses, even if a standing wave is not created, is covered in Physics 1. b. For standing sound waves, pressure nodes correspond to displacement antinodes, and vice versa. For example, the open end of a tube is a pressure node because the pressure equalizes with the surrounding air pressure and therefore does not oscillate. The closed end of a tube is a displacement node because the air adjacent to the closed end is blocked from oscillating.	13.10 p. 447–448 14.7, pp. 471–472

	situations in which standing waves result from the addition of incident and reflected waves confined to a region. **[SP 1.2]**		
	6.D: Interference and superposition lead to standing waves and beats. **6.D.4.1:** Challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source, regardless of the size of the region. **[SP 1.5, 6.1]** **6.D.4.2:** Calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined and calculate numerical values of wavelengths and frequencies. Examples include musical instruments. **[SP 2.2]**	**6.D.4:** The possible wavelengths of a standing wave are determined by the size of the region to which it is confined. a. A standing wave with zero amplitude at both ends can only have certain wavelengths. Examples include fundamental frequencies and harmonics. b. Other boundary conditions or other region sizes will result in different sets of possible wavelengths. c. The term first harmonic refers to the standing waves corresponding to the fundamental frequency (i.e., the lowest frequency corresponding to a standing wave). The second harmonic is the standing wave corresponding to the second lowest frequency that generates a standing wave in the given scenario. d. Resonance is another term for standing sound wave. $\lambda = \frac{v}{f}$ $T = \frac{1}{f}$	14.8–14.10, pp. 473–482 14.12, p. 484
	6.D: Interference and superposition lead to standing waves and beats. **6.D.5.1:** Use a visual representation to explain how waves of slightly different frequency give rise to the phenomenon of beats. **[SP 1.2]**	**6.D.5:** Beats arise from the addition of waves of slightly different frequency. a. Because of the different frequencies, the two waves are sometimes in phase and sometimes out of phase. The resulting regularly spaced amplitude changes are called beats. Examples include the tuning of an instrument. b. The beat frequency is the difference in frequency between the two waves. *[In Physics 1, only qualitative understanding of EK 6.D.5 is necessary.]*	14.11, pp. 482–483

