Correlation with the 2019 Updated AP® Physics Curriculum Framework

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Physics for Scientists and Engineers,
Physics C: Mechanics

TENTH EDITION

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Unit 1: Kinematics

Suggested Length: 13 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 1.1: Kinematics: Motion in One Dimension	**CHA–1:** There are relationships among the vector quantities of position, velocity, and acceleration for the motion of a particle along a straight line. **CHA–1.A:** a. Determine the appropriate expressions for velocity and position as a function of time for an object accelerating uniformly in one dimension with given initial conditions. b. Calculate unknown variables of motion such as acceleration, velocity or positions for an object undergoing uniformly accelerated motion in one dimension c. Calculate values such as average velocity or minimum or maximum velocity for an object in uniform acceleration.	**CHA-1.A.1:** The kinematic relationships for an object accelerating uniformly in one dimension are: $\boldsymbol{x} = \boldsymbol{x}_0 + \boldsymbol{v}_{x0}\boldsymbol{t} + \frac{1}{2}\boldsymbol{a}_x\boldsymbol{t}^2$ $\boldsymbol{v}_x = \boldsymbol{v}_{x0} + \boldsymbol{a}_x\boldsymbol{t}$ $\boldsymbol{v}_x^2 = \boldsymbol{v}_{x0}^2 + 2\boldsymbol{a}_x(\boldsymbol{x} - \boldsymbol{x}_0)$ i. **CHA-1.A.1.i:** The constant velocity model can be derived from the above relationships. $v_x = \frac{\Delta x}{\Delta t}$ ii. **CHA-1.A.1.ii:** The average velocity and acceleration models can also be derived from the above relationships. $v_{x(ave)} = \frac{\Delta x}{\Delta t}$ $a_{x(ave)} = \frac{\Delta v_x}{\Delta t}$	2.1–2.3, pp. 21–30 2.5, pp. 32–36 2.7, pp. 37–39
	CHA–1: There are relationships among the vector quantities of position, velocity, and acceleration for the motion of a particle along a straight line. **CHA-1.B:** Determine functions of position, velocity, and acceleration that are consistent with each other, for the motion of an object with a nonuniform acceleration.	**CHA-1.B.1:** Differentiation and integration are necessary for determining functions that relate, position, velocity, and acceleration for an object with nonuniform acceleration. $\boldsymbol{v}_x = \frac{d\boldsymbol{x}}{d\boldsymbol{t}}$ $\boldsymbol{a}_x = \frac{d\boldsymbol{v}_x}{d\boldsymbol{t}}$ i. **CHA-1.B.1.i:** These functions may include trigonometric, power, or exponential functions of time. ii. **CHA-1.B.1.ii:** Or a velocity dependent	2.9, pp. 44–45 6.4, pp. 138–143

		acceleration function (such as a resistive force).	
	CHA–1: There are relationships among the vector quantities of position, velocity, and acceleration for the motion of a particle along a straight line. **CHA-1.C:** Describe the motion of an object in terms of the consistency that exists between position and time, velocity and time, and acceleration and time.	**CHA-1.C.1:** Position, velocity, and acceleration versus time for a moving object are related to each other and depend on an understanding of slope, intercepts, asymptotes, and area, or upon conceptual calculus concepts. i. **CHA-1.C.1.i:** These functions may include trigonometric, power, exponential functions (of time) or velocity dependent functions.	2.2, pp. 25–26 2.3, pp. 27–28 2.5–2.6, pp. 33–39
Topic 1.2: Kinematics: Motion in Two Dimensions	**CHA-2:** There are multiple simultaneous relationships among the quantities of position, velocity, and acceleration for the motion of a particle moving in more than one dimension with or without net forces. **CHA-2.A:** a. Calculate the components of a velocity, position, or acceleration vector in two dimensions. b. Calculate a net displacement of an object moving in two dimensions. c. Calculate a net change in velocity of an object moving in two dimensions. d. Calculate an average acceleration vector for an object moving in two dimensions. e. Calculate a velocity vector for an object moving relative to another object (or frame of reference) that moves with a uniform velocity. f. Describe the velocity vector for one object relative to a second object with respect to its frame of reference.	**CHA-2.A.1:** All of the kinematic quantities are vector quantities and can be resolved into components (on a given coordinate system). i. **CHA-2.A.1.i:** Vector addition and subtraction are necessary to properly determine changes in quantities. ii. **CHA-2.A.1.ii:** The position, average velocity and average acceleration can be represented in the following vector notation: $\vec{r} = \vec{x} + \vec{y} + \vec{z}$ $\vec{v}_{avg} = \frac{\Delta \vec{r}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$	3.1–3.4, pp. 53–63 4.1, pp. 69–70 4.2, pp. 71–74 4.6, pp. 85–88

	CHA-2: There are multiple simultaneous relationships among the quantities of position, velocity, and acceleration for the motion of a particle moving in more than one dimension with or without net forces. **CHA-2.B:** Derive an expression for the vector position, velocity, or acceleration of a particle, at some point in its trajectory, using a vector expression or using two simultaneous equations.	**CHA-2.B.1:** Differentiation and integration are necessary for determining functions that relate position, velocity, and acceleration for an object in each dimension. $v_x = \frac{dx}{dt}$ $a_x = \frac{dv_x}{dt}$ i. **CHA-2.B.1.i:** The accelerations may be different in each direction and may be nonuniform. ii. **CHA-2.B.1.ii:** The resultant vector of a given quantity such as position, velocity, or acceleration is the vector sum of the components of each quantity.	2.9, pp. 44–45 4.1–4.2, pp. 69–74
	CHA-2: There are multiple simultaneous relationships among the quantities of position, velocity, and acceleration for the motion of a particle moving in more than one dimension with or without net forces. **CHA-2.C:** Calculate kinematic quantities of an object in projectile motion, such as: displacement, velocity, speed, acceleration, and time, given initial conditions of various launch angles, including a horizontal launch at some point in its trajectory.	**CHA-2.C.1:** Motion in two dimensions can be analyzed using the kinematic equations if the motion is separated into vertical and horizontal components. i. **CHA-2.C.1.i:** Projectile motion assumes negligible air resistance and therefore constant horizontal velocity and constant vertical acceleration (earth's gravitational acceleration). ii. **CHA-2.C.1.ii:** These kinematic relationships only apply to constant (uniform) acceleration situations and can be applied in both *x* and *y* directions. $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ $v_x = v_{x0} + a_x t$ $v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$	4.3, pp. 74–80
	CHA-2: There are multiple simultaneous relationships among the quantities of position, velocity, and acceleration for the motion of a particle moving in more than one dimension with or without net forces. **CHA-2.D:** Describe the motion of an	**CHA-2.D.1:** The position, velocity, and acceleration versus time for a moving object are related to each other and depend on understanding of slope, intercepts, asymptotes, and area, or upon conceptual calculus concepts.	2.2, pp. 25–26 2.3, pp. 27–28 2.5-2.6, pp. 33–39

	object in two-dimensional motion in terms of the consistency that exists between position and time, velocity and time, and acceleration and time.		

Unit 2: Newton's Laws of Motion

Suggested Length: 14 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 2.1: Newton's Laws of Motion: First and Second Laws	**INT-1:** A net force will change the translational motion of an object. **INT-1.A:** Describe an object (either in a state of equilibrium or acceleration) in different types of physical situations such as inclines, falling through air resistance, Atwood machines, or circular tracks).	**INT-1.A.1:** Newton's second law can be applied to an object in accelerated motion or in a state of equilibrium.	5.4, pp. 99–102 5.7, pp. 109, 112–113 5.8, p. 117 6.1, p. 130
	INT-1: A net force will change the translational motion of an object. **INT-1.B:** a. Explain Newton's first law in qualitative terms and apply the law to many different physical situations. b. Calculate a force of unknown magnitude acting on an object in equilibrium	**INT-1.B.1:** Newton's first law is the special case of the second law. When the acceleration of an object is zero (i.e., velocity is constant or equal to zero), the object is in a state of equilibrium and the following statements are true: $\sum F_x = 0$ $\sum F_y = 0$ i. **INT-1.B.1.i:** Forces can be resolved into components and these components can be separately added in their respective directions.	5.2, pp. 97–99 5.7, pp. 105–109, 113
	INT-1: A net force will change the translational motion of an object. **INT-1.C:** a. Calculate the acceleration of an object moving in one dimension when a single constant force (or a net constant force) act on the object during a known interval of time. b. Calculate the average force acting on an object moving	**INT-1.C.1:** The appropriate use of Newton's second law is one of the fundamental skills in mechanics. $\vec{a} = \frac{\sum \vec{F}}{m}$ i. **INT-1.C.1.i:** The second law is a vector relationship. It may be necessary to draw complete free-body diagrams to determine unknown forces acting on an object. ii. **INT-1.C.1.ii:** Forces acting parallel to the velocity vector have the capacity to change	5.4, pp. 99–102 5.7, pp. 105–114

	in a plane with a velocity vector that is changing over a specified time interval. c. Describe the trajectory of a moving object that experiences a constant force in a direction perpendicular to its initial velocity vector. d. Derive an expression for the net force on an object in translational motion. e. Derive a complete Newton's second law statement (in the appropriate direction) for an object in various physical dynamic situations (e.g., mass on incline, mass in elevator, strings/pulleys, or Atwood machines).	the speed of the object. iii. **INT-1.C.1.iii:** Forces acting in the perpendicular direction have the capacity to change the direction of the velocity vector.	
	INT-1: A net force will change the translational motion of an object. **INT-1.D:** Calculate a value for an unknown force acting on an object accelerating in a dynamic situation (e.g., inclines, Atwood Machines, falling with air resistance, pulley systems, mass in elevator, etc.).	**INT-1.D.1:** Using appropriate relationships derived from a Newton's second law analysis, unknown forces (or accelerations) can be determined from the given known physical characteristics.	5.4, pp. 99–102 5.7, pp. 105–114
	INT-1: A net force will change the translational motion of an object. **INT-1.E:** a. Describe the relationship between frictional force and the normal force for static friction and for kinetic friction. b. Explain when to use the static frictional relationship versus the kinetic frictional relationship in different physical situations (e.g., object sliding on surface or object not slipping on incline).	**INT-1.E.1:** The relationship for the frictional force acting on an object on a rough surface is: $\left\lvert \dot{F}_{f_s} \right\rvert \le \mu_s \left\lvert \dot{F}_N \right\rvert$ $\left\lvert \dot{F}_{f_k} \right\rvert = \mu_k \left\lvert \dot{F}_N \right\rvert$	5.8, pp. 114–119

	INT-1: A net force will change the translational motion of an object. **INT-1.F:** Describe the direction of frictional forces (static or kinetic) acting on an object under various physical situations.	**INT-1.F.1:** The direction of friction can be determined by the relative motion between surfaces in kinetic frictional cases. **INT-1.F.1.i:** In cases where the direction of friction is not obvious or is not directly evident from relative motion, then the net motion of the object and the other forces acting on the object are required to determine the direction of the frictional force	5.8, pp. 114–119
	INT-1: A net force will change the translational motion of an object. **INT-1.G:** a. a. Derive expressions that relate mass, forces, or angles of inclines for various slipping conditions with friction. b. Calculate the value for the static frictional force for an object in various dynamic situations (e.g., an object at rest on truck bed, an object at rest on incline, or an object pinned to a horizontal surface).	**INT-1.G.1:** The maximum value of static friction has a precise relationship: $\left\|\vec{F}_{f_s}\right\| = \mu_s \left\|\vec{F}_N\right\|$ This relationship can be used to determine values such as, "The maximum angle of incline at which the block will not slip."	5.8, pp. 114–119
	INT-1: A net force will change the translational motion of an object. **INT-1.H:** a. Derive an expression for the motion of an object freely falling with a resistive drag force (or moving horizontally subject to a resistive horizontal force). b. Describe the acceleration, velocity, or position in relation to time for an object subject to a resistive force (with different initial conditions, i.e., falling from rest or projected vertically).	**INT-1.H.1:** The standard "resistive force" in this course is defined as a velocity dependent force in the opposite direction of velocity, for example: $\vec{F}_r = -k\vec{v}$ or $\left\|\vec{F}_r\right\| = kv^2$	6.4, pp. 138–142

	INT-1: A net force will change the translational motion of an object. **INT-1.I:** Calculate the terminal velocity of an object moving vertically under the influence of a resistive force of a given relationship.	**INT-1.I.1:** The terminal velocity is defined as the maximum speed achieved by an object falling under the influence of a given drag force. The terminal condition is reached when the magnitude of the drag force is equal to the magnitude of the weight of the object.	6.4, pp. 140–141
	INT-1: A net force will change the translational motion of an object. **INT-1.J:** a. Derive a differential equation for an object in motion subject to a specified resistive force. b. Derive an expression for a time-dependent velocity function for an object moving under the influence of a given resistive force (with given initial conditions). c. Derive expressions for the acceleration or position of an object moving under the influence of a given resistive force.	**INT-1.J.1:** Because the resistive force is a function of velocity, applying Newton's second law correctly will lead to a differential equation for velocity. This is an example of that statement: $m\frac{dv}{dt} = -\frac{k}{m}v$ i. **INT-1.J.1.i:** Using the method of separation of variables, the velocity can be determined from relationships by correctly integrating over the proper limits of integration. ii. **INT-1.J.1.ii:** The acceleration or position can be determined using methods of calculus once a function for velocity is determined.	6.4, pp. 138–143
Topic 2.2: Circular Motion	**INT-2:** The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. **INT-2.A:** a. Calculate the velocity of an object moving in a horizontal circle with a constant speed, when subject to a known centripetal force. b. Calculate relationships among the radius of a circle, the speed of an object (or period of revolution), and the magnitude of centripetal acceleration for	**INT-2.A.1:** Centripetal acceleration is defined by: $a_c = \frac{v^2}{r}$ or defined using angular velocity: $a_c = \omega^2 r$ i. **INT-2.A.1.i:** Uniform circular motion is defined as an object moving in a circle with a constant speed. ii. **INT-2.A.1.ii:** The net force acting in the radial direction can be determined by applying Newton's second law in the radial direction.	6.1, pp. 123–133

	an object moving in uniform circular motion.		
	INT-2: The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. **INT-2.B:** a. Explain how a net force in the centripetal direction can be a single force, more than one force, or even components of forces that are acting on an object moving in circular motion. b. Describe forces that are exerted on objects undergoing horizontal circular motion, vertical circular motion, or horizontal circular motion on a banked curve. c. Describe forces that are acting on different objects traveling in different circular paths.	**INT-2.B.1:** In order for an object to undergo circular motion in any context, there must be a force, multiple forces, or components of forces acting in the radial direction. These forces can be represented with appropriate free-body diagrams.	6.1, pp. 128–133
	INT-2: The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. **INT-2.C:** a. Describe the direction of the velocity and acceleration vector for an object moving in two dimensions, circular motion, or uniform circular motion. b. Calculate the resultant acceleration for an object that changes its speed as it moves in a circular path.	**INT-2.C.1:** An object that changes directions will always have an acceleration component that is perpendicular to the velocity vector. The velocity vector will always be tangential to the path of the particle. i. **INT-2.C.1.i:** As an object moves in a circle with changing speed, the resultant acceleration, at any point, is the vector sum of the radial acceleration and tangential acceleration.	6.1, pp. 128–133

	INT-2: The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. **INT-2.D:** Derive expressions relating centripetal force to the minimum speed or maximum speed of an object moving in a vertical circular path.	**INT-2.D.1:** The centripetal force is provided only by the gravitational force for an object moving at minimum speed at the top of a vertical circle. This speed is called "critical speed" in certain textbooks. **INT-2.D.1.i:** The maximum speed occurs at the bottom of the circle and is related to all of the vertical forces acting on the object	6.2, pp. 134–135
	INT-2: The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. **INT-2.E:** Derive expressions relating the centripetal force to the maximum speed of an object or minimum speed of an object moving in a circular path on a banked surface with friction.	**INT-2.E.1:** Components of the static friction force and the normal force can contribute to the centripetal force for an object traveling in a circle on a banked surface.	6.1, pp. 131–132
Topic 2.3: Newton's Laws of Motion: Third Law	**INT-3:** There are force pairs with equal magnitude and opposite directions between any two interacting objects. **INT-3.A:** a. Describe the forces of interaction between two objects (Newton's third law). b. Describe pairs of forces that occur in a physical system due to Newton's third law. c. Describe the forces that occur between two (or more) objects accelerating together (e.g., in contact or connected by light strings, springs, or cords).	**INT-3.A.1:** The forces exerted between objects are equal in magnitude and opposite in direction. i. **INT-3.A.1.i:** Third law force pairs are always internal to the system of the two objects that are interacting. ii. **INT-3.A.1.ii:** Each force in the pair is always the same type of force.	5.6, pp. 103–105 5.7, pp. 110–114
	INT-3: There are force pairs with equal magnitude and opposite directions between any two interacting objects.	**INT-3.B.1:** To analyze a complete system of multiple connected masses in motion, several applications of Newton's second law in conjunction with Newton's third law may be necessary. This may involve solving two or three	5.7, pp. 110–114

	INT-3.B: Derive expressions that relate the acceleration of multiple connected masses moving in a system (e.g., Atwood machine) connected by light strings with tensions (and pulleys).	simultaneous linear equations.	

Unit 3: Work, Energy, and Power

Suggested Length: 10 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4:** Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 3.1: Work-Energy Theorem	**INT-4:** When a force is exerted on an object, and the energy of the object changes, then work was done on the object. **INT-4.A:** a. Calculate work done by a given force (constant or as a given function *F(x)*) on an object that undergoes a specified displacement. b. Describe the work done on an object as the result of the scalar product between force and displacement. b. Explain how the work done an object by an applied force acting on an object can be negative or zero.	**INT-4.A.1:** The component of the displacement that is parallel to the applied force is used to calculate the work. i. **INT-4.A.1.i:** The work done on an object by a force can be calculated using $W = \int_a^b \vec{F}(r) \cdot \mathrm{d}\vec{r}$ ii. **INT-4.A.1.ii:** Work is a scalar value that can be positive, negative, or zero. iii. **INT-4.A.1.iii:** The definition of work can be applied to an object when that object can be modeled as a point-like object.	7.2–7.4, pp. 151–157
	INT-4: When a force is exerted on an object, and the energy of the object changes, then work was done on the object. **INT-4.B:** Calculate a value for work done on an object from a force versus position graph.	**INT-4.B.1:** The area under the curve of a force versus position graph is equivalent to the work done on the object or system.	7.4, pp. 156–158
	INT-4: When a force is exerted on an object, and the energy of the object changes, then work was done on the object. **INT-4.C:** a. Calculate the change in kinetic energy due to the work done on an object or	**INT-4.C.1:** The net work done on an (point-like) object is equal to the object's change the kinetic energy. $W_{net} = \Delta K$ i. **INT-4.C.1.i:** This is defined as the Work-Energy Theorem. The Work-Energy Theorem can be used when an object or system can	7.5, pp. 161–164

	system by a single force or multiple forces. b. Calculate the net work done on an object that undergoes a specified change in speed or change in kinetic energy. c. Calculate changes in an object's kinetic energy or changes in speed that result from the application of specified forces.	be modeled as a point-like particle (i.e., non-deformable and not having the capacity for internal energy). ii. **INT-4.C.1.ii:** The definition of kinetic energy is: $K = \frac{1}{2}mv^2$ iii. **INT-4.C.1.iii:** Net work done on an object is equivalent to the sum of the individual work done on an object by each of the forces acting on the object (including conservative forces).	
Topic 3.2: Forces and Potential Energy	**CON-1:** Conservative forces internal to the system can change the potential energy of that system. **CON-1.A:** a. Compare conservative and dissipative forces. b. Describe the role of a conservative force or a dissipative force in a dynamic system.	**CON-1.A.1:** A force can be defined as a conservative force if the work done on an object by the force depends only on the initial and final position of the object. i. **CON-1.A.1.i:** The work done by a conservative force will be zero if the object undergoes a displacement that completes a complete closed path. ii. **CON-1.A.1.ii:** Common dissipative forces discussed in this course are friction, resistive forces, or externally applied forces from some object external to the system.	7.7, pp. 169–171
	CON-1: Conservative forces internal to the system can change the potential energy of that system. **CON-1.B:** a. Explain how the general relationship between potential energy functions and conservative forces are used to determine relationships between the two physical quantities. b. Derive an expression that represents the relationship between a conservative force acting in a system on an object to the potential energy of the system using the methods of calculus.	**CON-1.B.1:** A definition that relates conservative forces internal to the system to the potential energy function of the system is: $\Delta U = -\int_a^b \vec{F}_{cf} \cdot d\vec{r}$ i. **CON-1.B.1.i:** The differential version (in one dimension) of this relationship is: $F_x = -\frac{dU(x)}{dx}$	7.8, pp. 171–173

	CON-1: Conservative forces internal to the system can change the potential energy of that system. **CON-1.C:** Describe the force within a system and the potential energy of a system.	**CON-1.C.1:** The general relationship between a conservative force and a potential energy function can be described qualitatively and graphically. For example, basic curve sketching principles can be applied to generate a sketch (slopes, area under the curve, intercepts, etc.).	7.6, pp. 165–169 7.8, pp. 171–173
	CON-1: Conservative forces internal to the system can change the potential energy of that system. **CON-1.D:** a. Derive the expression for the potential energy function of an ideal spring. b. Derive an expression for the potential energy function of a nonideal spring that has a nonlinear relationship with position.	**CON-1.D.1:** An ideal spring acting on an object is an example of a conservative force within a system (spring-object system). The ideal spring relationship is modeled by the following law and is also called "linear spring": $\vec{F}_s = -k\Delta\vec{x}$ i. **CON-1.D.1.i:** Using the general relationship between conservative force and potential energy, the potential energy for an ideal spring can be shown as: $U_s = \frac{1}{2}k(\Delta x)^2$ ii. **CON-1.D.1.ii:** Nonlinear spring relationships can also be explored. These nonlinear forces are conservative since they are internal to the system (of spring-object) and dependent on position.	7.6, pp. 167–169 15.1, p. 387
	CON-1: Conservative forces internal to the system can change the potential energy of that system. **CON-1.E:** Calculate the potential energy of a system consisting of an object in a uniform gravitational field.	**CON-1.E.1:** The definition of the gravitational potential energy of a system consisting of the Earth and on object of mass *m* near the surface of the Earth is: $\Delta U_g = mg\Delta h$	7.6, pp. 165–166 7.8, pp. 171–173
	CON-1: Conservative forces internal to the system can change the potential energy of that system. **CON-1.F:** Derive an expression for the gravitational potential energy of a system consisting of a satellite	**CON-1.F.1:** Using the relationship between the conservative force and potential energy, it can be shown that the gravitational potential energy of the object–Earth system is: $U_G = -\frac{Gm_1m_2}{r}$ **CON-1.F.1.i:** The potential energy of the earth–	13.5, pp. 345–346

	or large mass (e.g., an asteroid) and the Earth at a great distance from the Earth.	mass system is defined to be zero at an infinite distance from the earth.	
Topic 3.3: Conservation of Energy	**CON-2:** The energy of a system can transform from one form to another without changing the total amount of energy in the system. **CON-2.A:** a. Describe physical situations in which mechanical energy of an object in a system is converted to other forms of energy in the system. b. Describe physical situations in which the total mechanical energy of an object in a system changes or remains constant.	**CON-2.A.1:** If only forces internal to the system are acting on an object in a physical system, then the total change in mechanical energy is zero. i. **CON-2.A.1.i:** Total mechanical energy is defined as the sum of potential and kinetic energy: $E = U_g + K + U_s$ ii. **CON-2.A.1.ii:** When nonconservative forces are acting on the system, the work they do changes the total energy of the system as follows: $W_{nc} = \Delta E$	8.1–8.2, pp. 182–191 8.4, pp. 194–200
	CON-2: The energy of a system can transform from one form to another without changing the total amount of energy in the system. **CON-2.B:** Describe kinetic energy, potential energy, and total energy in relation to time (or position) for a “conservative” mechanical system.	**CON-2.B.1:** In systems in which no external work is done, the total energy in that system is a constant. This is sometimes called a “conservative system.” **CON-2.B.1.i:** Some common systems that are frequently analyzed in this way are systems such as pendulum systems, ball/rollercoaster track, frictionless ramps or tracks, or mass/spring oscillator.	8.2, pp. 185–191
	CON-2: The energy of a system can transform from one form to another without changing the total amount of energy in the system. **CON-2.C:** a. Calculate unknown quantities (e.g., speed or positions of an object) that are in a conservative system of connected objects, such as the masses in Atwood machine, masses connected with pulley/string combinations, or the masses in a modified Atwood machine.	**CON-2.C.1:** The application of the conservation of total mechanical energy can be used in many physical situations.	8.1–8.2, pp. 182–191 8.4, pp. 199–200

	b. Calculate unknown quantities, such as speed or positions of an object that is under the influence of an ideal spring. c. Calculate unknown quantities, such as speed or positions of an object that is moving under the influence of some other nonconstant one-dimensional force.		
	CON-2: The energy of a system can transform from one form to another without changing the total amount of energy in the system. **CON-2.D:** Derive expressions such as positions, heights, angles, and speeds for an object in vertical circular motion or pendulum motion in an arc.	**CON-2.D.1:** In some cases, both Newton's second law and conservation of energy must be applied simultaneously to determine unknown physical characteristics in a system. One such example frequently explored is an object in a vertical circular motion in earth's gravity. A full treatment of force analysis and energy analysis would be required to determine some of the unknown features of the motion, such as the speed of the object at certain locations in the circular path.	13.6, pp. 347–350
Topic 3.4: Power	**CON-3:** The energy of an object or system can be changed at different rates. **CON-3.A:** a. Derive an expression for the rate at which a force does work on an object. b. Calculate the amount of power required for an object to maintain a constant acceleration. c. Calculate the amount of power required for an object to be raised vertically at a constant rate.	**CON-3.A.1:** Power is defined by the following expressions: i. **CON-3.A.1.i:** $P = \frac{dE}{dt}$ ii. **CON-3.A.1.ii:** $P = \vec{F} \cdot \vec{v}$	8.5, pp. 200–202

Unit 4: Systems of Particles and Linear Momentum

Suggested Length: 8 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 4:** Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 4.1: Center of Mass	**CHA-3:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. **CHA-3.A:** a. Calculate the center of mass of a system of point masses or a system of regular symmetrical objects. b. Calculate the center of mass of a thin rod of nonuniform density using integration.	**CHA-3.A.1:** A symmetrical, regular solid of uniform mass density has a center of mass at its geometric center. i. **CHA-3.A.1.i:** For a nonuniform solid that can be considered as a collection of regular masses or for a system of masses: $$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$$ ii. **CHA-3.A.1.ii:** The calculus definition: $$x_{cm} = \frac{\int x\,dm}{\int dm}$$	9.6, pp. 230–234
	CHA-3: The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. **CHA-3.B:** Describe the motion of the center of the mass of a system for various situations.	**CHA-3.B.1:** If there is no net force acting on an object or system, the center of mass does not accelerate; therefore, the velocity of the center of mass remains unchanged. i. **CHA-3.B.1.i:** A system of multiple objects can be represented as one single mass with a position represented by the center of mass. ii. **CHA-3.B.1.ii:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.	9.7, pp. 234–237
	CHA-3: The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. **CHA-3.C:** Explain the difference between	**CHA-3.C.1:** The center of gravity is not precisely the same scientific quantity as the center of mass. If the object experiencing a gravitational interaction with a large planet is of large dimensions (comparable to the planet), then the gravitational acceleration due to the large planet will be a nonuniform value over the length of the object. This would result in the center of gravity	12.2, pp. 312–313

	the terms “center of gravity” and “center of mass,” and identify physical situations when these terms have identical positions and when they have different positions.	location being a different location than the center of mass.	
Topic 4.2: Impulse and Momentum	**INT-5:** An impulse exerted on an object will change the linear momentum of the object. **INT-5.A:** a. Calculate the total momentum of an object or system of objects. b. Calculate relationships between mass, velocity, and linear momentum of a moving object.	**INT-5.A.1:** For a single object moving with some velocity, momentum is defined as: $\vec{p} = m\vec{v}$ **INT-5.A.1.i:** The total momentum of the system is the vector sum of the momenta of the individual objects.	9.1, pp. 211–213
	INT-5: An impulse exerted on an object will change the linear momentum of the object. **INT-5.B:** Calculate the quantities of force, time of collision, mass, and change in velocity from an expression relating impulse to change in linear momentum for a collision of two objects.	**INT-5.B.1:** Impulse is defined as the average force acting over a time interval: $\vec{J} = \vec{F}_{avg}\Delta t$ Impulse is also equivalent to the change in momentum of the object receiving the impulse. $\int \vec{F}\,dt = \Delta\vec{p} = \vec{J}$	9.3, pp. 215–219
	INT-5: An impulse exerted on an object will change the linear momentum of the object. **INT-5.C:** Describe relationships between a system of objects’ individual momenta and the velocity of the center of mass of the system of objects.	**INT-5.C.1:** A collection of objects with individual momenta can be described as one system with one center of mass velocity	9.7, pp. 234–236
	INT-5: An impulse exerted on an object will change the linear momentum of the object. **INT-5.D:** Calculate the momentum change in a collision using a force versus time graph for a collision.	**INT-5.D.1:** Impulse is equivalent to the area under a force versus time graph.	9.3, p. 217

	INT-5: An impulse exerted on an object will change the linear momentum of the object. **INT-5.E:** Calculate the change in momentum of an object given a nonlinear function, *F(t)*, for a net force acting on the object.	**INT-5.E.1:** Momentum changes can be calculated using the calculus relationship for impulse: $\vec{J} = \Delta\vec{p} = \int \vec{F}\,dt$	9.3, pp. 216–219
Topic 4.3: Conservation of Linear Momentum, Collisions	**CON-4:** In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.A:** a. Calculate the velocity of one part of a system after an explosion or collision of the system. b. Calculate energy changes in a system that undergoes a collision or explosion.	**CON-4.A.1:** Total momentum is conserved in the system and momentum is conserved in each direction in the absence of an external force.	9.4–9.5, pp. 219–230
	CON-4: In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.B:** Calculate the changes of momentum and kinetic energy as a result of a collision between two objects.	**CON-4.B.1:** In the absence of an external force, momentum is always conserved. i. **CON-4.B.1.i:** Kinetic energy is only conserved in elastic collisions. ii. **CON-4.B.1.ii:** In an inelastic collision some kinetic energy is transferred to internal energy of the system.	9.4, pp. 219–221
	CON-4: In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.C:** Describe the quantities that are conserved in a collision.	**CON-4.C.1:** Momentum is a vector quantity. i. **CON-4.C.1.i:** Momentum in each dimension is conserved in the absence of a net external force exerted on the object or system. ii. **CON-4.C.1.ii:** Kinetic energy is conserved only if the collision is totally elastic.	9.4, p. 220

	CON-4: In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.D:** Calculate the speed of the center of mass of a system.	**CON-4.D.1:** Forces internal to a system do not change the momentum of the center of mass.	9.7, pp. 234–237
	CON-4: In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.E:** a. Calculate the changes in speeds, changes in velocities, changes in kinetic energy, or changes in momenta of objects in all types of collisions (elastic or inelastic) in one dimension, given the initial conditions of the objects. b. Derive expressions for the conservation of momentum for a particular collision in one dimension.	**CON-4.E.1:** Conservation of momentum states that the momentum of a system remains constant when there are no external forces exerted on the system. i. **CON-4.E.1.i:** Momentum is a vector quantity. ii. **CON-4.E.1.ii:** An elastic collision is defined as a system where the total kinetic energy is conserved in the collision.	9.4, pp. 219–227
	CON-4: In the absence of an external force, the total momentum within a system can transfer from one object to another without changing the total momentum in the system. **CON-4.F:** a. Calculate the changes in speeds, changes in velocities, changes in kinetic energy, or changes in momenta of objects involved in a two-dimensional collision (including an elastic collision), given the initial conditions of the objects.	**CON-4.F.1:** In the absence of a net external force during an interaction, linear momentum is conserved. i. **CON-4.F.1.i:** Momentum is a vector quantity. The momenta in each dimension (horizontal and vertical) are also conserved. ii. **CON-4.F.1.ii:** Using momentum components can be useful in this approach.	9.5, pp. 227–230

	b. Derive expressions for the conservation of momentum for a particular two-dimensional collision of two objects.		

Unit 5: Rotation

Suggested Length: 12 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 4:** Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 5.1: Torque and Rotational Statics	**INT-6:** When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. **INT-6.A:** a. Calculate the magnitude and direction of the torque associated with a given force acting on a rigid body system. b. Calculate the torque acting on a rigid body due to the gravitational force.	**INT-6.A.1:** The definition of torque is: $\vec{\tau} = \vec{r} \times \vec{F}$ i. **INT-6.A.1.i:** Torque is a vector product (or cross-product) and it has a direction that can be determined by the vector product or by applying the appropriate right-hand rule. ii. **INT-6.A.1.ii:** The idea of the "moment-arm" is useful when computing torque. The moment arm is the perpendicular distance between the pivot point and the line of action of the point of application of the force. The magnitude of the torque vector is equivalent to the product of the moment arm and the force.	10.4–10.5, pp. 257–263 11.1, pp. 286–288
	INT-6: When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. **INT-6.B:** a. Describe the two conditions of equilibrium for an extended rigid body. b. Calculate unknown magnitudes and directions of forces acting on an extended rigid body that is in a state of translational and rotational equilibrium.	**INT-6.B.1:** The two conditions of equilibrium are: i. **INT-6.B.1.i:** $\sum \vec{F} = 0$ ii. **INT-6.B.1.ii:** $\sum \vec{\tau} = 0$ **INT-6.B.2:** Both conditions must be satisfied for an extended rigid body to be in equilibrium.	12.1, pp. 311–312 12.3, pp. 313–319

	INT-6: When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. **INT-6.C:** a. Explain the differences in the moments of inertia between different objects such as rings, discs, spheres, or other regular shapes by applying the general definition of moment of inertia (rotational inertia) of a rigid body. b. Calculate by what factor an object's rotational inertia will change when a dimension of the object is changed by some factor. c. Calculate the moment of inertia of point masses that are located in a plane about an axis perpendicular to the plane.	**INT-6.C.1:** The general definition of moment of inertia is: $I = \sum m_i r_i^2$	10.6, pp. 263–267
	INT-6: When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. **INT-6.D:** a. Derive the moment of inertia, using calculus, of a thin rod of uniform density about an arbitrary axis perpendicular to the rod. b. Derive the moment of inertia, using calculus, of a thin rod of nonuniform density about an arbitrary axis perpendicular to the rod. c. Derive the moments of inertia for a thin cylindrical shell or disc about its axis or an object that can be considered to be made up	**INT-6.D.1:** The calculus definition of moment of inertia is: $I = \int r^2 dm$ **INT-6.D.1.i:** The differential *dm* must be determined from the linear mass density of the rod or object.	10.6, pp. 263–267

	of coaxial shells (e.g., annular ring).		
	INT-6: When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. **INT-6.E:** Derive the moments of inertia of an extended rigid body for different rotational axes (parallel to an axis that goes through the object's center of mass) if the moment of inertia is known about an axis through the object's center of mass.	**INT-6.E.1:** The parallel axis theorem is a simple powerful theorem that allows the moments of inertia to be computed for an object through any axis that is parallel to an axis through its' center of mass. $I' = I_{cm} + Md^2$	10.7, p. 266
Topic 5.2: Rotational Kinematics	**CHA-4:** There are relationships among the physical properties of angular velocity, angular position, and angular acceleration. **CHA-4.A:** a. Explain how the angular kinematic relationships for uniform angular acceleration are directly analogous to the relationships for uniformly linearly accelerated motion. b. Calculate unknown quantities such as angular positions, displacement, angular speeds, or angular acceleration of a rigid body in uniformly accelerated motion, given initial conditions. c. Calculate unknown quantities such as angular positions, displacement, angular velocity, or rotational kinetic energy of a rigid body rotating with a specified nonuniform angular acceleration.	**CHA-4.A.1:** There are angular kinematic relationships for objects experiencing a uniform angular acceleration. These are the relationships: $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$ $\omega = \omega_0 + \alpha t$ Other relationships can be derived from the above two relationships. i. **CHA-4.A.1.i:** The appropriate unit for angular position is radians. ii. **CHA-4.A.1.ii:** The general calculus kinematic linear relationships have analogous representations in rotational motion such as: $\omega = \frac{d\theta}{dt}$	10.1–10.3, pp. 250–257

	CHA-4: There are relationships among the physical properties of angular velocity, angular position, and angular acceleration. **CHA-4.B:** a. Explain the use of the relationships that connect linear translational motion to rotational motion, in appropriate physical situations. b. Calculate the translational kinematic quantities from an object's rotational kinematic quantities for objects that are rolling without slipping. c. Calculate the (tangential) linear acceleration of a point on a rotating object given the object's angular acceleration.	**CHA-4.B.1:** For objects that are rolling without slipping on a surface, the angular motion is related to the linear translational motion by the following relationships: $v = r\omega$ $a = r\alpha$ $\Delta x = r\Delta\theta$	10.3, pp. 254–257 10.8, p. 270
Topic 5.3: Rotational Dynamics and Energy	**INT-7:** A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. **INT-7.A:** a. Describe the complete analogy between fixed axis rotation and linear translation for an object subject to a net torque. b. Calculate unknown quantities such as net torque, angular acceleration, or moment of inertia for a rigid body undergoing rotational acceleration. c. Calculate the angular acceleration of an extended rigid body, of known moment of inertia, about a	**INT-7.A.1:** The rotational analog to Newton's second law is: $\vec{\alpha} = \frac{\sum \vec{\tau}}{I}$ **INT-7.A.1.i:** In the appropriate cases, both laws (Newton's second law and the analogous rotational law) can be applied to a dynamic system and the two laws are independent from each other.	10.5, pp. 259–263

	fixed axis or about its center of mass when it is experiencing a specified net torque due to one or several applied forces.		
	INT-7: A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. **INT-7.B:** a. Describe the net torque experienced by a rigid extended body in situations such as, but not limited to, rolling down inclines, pulled along horizontal surfaces by external forces, a pulley system (with rotational inertia), simple pendulums, physical pendulums, and rotating bars. b. Derive an expression for all torques acting on a rigid body in various physical situations using Newton's second law of rotation.	**INT-7.B.1:** All real forces acting on an extended rigid body can be represented by a rigid body diagram. The point of application of each force can be indicated in the diagram. i. **INT-7.B.1.i:** The rigid body diagram is helpful in applying the rotational Newton's second law to a rotating body.	10.4, pp. 257–263 15.5, pp. 402–404
	INT-7: A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. **INT-7.C:** Derive expressions for physical systems such as Atwood Machines, pulleys with rotational inertia, or strings connecting discs or strings connecting multiple pulleys that relate linear or translational motion characteristics to the angular motion characteristics of rigid bodies in the system that are: (a) rolling (or rotating on a fixed axis) without slipping. (b) rotating and sliding simultaneously.	**INT-7.C.1:** A complete analysis of a dynamic system that is rolling without slipping can be performed by applying both of Newton's second laws properly to the system. i. **INT-7.C.1.i:** The rotational characteristics may be related to the linear motion characteristics with the relationships listed in section 5.B. (i.e., $v = r\omega$) ii. **INT-7.C.1.ii:** If the rigid body undergoing motion has a rotational component of motion and an independent translational motion (i.e., the object is slipping), then the rolling condition relationships do not hold. ($v \neq r\omega$)	10.9, pp. 272–277

	INT-7: A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. **INT-7.D:** a. Calculate the rotational kinetic energy of a rotating rigid body. b. Calculate the total kinetic energy of a rolling body or a body that has both translation and rotational motion. c. Calculate the amount of work done on a rotating rigid body by a specified force applied to the rigid body over a specified angular displacement.	**INT-7.D.1:** The definition of rotational kinetic energy is: $K_R = \frac{1}{2} I\omega^2$ i. **INT-7.D.1.i:** Total kinetic energy of a rolling body or a body with both forms of motion is the sum of each kinetic energy term. ii. **INT-7.D.1.ii:** The definition of work also has an analogous form in rotational dynamics: $W = \int \tau \, d\theta$	10.7–10.9, pp. 267–277
	INT-7: A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. **INT-7.E:** Derive expressions using energy conservation principles for physical systems such as rolling bodies on inclines, Atwood Machines, pendulums, physical pendulums, and systems with massive pulleys that relate linear or angular motion characteristics to initial conditions (such as height or position) or properties of rolling body (such as moment of inertia or mass).	**INT-7.E.1:** If a rigid body is defined as “rolling,” this implies (in the ideal case) that the frictional force does no work on the rolling object. The consequence of this property is that in some special cases (such as a sphere rolling down an inclined surface), the conservation of mechanical energy can be applied to the system.	10.7–10.9, pp. 267–277
Topic 5.4: Angular Momentum and Its Conservation	**CON-5:** In the absence of an external torque, the total angular momentum of a system can transfer from one object to another within the system without changing the total angular momentum of the system. **CON-5.A:** a. Calculate the angular	**CON-5.A.1:** The definition of angular momentum of a rotating rigid body is: $\vec{L} = I\vec{\omega}$ i. **CON-5.A.1.i:** Angular impulse is equivalent to the change in angular momentum. The definition of this relationship is:	11.2–11.3, pp. 288–295

	impulse acting on a rotating rigid body given specified angular properties or forces acting over time intervals. b. Calculate the angular momentum vector of a rotating rigid body in cases in which the vector is parallel to the angular velocity vector.	$\int \vec{\tau} dt = \Delta \vec{L}$ ii. **CON-5.A.1.ii:** or the differential definition: $\vec{\tau} = \frac{d\vec{L}}{dt}$	
	CON-5: In the absence of an external torque, the total angular momentum of a system can transfer from one object to another within the system without changing the total angular momentum of the system. **CON-5.B:** Calculate the angular momentum vector of a linearly translating particle about a defined stationary point of reference.	**CON-5.B.1:** The angular momentum of a linearly translating particle can be defined about some arbitrary point of reference or origin. The definition is: $\vec{L} = \vec{r} \times \vec{p}$ i. **CON-5.B.1.i:** The direction of this particle's angular momentum is determined by the vector product (cross-product).	11.2–11.3, pp. 288–295
	CON-5: In the absence of an external torque, the total angular momentum of a system can transfer from one object to another within the system without changing the total angular momentum of the system. **CON-5.C:** a. Describe the conditions under which a rotating system's angular momentum is conserved. b. Explain how a one- or two-particle system (rotating object or satellite orbits) may have a change in angular velocity when other properties of the system change (such as radius or inertia).	**CON-5.C.1:** In the absence of external torques acting on a rotating body or system, the total angular momentum of the system is a constant.	11.4, pp. 295–300

	CON-5: In the absence of an external torque, the total angular momentum of a system can transfer from one object to another within the system without changing the total angular momentum of the system. **CON-5.D:** a. Calculate changes in angular velocity of a rotating rigid body when the moment of inertia of the body changes during the motion (such as a satellite in orbit). b. Calculate the increase or decrease in angular momentum of a rigid body when a point mass particle has a collision with the rigid body. c. Calculate the changes of angular momentum of each disc in a rotating system of two rotating discs that collide with each other inelastically about a common rotational axis.	**CON-5.D.1:** The conservation of angular momentum can be applied to many types of physical situations. In all cases, it must be determined that there is no net external torque on the system. i. **CON-5.D.1.i:** In the case of collisions (such as two discs colliding with each other), the torques applied to each disc are "internal" if the system is considered to be the two discs. ii. **CON-5.D.1.ii:** In the case of a particle colliding with a rod or physical pendulum, the system is considered to be the particle and the rod together.	10.7–10.9, pp. 267–277

Unit 6: Oscillations

Suggested Length: 6 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 4:** Conservation laws constrain interactions.

Topic	**Enduring Understanding and Learning Objective**	**Essential Knowledge**	**Text Section(s)**
Topic 6.1: Simple Harmonic Motion, Springs, and Pendulums	**INT-8:** There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.A:** a. Describe the general behavior of a spring-mass system in Simple Harmonic Motion (SHM) in qualitative terms. b. Describe the relationship between the phase angle and amplitude in a SHM system.	**INT-8.A.1:** The general relationship for SHM is given by the following relationship: $x = x_{\max}\cos(\omega t + \varphi)$ φ is the phase angle and $x_{\max}$ is the amplitude of the oscillation. This expression can be simplified given initial conditions of the system	15.1, pp. 387–388 15.2, pp. 388–394
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.B:** a. Describe the displacement in relation to time for a mass/spring system in SHM. b. Identify the period, frequency, and amplitude of the SHM in a mass/spring system from the features of a plot.	**INT-8.B.1:** The period of SHM is related to the angular frequency by the following relationship: $T = \frac{2\pi}{\omega} = \frac{1}{f}$	15.2, pp. 388–394
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.C:** a. Describe each of the three kinematic characteristics of a spring-mass system in SHM in relation to time	**INT-8.C.1:** Using calculus and the position in relation to time relationship for an object in SHM, all three kinematic characteristics can be explored. Recognizing the positions or times where the trigonometric functions have extrema or zeroes can provide more detail in qualitatively describing the behavior of the motion.	15.2, pp. 388–394

	(displacement, velocity, and acceleration). b. For a spring-mass system in SHM: o Describe the general features of the motion; and o Identify the places on a graph where these values are zero or have maximum positive values or maximum negative values.		
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.D:** Derive a differential equation to describe Newton's second law for a spring-mass system in SHM or for the simple pendulum.	**INT-8.D.1:** Using Newton's second law, the following characteristic differential equation of SHM can be derived: $\frac{d^2x}{dt^2} = -\omega^2 x$ The physical characteristics of the spring-mass system (or pendulum) can be determined from the differential relationship.	15.2, pp. 388–394
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.E:** Calculate the position, velocity, or acceleration of a spring-mass system in SHM at any point in time or at any known position from the initial conditions and known spring constant and mass.	**INT-8.E.1:** All of the characteristics of motion in SHM can be determined by using the general relationship $x = x_{\max} \cos(\omega t + \varphi)$ and calculus relationships.	15.2, pp. 388–394
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.F:** Derive the expression for the period of oscillation for various physical systems oscillating in SHM.	**INT-8.F.1:** The period can be derived from the characteristic differential equation. The following types of SHM systems can be explored: i. **INT-8.F.1.i:** Mass oscillating on spring in vertical orientation. ii. **INT-8.F.1.ii:** Mass oscillating on spring in horizontal orientation. iii. **INT-8.F.1.iii:** Mass/spring system with springs in series or parallel.	15.2, pp. 388–394 15.5, pp. 400–404

		iv. **INT-8.F.1.iv:** Simple pendulum. v. **INT-8.F.1.v:** Physical pendulum. vi. **INT-8.F.1.vi:** Torsional pendulum.	
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.G:** Calculate the mechanical energy of an oscillating system. Show that this energy is conserved in an ideal SHM spring-mass system.	**INT-8.G.1:** Potential energy can be calculated using the spring constant and the displacement from equilibrium of a mass-spring system: $U_s = \frac{1}{2}k(\Delta x)^2$ i. **INT-8.G.1.i:** Mechanical energy is always conserved in an ideal oscillating spring/mass system. ii. **INT-8.G.1.ii:** Maximum potential energy occurs at maximum displacement, where velocity is zero and kinetic energy is zero. This maximum potential energy is equivalent to the total mechanical energy of the system. iii. **INT-8.G.1.iii:** These energy relationships are true in the following three types of SHM systems: ○ **INT-8.G.1.iii-a:** Mass/spring in horizontal orientation. ○ **INT-8.G.1.iii-b:** Mass/spring in vertical orientation. ○ **INT-8.G.1.iii-c:** Simple pendulum.	15.3, pp. 394–398
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.H:** Describe the effects of changing the amplitude of a spring-mass system.	**INT-8.H.1:** Total energy of a spring-mass system is proportional to the square of the amplitude. $E_{total} = \frac{1}{2}kA^2 = \frac{1}{2}kx^2_{max}$ i. **INT-8.H.1.i:** The total energy is composed of the two contributing mechanical energies of the spring-mass system. $E_{total} = K + U_s$	15.1–15.3, pp. 387–397
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.I:**	**INT-8.I.1:** The total mechanical energy of a system in SHM is conserved. The potential energy of the spring-mass system is: $U_s = \frac{1}{2}k(\Delta x)^2$	15.3, pp. 394–397

	Describe the kinetic energy as a function of time (or position), potential energy as a function of time (or position), and total mechanical energy as a function of time (or position) for a spring/mass system in SHM, identifying important features of the oscillating system and where these features occur.	and the kinetic energy of the system is: $K = \frac{1}{2}mv^2$ The total energy in the system is defined above in **INT-8.H.1.**	
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.J:** Explain how the model of SHM can be used to determine characteristics of motion for other physical systems that can exhibit this behavior.	**INT-8.J.1:** Any physical system that creates a linear restoring force ($\vec{F}_{rest} = -k\Delta\vec{x}$) will exhibit the characteristics of simple harmonic motion.	15.1, pp. 387–388
	INT-8: There are certain types of forces that cause objects to repeat their motions with a regular pattern. **INT-8.K:** Describe a linear relationship between the period of a system oscillating in SHM and physical constants of the system.	**INT-8.K.1:** The period of a system oscillating in SHM is $T = 2\pi\sqrt{\frac{m}{k}}$ (or its equivalent for a pendulum or physical pendulum) and this can be shown to be true experimentally from a plot of the appropriate data. $T = 2\pi\sqrt{\frac{l}{g}}$	15.2, p. 390 15.5, p. 401

Unit 7: Gravitation

Suggested Length: 6 class periods

- **Big Idea 1:** Interactions that produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4:** Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 7.1: Gravitational Forces	**FLD-1:** Objects of large mass will cause gravitational fields that create an interaction at a distance with other objects with mass. **FLD-1.A:** Calculate the magnitude of the gravitational force between two large spherically symmetrical masses.	**FLD-1.A.1:** The magnitude of the gravitational force between two masses can be determined by using Newton's Universal Law of Gravitation. $\left\|\vec{F}_G\right\| = \frac{Gm_1m_2}{r^2}$	13.1, pp. 333–335
	FLD-1: Objects of large mass will cause gravitational fields that create an interaction at a distance with other objects with mass. **FLD-1.B:** Calculate the value for "g" or gravitational acceleration on the surface of earth (or some other large planetary object) and at other points outside of the earth.	**FLD-1.B.1:** Using Newton's laws it can be shown that the value for gravitational acceleration at the surface of the earth is: $g = \frac{GM_e}{R_e^2}$ and if the point of interest is located far from the earth's surface, then g becomes: $g = \frac{GM_e}{r^2}$	13.2–13.3, pp. 335–339
	FLD-1: Objects of large mass will cause gravitational fields that create an interaction at a distance with other objects with mass. **FLD-1.C:** Describe the motion in a qualitative way, of an object under the influence of a variable gravitational force, such as in the case where an object falls toward the earth's surface when dropped from distances much	**FLD-1.C.1:** The gravitational force is proportional to the inverse of distance squared; therefore, the acceleration of an object under the influence of this type of force will be nonuniform.	13.2–13.3, pp. 335–339

	larger than the earth's radius.		
Topic 7.2: Orbits of Planets and Satellites	**CON-6:** Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.A:** Calculate quantitative properties (such as period, speed, radius of orbit) of a satellite in circular orbit around a planetary object.	**CON-6.A.1:** The centripetal force acting on a satellite is provided by the gravitational force between satellite and planet. **CON-6.A.1.i:** The velocity of a satellite in circular orbit is inversely proportional to the square root of the radius and is independent of the satellite's mass.	13.6, pp. 347–350
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.B:** Derive Kepler's Third Law for the case of circular orbits.	**CON-6.B.1**: In a circular orbit, Newton's second law analysis can be applied to the satellite to determine the orbital velocity relationship for satellite of mass *m* about a central body of mass *M*. i. **CON-6.B.1.i:** With proper substitutions, this can be reduced to expressing the period's dependence on orbital distance as Kepler's Third Law shows: $T^2 = \frac{4\pi^2}{GM} r^3$	13.4, pp. 342–343
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.C:** Describe a linear relationship to verify Kepler's Third Law.	**CON-6.C.1:** Verifying Kepler's third law with actual data provides experimental verification of the law.	13.4, pp. 342–343
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.D:** Calculate the gravitational potential energy and the kinetic energy of a satellite/Earth system in which the satellite is in circular orbit around the earth.	**CON-6.D.1:** The gravitational potential energy of a satellite/Earth system (or other planetary/satellite system) in orbit is defined by the potential energy function of the system: $U_g = -\frac{Gm_e m_{sat}}{r}$ i. **CON-6.D.1.i:** The kinetic energy of a satellite in circular orbit can be reduced to an expression that is only dependent on the satellite's system and position.	13.5, pp. 345–347

	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.E:** Derive the relationship of total mechanical energy of a satellite/earth system as a function of radial position.	**CON-6.E.1:** The total mechanical energy of a satellite is inversely proportional to the orbital distance and is always a negative value and equal to one half of the gravitational potential energy.	13.6, pp. 347–349
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.F:** a. Derive an expression for the escape speed of a satellite using energy principles b. Describe the motion of a satellite launched straight up (or propelled toward the planet) from the planet's surface, using energy principles.	**CON-6.F.1:** In ideal situations, the energy in a planet/satellite system is a constant. i. **CON-6.F.1.i**: The gravitational potential energy of planet/satellite system is defined to have a zero value when the satellite is at an infinite distance (very large planetary distance) away from the planet. ii. **CON-6.F.1.ii:** By definition, the "escape speed" is the minimum speed required to escape the gravitational field of the planet. This could occur at a minimum when the satellite reaches a nominal speed of approximately zero at some very large distance away from the planet.	13.6, pp. 347–350
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.G:** Calculate positions, speeds, or energies of a satellite launched straight up from the planet's surface, or a satellite that is projected straight toward the planet's surface, using energy principles.	**CON-6.G.1:** In ideal nonorbiting cases, a satellite's physical characteristics of motion can be determined using the conservation of energy.	13.6, pp. 347–350
	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.H:** Describe elliptical satellite orbits using Kepler's three laws of planetary motion.	**CON-6.H.1:** The derivation of Kepler's Third Law is only required for a satellite in a circular orbit.	13.4, pp. 339–343

	CON-6: Angular momentum and total mechanical energy will not change for a satellite in an orbit. **CON-6.I:** a. Calculate the orbital distances and velocities of a satellite in elliptical orbit using the conservation of angular momentum. b. Calculate the speeds of a satellite in elliptical orbit at the two extremes of the elliptical orbit (perihelion and aphelion).	**CON-6.I.1:** In all cases of orbiting satellites, the total angular momentum of the satellite is a constant. i. **CON-6.I.1.i:** The conservation of mechanical energy and the conservation of angular momentum can both be used to determine speeds at different positions in the elliptical orbit.	13.4, pp. 341–342

Correlation with the 2019 Updated AP® Physics Curriculum Framework

Physics for Scientists and Engineers,
Physics C: Electricity and Magnetism

TENTH EDITION

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Unit 1: Electrostatics

AP® Exam Weighting: 21 class periods

- **Big Idea 1:** Interactions produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4**: Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 1.1: Electrostatics: Charge and Coulomb's Law	**ACT-1:** Objects with an electric charge will interact with each other by exerting forces on each other. **ACT-1.A:** Describe behavior of charges or system of charged objects interacting with each other.	**ACT-1.A.1:** Particles and objects may contain electrostatic charges. The law of electrostatics states that like charges repel and unlike charges attract through electrostatic interactions.	22.1, pp. 589–590
	ACT-1: Objects with an electric charge will interact with each other by exerting forces on each other. **ACT-1.B:** Explain and/or describe the behavior of a neutral object in the presence of a charged object or a system of charges.	**ACT-1.B.1:** The presence of an electric field will polarize a neutral object (conductor or insulator). This can create an "induced" charge on the surface of the object. **ACT-1.B.1.i:** As a consequence of this polarization, a charged object can interact with a neutral object, producing a net attraction between the charged object and the neutral object.	22.2, pp. 591–592 22.1, p. 590
	ACT-1: Objects with an electric charge will interact with each other by exerting forces on each other. **ACT-1.C:** a. Calculate the net electrostatic force on a single point charge due to other point charges. b. Calculate unknown quantities such as the force acting on a specified charge or the distances between charges in a system of static point charges.	**ACT-1.C.1:** Point charge is defined as a charged object where the object is of negligible mass and size and takes up virtually no space. **ACT-1.C.1.i:** The magnitude of electrostatic force between two point charges is given by Coulomb's law: $\left\|\vec{F}\right\| = \frac{1}{4\pi\varepsilon_o}\left\|\frac{q_1 q_2}{r^2}\right\|$ **ACT-1.C.1.ii:** Net force can be determined by superposition of all forces acting on a point charge due to the vector sum of other point charges.	22.3, pp. 593–598

	ACT-1: Objects with an electric charge will interact with each other by exerting forces on each other. **ACT-1.D:** Determine the motion of a charged object of specified charge and mass under the influence of an electrostatic force.	**ACT-1.D.1:** Knowing the force acting on the charged object and the initial conditions of the charged object (such as initial velocity), the motion of the object (characteristics such as the acceleration, velocity and velocity changes, and trajectory of the object) can be determined.	22.3, pp. 593–598 22.6, p. 610
Topic 1.2: Electrostatics: Electric Field and Electric Potential	**FIE-1:** Objects with electric charge will create an electric field. **FIE-1.A:** Using the definition of electric field, unknown quantities (such as charge, force, field, and direction of field) can be calculated in an electrostatic system of a point charge or an object with a charge in a specified electric field.	**FIE-1.A.1:** The definition of electric field is defined as: $\vec{E} = \frac{\vec{F}}{q}$ where *q* is defined as a "test charge." **FIE-1.A.1.i:** A test charge is a small positively charged object of negligible size and mass. **FIE-1.A.1.ii:** The direction of an electric field is the direction in which a test charge would move if placed in the field.	22.4, pp. 598–602
	FIE-1: Objects with electric charge will create an electric field. **FIE-1.B:** Describe and calculate the electric field due to a single point charge.	**FIE-1.B.1:** The electric field of a single point charge can be determined by using the definition of the electric field and Coulomb's law.	22.4, pp. 599–600
	FIE-1: Objects with electric charge will create an electric field. **FIE-1.C:** Describe and calculate the electric field due to a dipole or a configuration of two or more static-point charges.	**FIE-1.C.1:** The electric field due to a configuration of static-point charges can be determined by applying the definition of electric field and the principle of superposition using the vector nature of the fields.	22.4, pp. 601–603
	FIE-1: Objects with electric charge will create an electric field.	**FIE-1.D.1:** Electric-field lines have properties that show the relative magnitude of the electric-field strength and the direction of the electric-field	22.5, pp. 603–605

	FIE-1.D: Explain or interpret an electric-field diagram of a system of charges.	vector at any position in the diagram.	
	FIE-1: Objects with electric charge will create an electric field. **FIE-1.E:** Sketch an electric-field diagram of a single point charge, a dipole, or a collection of static-point charges.	**FIE-1.E.1:** Using the properties of electric-field diagrams, a general-field line diagram can be drawn for static-charged situations.	22.5, pp. 603–605
	FIE-1: Objects with electric charge will create an electric field. **FIE-1.F:** Determine the qualitative nature of the motion of a charged particle of specified charge and mass placed in a uniform electric field.	**FIE-1.F.1:** A charged particle in a uniform electric field will be subjected to a constant electrostatic force.	22.6, pp. 605–607
	FIE-1: Objects with electric charge will create an electric field. **FIE-1.G:** Sketch the trajectory of a known charged particle placed in a known uniform electric field.	**FIE-1.G.1:** The trajectory of a charged particle can be determined when placed in a known uniform electric field. **FIE-1.G.1.i:** The initial conditions of motion are necessary to provide a complete description of the trajectory. **FIE-1.G.1.ii:** The force acting on the particle will be a constant force.	22.6, pp. 605–607
Topic 1.3: Electrostatics: Electric Potential Due to Point Charges and Uniform Fields	**CNV-1:** The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.A:** Calculate the value of the electric potential in the vicinity of one or more point charges.	**CNV-1.A.1:** The definition of electric potential at a particular location due to a single point charge is: $V = \frac{1}{4\pi\varepsilon_o}\frac{q}{r}$ **CNV-1.A.1.i:** The potential due to multiple point charges can be determined by the principle of superposition in scalar terms of the charges by using the following expression: $V = \frac{1}{4\pi\varepsilon_o}\sum_i \frac{q_i}{r_i}$ **CNV-1.A.1.ii:** The electric potential is defined to be zero at an infinite distance from the point charge.	24.3, pp. 642–643

	CNV-1: The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.B:** Mathematically represent the relationships between the electric charge, the difference in electric potential, and the work done (or electrostatic potential energy lost or gained) in moving a charge between two points in a known electric field.	**CNV-1.B.1:** The definition for stored electrostatic potential energy in an electrostatic system of a point charge and a known electric field is: $\Delta U = q\Delta V$	24.1, pp. 637–639
	CNV-1: The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.C:** a. Calculate the electrostatic potential energy of a collection of two or more point charges held in a static configuration. b. Calculate the amount of work needed to assemble a configuration of point charges in some known static configuration.	**CNV-1.C.1:** The electrostatic potential energy of two point charges near each other is defined in this way: $U_E = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r}$ **CNV-1.C.1.i:** The total potential energy of an arrangement of more than two charges is the scalar sum of all of the electrostatic potential energy interactions between each pair of charges.	24.3, pp. 643–645
	CNV-1: The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.D:** Calculate the potential difference between two points in a uniform electric field and determine which point is at the higher potential.	**CNV-1.D.1:** The work done in moving a test charge between two points in a uniform electric field can be calculated. **CNV-1.D.1.i:** Use the definition of electric potential difference and the definition of a conservative field to determine the difference in electric potential in this case.	24.1, pp. 637–638 24.2, pp. 639–640 24.4, pp. 645–646
	CNV-1: The total energy of a system composed of a collection of point charges can transfer	**CNV-1.E.1:** An electrostatic configuration or field is a conservative field, and the work done in an electric field in moving a known charge through a	24.1, p. 637 24.2, p. 641

	from one form to another without changing the total amount of energy in the system. **CNV-1.E:** Calculate the work done or changes in kinetic energy (or changes in speed) of a charge particle when it is moved through some known potential difference.	known electric field is equivalent to the potential energy lost or gained by that charge. Changes in kinetic energy can be determined by using the principle of conservation of energy.	
	CNV-1: The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.F:** a. Describe the relative magnitude and direction of an electrostatic field given a diagram of equipotential lines. b. Describe characteristics of a set of equipotential lines given a diagram of an electric field. c. Describe the general relationship between electric-field lines and a set of equipotential lines for an electrostatic field.	**CNV-1.F.1:** The characteristics and direction of an electric field can be determined from the characteristics of equipotential lines. **CNV-1.F.1.i:** The relative magnitude of an electricfield can be determined by the gradient of the potential lines. **CNV-1.F.1.ii:** The direction of the electric field is defined to be perpendicular to an equipotential line and pointing in the direction of the decreasing potential.	24.2, p. 640 24.6, pp. 651–653
	CNV-1: The total energy of a system composed of a collection of point charges can transfer from one form to another without changing the total amount of energy in the system. **CNV-1.G:** **a.** Use the general relationship between electric field and electric potential to calculate the relationships between the magnitude of electric field or the potential difference as a function of position. **b.** Use integration techniques to calculate a potential difference between two points on a line,	**CNV-1.G.1:** The general definition of potential difference that can be used in most cases is: $\Delta V = V_b - V_a = -\int_a^b \vec{E} \cdot d\vec{r}$ or in the differential form: $E_x = -\frac{dV}{dx}$	24.2, pp. 639–641

	given the electric field as a function of position on that line.		
Topic 1.4: Electrostatics: Gauss's Law	**CNV-2:** There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. **CNV-2.A:** a. State and apply the general definition of electric flux. b. Calculate the electric flux through an arbitrary area or through a geometric shape (i.e., cylinder, sphere, etc.). c. Calculate the flux through a rectangular area when the electric field is perpendicular to the rectangle and is a function of one position coordinate only.	**CNV-2.A.1:** The general definition of electric flux is: $\Phi = \int \vec{E} \cdot d\vec{A}$ **CNV-2.A.1.i:** The definition for the total flux through a geometric closed surface is defined by the "surface integral" defined as: $\varphi_{surface} = \oint \vec{E} \cdot d\vec{A}$ **CNV-2.A.1.ii:** The sign of the flux is given by the dot product between the electric-field vector and the area vector. **CNV-2.A.1.iii:** The area vector is defined to be perpendicular to the plane of the surface and directed outward from a closed surface.	23.2, pp. 620–623 23.3, pp. 623–625 23.4, pp. 625–629
	CNV-2: There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. **CNV-2.B.1:** Gauss's law can be defined in a qualitative way as the total flux through a closed Gaussian surface being proportional to the charge enclosed by the Gaussian surface. The flux is also independent of the size of the Gaussian shape.	**CNV-2.B:** Qualitatively apply Gauss's law to a system of charges or charged region to determine characteristics of the electric field, flux, or charge contained in the system.	23.3–23.4, pp. 623–629
	CNV-2: There are laws that use symmetry and calculus to derive mathematical relationships that	**CNV-2.C.1:** Gauss's law in integral form is: $\oint \vec{E} \cdot d\vec{A} = \frac{q_{enclosed}}{\varepsilon_o}$	23.4, p. 625

	can be applied to physical systems containing electrostatic charge. **CNV-2.C:** State and use Gauss's law in integral form to derive unknown electric fields for planar, spherical, or cylindrically symmetrical charge distributions.		
	CNV-2: There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. **CNV-2.D:** a. Using appropriate mathematics (which may involve calculus), calculate the total charge contained in lines, surfaces, or volumes when given a linear-charge density, a surface-charge density, or a volume-charge density of the charge configuration. b. Use Gauss's law to calculate an unknown charge density or total charge on surface in terms of the electric field near the surface.	**CNV-2.D.1:** In general, if a function of known charge density is given, the total charge can be determined using calculus, such as: $Q_t = \int \rho(r)dV$ The above is the general case for a volume-charge distribution.	23.1, pp. 616–620
	CNV-2: There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. **CNV-2.E:** a. Qualitatively describe electric fields around symmetrically (spherically, cylindrically, or planar) charged distributions. b. Describe the general features of an electric field due to symmetrically shaped charged	**CNV-2.E.1:** Gauss's law can help in describing features of electric fields of charged systems at the surface, inside the surface, or at some distance away from the surface of charged objects.	23.4, pp. 625–629

	distributions.		
	CNV-2: There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. **CNV-2.F:** Describe the general features of an unknown charge distribution, given other features of the system.	**CNV-2.F.1:** Gauss's law can be useful in determining the charge distribution that created an electric field, especially if the distribution is spherically, cylindrically, or planarly symmetric.	23.4, pp. 625–629
Topic 1.5: Electrostatics: Fields and Potentials of Other Charge Distributions	**CNV-3:** There are laws that use calculus and symmetry to derive mathematical relationships that can be applied to electrostatic-charge distributions. **CNV-3.A:** Derive expressions for the electric field of specified charge distributions using integration and the principle of superposition. Examples of such charge distributions include a uniformly charged wire, a thin ring of charge (along the axis of the ring), and semicircular or part of a semicircular arc.	**CNV-3.A.1:** The electric field of any charge distribution can be determined using the principle of superposition, symmetry, and the definition of electric field due to a differential charge dq . One step in the solution is shown to be: $d\vec{E} = \frac{1}{4\pi\varepsilon_o}\frac{dq}{r^2}\hat{r}$ If this is applied appropriately and evaluated over the appropriate limits, the electric fields of the stated charge distributions can be determined as a function of position. The following charge distributions can be explored using this method: **CNV-3.A.1.i:** An infinitely long, uniformly charged wire or cylinder—determine field at distances along perpendicular bisector. **CNV-3.A.1.ii:** A thin ring of charge (along the axis of the ring). **CNV-3.A.1.iii:** A semicircular or part of a semicircular arc. **CNV-3.A.1.iv:** A field due to a finite-wire or line charge at a distance that is collinear with the line charge.	23.1, pp. 616–620 22.4, pp. 599–603

	CNV-3: There are laws that use calculus and symmetry to derive mathematical relationships that can be applied to electrostatic-charge distributions. **CNV-3.B:** a. Identify and qualitatively describe situations in which the direction and magnitude of the electric field can be deduced from symmetry considerations and understanding the general behavior of certain charge distributions. b. Describe an electric field as a function of distance for the different types of symmetrical charge distributions.	**CNV-3.B.1:** The general characteristics of electric fields can be proven from the calculus definitions (or Gauss's law) and/or the principle of superposition. The following electric fields can be explored: **CNV-3.B.1.i:** Electric fields with planar symmetry, infinite sheets of charge, combinations of infinite sheets of charge, or oppositely charged plates. **CNV-3.B.1.ii:** Linearly charged wires or charge distributions. **CNV-3.B.1.iii:** Spherically symmetrical charge distributions on spheres or spherical shells of charge. **CNV-3.B.2:** Other distributions of charge that can be deduced using Gauss's law or the principle of superposition.	23.4, pp. 625–629
	CNV-3: There are laws that use calculus and symmetry to derive mathematical relationships that can be applied to electrostatic-charge distributions. **CNV-3.C:** a. Derive expressions for the electric potential of a charge distribution using integration and the principle of superposition. b. Describe electric potential as a function of distance for the different types of symmetrical charge distributions. c. Identify regions of higher and lower electric potential by using a qualitative (or quantitative) argument to apply to the charged region of space.	**CNV-3.C.1:** The integral definition of the electric potential due to continuous charge distributions is defined as: $V = \frac{1}{4\pi\varepsilon_o}\int \frac{dq}{r}$ If this is applied appropriately and evaluated over the appropriate limits of integration, the potential due to the charge distribution can be determined as a function of position. The following charge distributions can be explored using this method: **CNV-3.C.1.i:** A uniformly charged wire. **CNV-3.C.1.ii:** A thin ring of charge (along the axis of the ring). **CNV-3.C.1.iii:** A semicircular arc or part of a semicircular arc. **CNV-3.C.1.iv:** A uniformly charged disk.	24.3, pp. 642–645 24.5, pp. 648–651

Unit 2: Conductors, Capacitors, Dielectrics

AP® Exam Weighting: 10 class periods

- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4**: Conservation laws constrain interactions

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 2.1: Conductors, Capacitors, Dielectrics: Electrostatics with Conductors	**ACT-2:** Excess charge on an insulated conductor will spread out the entire conductor until there is no more movement of the charge. **ACT-2.A:** a. Recognize that the excess charge on a conductor in electrostatic equilibrium resides entirely on the surface of a conductor. b. Describe the consequence of the law of electrostatics and that it is responsible for the other law of conductors (that states there is an absence of an electric field inside of a conductor).	**ACT-2.A.1:** The mutual repulsion of all charges on the surface of a conductor will eventually create a state of electrostatic equilibrium on the conductor. This will result in a uniform charge density for uniform shapes (spheres, cylinders, planes, etc.) and an absence of an electric field inside of all conductors (uniform or non-uniform shapes). **ACT-2.A.1.i:** The electric field just outside of a conductor must be completely perpendicular to the surface and have no components tangential to the surface. This is also a consequence of the electrostatic equilibrium on the surface of a conductor.	24.6, pp. 651–655
	ACT-2: Excess charge on an insulated conductor will spread out the entire conductor until there is no more movement of the charge. **ACT-2.B:** a. Explain why a conducting surface must be an equipotential surface. b. Describe the consequences of a conductor being an equipotential surface. c. Explain how a change to a conductor's charge density due to an external electric field will not change the electric-field value inside the conductor.	**ACT-2.B.1:** An equipotential surface has the mathematical and physical property of having no electric field within the conductor (inside the metal and inside a cavity within the metal). **ACT-2.B.1.i:** The equipotential condition on a conductor remains, even if the conductor is placed in an external electric field.	24.6, pp. 651–655

	ACT-2: Excess charge on an insulated conductor will spread out the entire conductor until there is no more movement of the charge. **ACT-2.C:** a. Describe the process of charging a conductor by induction. b. Describe the net charge residing on conductors during the process of inducing a charge on an electroscope/conductor.	**ACT-2.C.1:** A charge can be induced on a conductor by bringing a conductor near an external electric field and then simultaneously attaching a grounding wire/ground to the conductor.	22.2, pp. 591–592
	ACT-2: Excess charge on an insulated conductor will spread out the entire conductor until there is no more movement of the charge. **ACT-2.D:** Explain how a charged object can attract a neutral conductor.	**ACT-2.D.1:** A conductor can be completely polarized in the presence of an electric field. **ACT-2.D.1.i:** The complete polarization of the conductor is a consequence of the conductor remaining an equipotential in the presence of an external electric field.	22.4, pp. 591–592 24.6, pp. 651–655
	ACT-2: Excess charge on an insulated conductor will spread out the entire conductor until there is no more movement of the charge. **ACT-2.E:** Describe the concept of electrostatic shielding.	**ACT-2.E.1:** Electrostatic shielding is the process of surrounding an area by a completely closed conductor to create a region free of an electric field.	24.6, p. 654
	ACT-3: Excess charge on an insulated sphere or spherical shell will spread out on the entire surface of the sphere until there is no more movement of the charge because the surface is an equipotential. **ACT-3.A:** a. For charged conducting spheres or spherical shells, describe the electric field with respect to position. b. For charged conducting spheres or spherical shells, describe the electric	**ACT-3.A.1:** The electric field has a value of zero within a spherical conductor, and the sketch should indicate this fact. **ACT-3.A.1.i:** The electric potential within a conducting sphere and on its surface is considered an equipotential surface. This implies that the potential inside of a conducting sphere is constant and is the same value as the potential on the surface of the sphere.	24.6, pp. 651–655

	potential with respect to position.		
	ACT-3: Excess charge on an insulated sphere or spherical shell will spread out on the entire surface of the sphere until there is no more movement of the charge because the surface is an equipotential. **ACT-3.B:** Calculate the electric potential on the surfaces of two charged conducting spheres when connected by a conducting wire.	**ACT-3.B.1:** The net charge in a system must remain constant. The entire system of connected spheres must be at the same potential. **ACT-3.B.1.i:** Charges will redistribute on two connected spheres until the two conditions above are met.	24.6, pp. 653–654
Topic 2.2 Conductors, Capacitors, Dielectrics: Capacitors	**CNV-4:** There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.A:** a. Apply the general definition of capacitance to a capacitor attached to a charging source. b. Calculate unknown quantities such as charge, potential difference, or capacitance for physical system with a charged capacitor.	**CNV-4.A.1:** The general definition of capacitance is given by the following relationship: $C = \dfrac{Q}{\Delta V}$	25.1, p. 664
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.B:** a. Use the relationship for stored electrical potential energy for a capacitor. b. Calculate quantities such as charge, potential difference, capacitance, and potential energy of a physical system with a charged capacitor.	**CNV-4.B.1:** The energy stored in a capacitor is determined by the following relationship: $U_E = \dfrac{1}{2}C(\Delta V)^2$ (or an equivalent expression)	24.4, pp. 673–674
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy.	**CNV-4.C.1:** The conservation of charge and energy can be applied to a closed physical system containing charge, capacitors, and a source of	25.3, pp. 668–672

	CNV-4.C: Explain how a charged capacitor, which has stored energy, may transfer that energy into other forms of energy.	potential difference.	25.4, pp. 672–676
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.D:** a. Derive an expression for a parallel-plate capacitor in terms of the geometry of the capacitor and fundamental constants. b. Describe the properties of a parallel plate capacitor in terms of the electric field between the plates, the potential difference between the plates, the charge on the plates, and distance of separation between the plates. c. Calculate physical quantities such as charge, potential difference, electric field, surface area, and distance of separation for a physical system that contains a charged parallel-plate capacitor. d. Explain how a change in the geometry of a capacitor will affect the capacitance value.	**CNV-4.D.1:** The general definition of capacitance can be used in conjunction with the properties of the electric field of two large oppositely charged plates to determine the general definition for the parallel-plate capacitor in terms of the geometry of that capacitor. The relationship is: $C = \frac{\varepsilon_o A}{d}$ where A is the surface area of a plate and d is the distance of separation between the plates. The plates in a capacitor can be considered to have a very large surface area compared with the distance of separation between the plates. This condition makes this an ideal capacitor with a constant electric field between the plates.	25.2, pp. 665–668
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.E:** Apply the relationship between the electric field between the capacitor plates and the surface-charge density on the plates.	**CNV-4.E.1:** The electric field of oppositely charged plates can be determined by applying Gauss's law or by applying the principle of superposition. The electric field between the two plates of a parallel-plate capacitor has the following properties: **CNV-4.E.1.i:** The electric field is constant in magnitude and is independent of the geometry of the capacitor. **CNV-4.E.1.ii:** The electric field is proportional to the surface-charge density of the charge on one plate.	25.2, pp. 665–666

	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.F:** Derive expressions for the energy stored in a parallel-plate capacitor or the energy per volume of the capacitor.	**CNV-4.F.1:** The energy of the parallel-plate capacitor can be expressed in terms of the fundamental properties of the capacitor (i.e., area, distance of separation), fundamental properties of the charged system (i.e., charge density), and fundamental constants.	25.2, p. 666
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.G:** a. Describe the consequences to the physical system of a charged capacitor when a conduction slab is inserted between the plates or when the conducting plates are moved closer or farther apart. b. Calculate unknown quantities such as charge, potential difference, charge density, electric field, and stored energy when a conducting slab is placed in between the plates of a charged capacitor or when the plates of a charged capacitor are moved closer or farther apart.	**CNV-4.G.1:** The charged-capacitor system will have different conserved quantities depending on the initial conditions or conditions of the capacitor. If the capacitor remains attached to a source of a potential difference, then the charge in the system can change in accordance to the changes to the system. If the capacitor is isolated and unattached to a potential source, then the charge in the capacitor system remains constant and other physical quantities can change in response to changes in the physical system.	25.3, pp. 668–672 25.4, pp. 672–676
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.H:** Derive expressions for a cylindrical capacitor or a spherical capacitor in terms of the geometry of the capacitor and fundamental constants.	**CNV-4.H.1:** Using the definition of capacitance and the properties of electrostatics of charged cylinders or spheres, the capacitance of a cylindrical or spherical capacitor can also be determined in terms of its geometrical properties and fundamental constants.	25.2, pp. 667–668
	CNV-4: There are electrical devices that store and transfer electrostatic potential energy. **CNV-4.I:** Calculate physical quantities such as charge, potential difference, electric field, surface area, and distance	**CNV-4.I.1:** The properties of capacitance still hold for all types of capacitors (spherical or cylindrical).	25.2, pp. 667–668

	of separation for a physical system that contains a charged capacitor.		
Topic 2.3 Conductors, Capacitors, Dielectrics: Dielectrics	**FIE-2:** An insulator has different properties (than a conductor) when placed in an electric field. **FIE-2.A:** Describe and/or explain the physical properties of an insulating material when the insulator is placed in an external electric field.	**FIE-2.A.1:** An insulator's molecules will polarize to various degrees (slightly polarize or largely polarize). This effect is determined by a physical constant called the "dielectric constant." The dielectric constant has values between 1 and larger numbers.	25.2, pp. 667–668 22.5, pp. 676–677
	FIE-2: An insulator has different properties (than a conductor) when placed in an electric field. **FIE-2.B:** Explain how a dielectric inserted in between the plates of a capacitor will affect the properties of the capacitor, such as potential difference, electric field between the plates, and charge on the capacitor.	**FIE-2.B.1:** The dielectric will become partially polarized and create an electric field inside of the dielectric material. The net electric field between the plates of the capacitor is the resultant of the two fields—the fields between the plates and the induced field in the dielectric medium. This field is always a reduction in the field between the plate and therefore a reduction in the potential difference between the plates.	25.5, pp. 676–678 25.7, pp. 681–683
	FIE-2: An insulator has different properties (than a conductor) when placed in an electric field. **FIE-2.C:** Use the definition of the capacitor to describe changes in the capacitance value when a dielectric is inserted between the plates.	**FIE-2.C.1:** The capacitance of a parallel-plate capacitor with a dielectric material inserted between the plates can be calculated as follows: $C = \frac{\kappa \varepsilon_o A}{d}$ where the constant κ is the dielectric constant of the material.	25.5, pp. 676–678
	FIE-2: An insulator has different properties (than a conductor) when placed in an electric field. **FIE-2.D:** a. Calculate changes in energy, charge, or potential difference when a dielectric is inserted into an isolated charge capacitor. b. Calculate changes in energy, charge, or potential difference when a dielectric is inserted into a capacitor that is attached to a source of potential difference.	**FIE-2.D.1:** The initial condition of the capacitor system can determine which relationship to use when attempting to calculate unknown quantities in a capacitor system.	25.5, pp. 676–678 25.7, pp. 681–683

Unit 3: Electric Circuits

AP® Exam Weighting: 14 class periods

- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4**: Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 3.1: Electric Circuits: Current, Resistance, and Power	**FIE-3:** The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.A:** a. Calculate unknown quantities relating to the definition of current. b. Describe the relationship between the magnitude and direction of current to the rate of flow of positive or negative charge.	**FIE-3.A.1:** The definition of current is: $I = \frac{dQ}{dt}$ Conventional current is defined as the direction of positive charge flow.	26.1, pp. 692–694
	FIE-3: The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.B:** a. Describe the relationship between current, potential difference, and resistance of resistor using Ohm's law. b. Apply Ohm's law in an operating circuit with a known resistor or resistances.	**FIE-3.B.1:** Ohm's law is defined as: $I = \frac{\Delta V}{R}$	26.2, p. 695
	FIE-3: The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.C:** a. Explain how the properties of a conductor affect resistance. b. Compare resistances of conductors with different	**FIE-3.C.1:** The definition of resistance in terms of the properties of the conductor is: $R = \frac{\rho \ell}{A}$ where ρ is defined as the resistivity of the conductor.	26.2, pp. 694–699

	geometries or material. c. Calculate the resistance of a conductor of known resistivity and geometry.		
	FIE-3: The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.D:** Describe the relationship between the electric field strength through a conductor and the current density within the conductor.	**FIE-3.D.1:** The relationship that defines current density (current per cross-sectional area) in a conductor is: $\vec{E} = \rho \vec{J}$ Notice that current density is a vector, whereas current is a scalar.	26.2, pp. 694–695 26.4, p. 700
	FIE-3: The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.E:** Using the microscopic definition of current in a conductor, describe the properties of the conductor and the idea of "drift velocity."	**FIE-3.E.1:** The definition of current in a conductor is: $I = Nev_d A$ where: *N* is number of charge carriers per unit volume, e is charge on electron, A is cross sectional area, v_d is drift velocity of electrons.	26.4, p. 700
	FIE-3: The rate of charge flow through a conductor depends on the physical characteristics of the conductor. **FIE-3.F:** Derive the expression for resistance of a conductor of uniform cross-sectional area in terms of its dimensions and resistivity.	**FIE-3.F.1:** The definition of resistance can be derived using the microscopic definition of current and the relationship between electric field and current density.	26.2, pp. 694–699
Topic 3.2: Electric Circuits: Current, Resistance Power	**CNV-5:** There are electrical devices that convert electrical potential energy into other forms of energy. **CNV-5.A:** a. Derive expressions that relate current, voltage, and resistance to the rate at which heat is produced in a resistor. b. Calculate different rates of heat production for	**CNV-5.A.1:** The definition of power or the rate of heat loss through a resistor is: $P = I\Delta V$ or an equivalent expression that can be simplified using Ohm's law.	26.6, p. 704

	different resistors in a circuit.		
	CNV-5: There are electrical devices that convert electrical potential energy into other forms of energy. **CNV-5.B:** Calculate the amount of heat produced in a resistor given a known time interval and the circuit characteristics.	**CNV-5.B.1:** The total amount of heat energy transferred from electrical potential energy to heat can be determined using the definition of power.	26.6, pp. 704–706
Topic 3.3 Electric Currents: Steady-State Direct-Current Circuits with Batteries and Resistors Only	**CNV-6:** Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.A:** a. Identify parallel or series arrangement in a circuit containing multiple resistors. b. Describe a series or a parallel arrangement of resistors.	**CNV-6.A.1:** Series arrangement of resistors is defined as resistors arranged one after the other, creating one possible branch for charge flow. Parallel arrangement of resistors is defined as resistors attached to the same to points (electrically), creating multiple pathways for charge flow.	27.2, pp. 716–722
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.B:** Calculate equivalent resistances for a network of resistors that can be considered a combination of series and parallel arrangement.	**CNV-6.B.1:** The rule for equivalent resistance for resistors arranged in series is: $R_S = \sum_i R_i$ The rule for equivalent resistance for resistors arranged in parallel is: $\frac{1}{R_P} = \sum_i \frac{1}{R_i}$	27.2, pp. 717, 719
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.C:** a. Calculate voltage, current, and power dissipation for any resistor in a circuit containing a network of known resistors with a single battery or energy	**CNV-6.C.1:** The current in a circuit containing resistors arranged in series or a branch of a circuit containing resistors arranged in series is the same at every point in the circuit or branch. **CNV-6.C.1.i:** The potential difference is the same value across multiple branches of resistors or branches that are in parallel. **CNV-6.C.1.ii:** The reduction of a circuit containing a network of resistors in parallel and series arrangement is necessary to determine the	27.2, pp. 717–718, 721–722

	source. b. Calculate relationships between the potential difference, current, resistance, and power dissipation for any part of a circuit, given some of the characteristics of the circuit (i.e., battery voltage or current in the battery, or a resistor or branch of resistors).	current through the battery. **CNV-6.C.1.iii:** Once the current through the battery is known, other quantities can be determined more easily. **CNV-6.C.1.iv:** Ohm's law can be applied for every resistor in the circuit and for every branch in the circuit.	
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.D:** Describe a circuit diagram that will properly produce a given current and a given potential difference across a specified component in the circuit.	**CNV-6.D.1:** Conventional circuit symbols and circuit-diagramming technique should be used in order to properly represent appropriate circuit characteristics.	27.2, pp. 717–718
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.E:** a. Calculate the terminal voltage and the internal resistance of a battery of specified EMF and known current through the battery. b. Calculate the power distribution of a circuit with a non-ideal battery (i.e., power loss due to the battery's resistance versus the total power supplied by the battery).	**CNV-6.E.1:** In a non-ideal battery, an internal resistance will exist within the battery. This resistance will add in series to the total external circuit resistance and reduce the operating current in the circuit.	27.1, pp. 714–715
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.F:** a. Calculate a single unknown	**CNV-6.F.1:** Kirchhoff's rules allow for the determination of currents and potential differences in complex multi-loop circuits that cannot be reduced using conventional (series/parallel rules) methods. **CNV-6.F.1.i:** According to Kirchhoff's current rule,	27.3, pp. 723–726

	current, potential difference, or resistance in a multi-loop circuit using Kirchhoff's rules. b. Set up simultaneous equations to calculate at least two unknowns (currents or resistance values) in a multi-loop circuit. c. Explain why Kirchhoff's rules are valid in terms of energy conservation and charge conservation around a circuit loop. d. Identify when conventional circuit-reduction methods can be used to analyze a circuit and when Kirchhoff's rules must be used to analyze a circuit.	the current into a junction or node must be equal to the current out of that junction or node. This is a consequence of charge conservation. **CNV-6.F.1.ii:** According to Kirchhoff's loop rule, the sum of the potential differences around a closed loop must be equal to zero. This is a consequence of the conservation of energy in a circuit loop.	
	CNV-6: Total energy and charge are conserved in a circuit containing resistors and a source of energy. **CNV-6.G:** a. Describe the proper use of an ammeter and a voltmeter in an experimental circuit and correctly demonstrate or identify these methods in a circuit diagram. b. Describe the effect on measurements made by voltmeters or ammeters that have non-ideal resistances.	**CNV-6.G.1:** An ideal ammeter has a resistance that is close to zero (negligible), and an ideal voltmeter has a resistance that is very large (infinite). **CNV-6.G.1.i:** To properly measure current in a circuit branch, an ammeter must be placed in series within the branch. To properly measure potential difference across a circuit element, a voltmeter must be used in a parallel arrangement with the circuit element being measured.	*This subsection of the essential knowledge is not directly addressed in this edition.*
Topic 3.4: Capacitors in Circuits	**CNV-7:** Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.A:** a. Calculate the equivalent capacitance for capacitors arranged in series or parallel, or a combination of both, in steady-state	**CNV-7.A.1:** The equivalent capacitance of capacitors arranged in series can be determined by the following relationship: $\frac{1}{C_S} = \sum_i \frac{1}{C_i}$ **CNV-7.A.1.i:** The equivalent capacitance of capacitors arranged in parallel can be determined by the following relationship:	25.3, pp. 669–672

	situations. b. Calculate the potential differences across specified capacitors for an arrangement of capacitors in series in a circuit. c. Calculate the stored charge in a system of capacitors and on individual capacitors for an arrangement of capacitors in series or in parallel.	$C_p = \sum_i C_i$ **CNV-7.A.1.ii:** The system of capacitors will behave as if the one equivalent capacitance were connected to the voltage source. **CNV-7.A.1.iii:** For capacitors arranged in parallel, the total charge stored in the system is equivalent to the sum of the individual stored charges on each capacitor. **CNV-7.A.1.iv:** For capacitors arranged in series, the total stored charge in the system is Q_T, and each individual capacitor also has a charge value of Q_T.	
	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.B:** a. Calculate the potential difference across a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions. b. Calculate the stored charge on a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions.	**CNV-7.B.1:** When a circuit containing resistors and capacitors reaches a steady-state condition, the potential difference across the capacitor can be determined using Kirchhoff's rules.	27.4, pp. 726–731
	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.C:** In transient circuit conditions (i.e., RC circuits), calculate the time constant of a circuit containing resistors and capacitors arranged in series.	**CNV-7.C.1:** Under transient conditions for *t* = 0 to *t* = steady-state conditions, the time constant in an RC circuit is equal to the product of equivalent resistance and the equivalent capacitance.	27.4, p. 728
	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy.	**CNV-7.D.1:** The changes in the electrical characteristics of a capacitor or resistor in an RC circuit can be described by fundamental differential equations that can be integrated over	27.4, pp. 726–731

	CNV-7.D: a. Derive expressions using calculus to describe the time dependence of the stored charge or potential difference across the capacitor, or the current or potential difference across the resistor in an RC circuit when charging or discharging a capacitor. b. Recognize the model of charging or discharging a capacitor in an RC circuit, and apply the model to a new RC circuit.	the transient time interval. **CNV-7.D.1.i:** The general model for the charging or discharging of a capacitor in an RC circuit contains a factor of $e^{-\frac{t}{RC}}$.	
	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.E:** a. Describe stored charge or potential difference across a capacitor or current, or potential difference of a resistor in a transient RC circuit. b. Describe the behavior of the voltage or current behavior over time for a circuit that contains resistors and capacitors in a multi-loop arrangement.	**CNV-7.E.1:** The time constant ($\tau = RC$) is a significant feature on the sketches for transient behavior in an RC circuit. **CNV-7.E.1.i:** These particular sketches will always have the exponential decay factor and will either have an asymptote of zero or an asymptote that signifies some physical final state of the system (i.e., final stored charge, etc.). **CNV-7.E.1.ii:** The initial conditions of the circuit will be represented on the sketch by the vertical intercept of the graph (i.e., initial current, etc.). **CNV-7.E.1.iii:** The capacitor in a circuit behaves as a “bare wire” with zero resistance at a time immediately after *t* = 0 seconds. **CNV-7.E.1.iv:** The capacitor in a circuit behaves as an “open circuit” or having an infinite resistance in a condition of time much greater than the time constant of the circuit.	27.4, pp. 726–731
	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.F:** Calculate expressions that determine electrical potential energy stored in a capacitor as a function of time in a transient RC circuit.	**CNV-7.F.1:** The electrical potential energy stored in a capacitor is defined by the following expression: $U_E = \frac{1}{2}C(\Delta V)^2$ This term will vary in time in accordance with the time dependence of the potential difference.	27.4, pp. 726–731

	CNV-7: Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. **CNV-7.G**: a. Describe the energy transfer in charging or discharging a capacitor in an RC circuit. b. Calculate expressions that account for the energy transfer in charging or discharging a capacitor.	**CNV-7.G.1**: The total energy provided by the energy source (battery) that is transferred into an RC circuit during the charging process is split between the capacitor and the resistor.	27.4, pp. 726–731

Unit 4: Magnetic Fields

AP® Exam Weighting: 14 class periods

- **Big Idea 1:** Interactions produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4**: Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 4.1: Magnetic Fields: Forces on Moving Charges in Magnetic Fields	**CHG-1:** Charged particles moving through a magnetic field may change the direction of their motion. **CHG-1.A:** a. Calculate the magnitude and direction of the magnetic force of interaction between a moving charged particle of specified charge and velocity moving in a region of a uniform magnetic field. b. Describe the direction of a magnetic field from the information given by a description of the motion or trajectory of a charged particle moving through a uniform magnetic field. c. Describe the conditions that are necessary for a charged particle to experience no magnetic force of interaction between the particle and the magnetic field.	**CHG-1.A.1:** The magnetic force of interaction between a moving charged particle and a uniform magnetic field is defined by the following expression: $\vec{F}_M = q(\vec{v} \times \vec{B})$ **CHG-1.A.1.i:** The direction of the magnetic force is determined by the cross-product or can be determined by the appropriate right-hand rule. **CHG-1.A.1.ii:** If the moving charged particle moves in a direction that is parallel to the magnetic-field direction, then the magnetic force of interaction is zero. **CHG-1.A.1.iii:** The charged particle must have a velocity to interact with the magnetic field.	28.1, pp. 744–748
	CHG-1: Charged particles moving through a magnetic field may change the direction of their motion. **CHG-1.B:** Describe the path of different moving charged particles (i.e., of different type of charge or mass) in a uniform magnetic field.	**CHG-1.B.1:** The direction of the magnetic force is always in a direction perpendicular to the velocity of the moving charged particle. This results in a trajectory that is either a curved path or a complete circular path (if it moves in the field for a long enough time).	28.1, pp. 746–747

	CHG-1: Charged particles moving through a magnetic field may change the direction of their motion. **CHG-1.C:** Derive an expression for the radius of a circular path for a charged particle of specified characteristics moving in a specified magnetic field.	**CHG-1.C.1:** The magnetic force is always acting in a perpendicular direction to the moving particle. The result of this is a centripetal force of a constant magnitude and a centripetal acceleration of constant magnitude. **CHG-1.C.1.i:** The radius of the circular path can be determined by applying a Newton's second law analysis for the moving charged particle in the centripetal direction.	28.2, pp. 748–752
	CHG-1: Charged particles moving through a magnetic field may change the direction of their motion. **CHG-1.D:** Explain why the magnetic force acting on a moving charge particle does not work on the moving charged particle.	**CHG-1.D.1:** The magnetic force is defined as cross-product between the velocity vector and the magnetic-field vector. The result of this is a force that is always perpendicular to the velocity vector.	28.1, p. 745
	CHG-1: Charged particles moving through a magnetic field may change the direction of their motion. **CHG-1.E:** Describe the conditions under which a moving charged particle can move through a region of crossed electric and magnetic fields with a constant velocity.	**CHG-1.E.1:** In a region containing both a magnetic field and an electric field, a moving charged particle will experience two different forces independent from each other. Depending on the physical parameters, it is possible for each force to be equal in magnitude and opposite in direction, thus producing a net force of zero on the moving charged particle.	28.3, pp. 752–753
Topic 4.2: Magnetic Fields: Forces on Current-Carrying Wires in Magnetic Fields	**FIE-4:** A magnetic field can interact with a straight conducting wire with current. **FIE-4.A:** a. Calculate the magnitude of the magnetic force acting on a straight-line segment of a conductor with current in a uniform magnetic field. b. Describe the direction of the magnetic force of interaction on a segment of a straight current-carrying	**FIE-4.A.1:** The definition of a the magnetic force acting on a straight-line segment of a current-carrying conductor in a uniform magnetic field is: $\vec{F}_M = \int I(d\vec{\ell} \times \vec{B})$ **FIE-4.A.1.i:** The direction of the force can be determined by the cross-product or by the appropriate right-hand rule.	28.5, pp. 755–757

	conductor in a specified uniform magnetic field.		
	FIE-4: A magnetic field can interact with a straight conducting wire with current. **FIE-4.B:** a. Describe or indicate the direction of magnetic forces acting on a complete conductive loop with current in a region of uniform magnetic field. b. Describe the mechanical consequences of the magnetic forces acting on a current-carrying loop of wire.	**FIE-4.B.1:** A complete conductive loop (rectangular or circular) will experience magnetic forces at all points on the wire. The net direction of all of the forces will result in a net force of zero acting on the center of mass of the loop. **FIE-4.B.1.i:** Depending on the orientation of the loop and the field, the forces may result in a torque that acts on the loop.	28.5, pp. 757–760
	FIE-4: A magnetic field can interact with a straight conducting wire with current. **FIE-4.C:** Calculate the magnitude and direction of the net torque experienced by a rectangular loop of wire carrying a current in a region of a uniform magnetic field.	**FIE-4.C.1:** The definition of torque can be applied to the loop to determine a relationship between the torque, field, current, and area of the loop.	28.5, pp. 757–760
Topic 4.3: Magnetic Fields: Fields of Long, Current-Carrying Wires	**FIE-5:** Current-carrying conductors create magnetic fields that allow them to interact at a distance with other magnetic fields. **FIE-5.A:** a. Calculate the magnitude and direction of a magnetic field produced at a point near a long, straight current-carrying wire. b. Apply the right-hand rule for magnetic field of a straight wire (or correctly use the Biot–Savart law found in 4.D.1) to deduce the direction of a magnetic	**FIE-5.A.1:** It can be shown or experimentally verified that the magnetic field of a long, straight current-carrying conductor is: $B = \frac{\mu_o I}{2\pi r}$ **FIE-5.A.1.i:** The magnitude of the field is proportional to the inverse of distance from the wire. **FIE-5.A.1.ii:** The magnetic-field vector is always mutually perpendicular to the position vector and the direction of the conventional current. The result of this is a magnetic field line that is in a circular path around the wire in a sense (clockwise or counterclockwise) determined by the appropriate right-hand rule.	29.1, pp. 772–774

	field near a long, straight, current-carrying wire.		
	FIE-5: Current-carrying conductors create magnetic fields that allow them to interact at a distance with other magnetic fields. **FIE-5.B:** a. Describe the direction of a magnetic-field vector at various points near multiple long, straight, current-carrying wires. b. Calculate the magnitude of a magnetic field at various points near multiple long, straight, current-carrying wires. c. Calculate an unknown current value or position value given a specified magnetic field at a point due to multiple long, straight, current-carrying wires.	**FIE-5.B.1:** The principle of superposition can be used to determine the net magnetic field at a point due to multiple long, straight, current-carrying wires.	29.2, pp. 777–778
	FIE-5: Current-carrying conductors create magnetic fields that allow them to interact at a distance with other magnetic fields. **FIE-5.C:** a. Calculate the force of attraction or repulsion between two long, straight, current-carrying wires. b. Describe the consequence (attract or repel) when two long, straight, current-carrying wires have known current directions.	**FIE-5.C.1:** The field of a long, straight wire can be used as the external field in the definition of magnetic force acting on a segment of current carrying wire. **FIE-5.C.1.i:** The direction of the force can be determined from the cross-product definition or from the appropriate right-hand rule.	29.2, pp. 777–778

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<td>Topic 4.4
Magnetic Fields: Biot-Savart Law and Ampere’s Law</td>
<td>CNV-8: There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge.

CNV-8.A:
a. Describe the direction of the contribution to the magnetic field made by a short (differential) length of straight segment of a current-carrying conductor.
b. Calculate the magnitude of the contribution to the magnetic field due to a short (differential) length of straight segment of a current-carrying conductor.</td>
<td>CNV-8.A.1: The Biot–Savart law is the fundamental law of magnetism that defines the magnitude and direction of a magnetic field due to moving charges or current-carrying conductors. The law in differential form is:

$$d\vec{B} = \frac{\mu_o}{4\pi}\frac{I\left(d\vec{\ell}\times\hat{r}\right)}{r^2}$$</td>
<td>29.1, pp. 772–777</td>
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<td>CNV-8: There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge.

CNV-8.B:
a. Derive the expression for the magnitude of magnetic field on the axis of a circular loop of current or a segment of a circular loop.
b. Explain how the Biot–Savart law can be used to determine the field of a long, straight, current-carrying wire at perpendicular distances close to the wire.</td>
<td>CNV-8.B.1: The Biot–Savart law can be used to derive the magnitude and directions of magnetic fields of symmetric current-carrying conductors (e.g., circular loops), long, straight conductors, or segments of loops.</td>
<td>29.1, pp. 772–777</td>
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<td>CNV-8: There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge.

CNV-8.C:
a. Explain Ampère’s law and justify the use of the appropriate Amperian loop for current-carrying conductors of different</td>
<td>CNV-8.C.1: Ampère’s law is a fundamental law of magnetism that relates the magnitude of the magnetic field to the current enclosed by a closed imaginary path called an Amperian loop. The law in integral form is:

$$\oint \vec{B}\cdot d\vec{\ell} = \mu_o I$$
where I in this case is the enclosed current by the Amperian loop.

CNV-8.C.1.i: Ampère’s law for magnetism is</td>
<td>29.3, pp. 779–782</td>
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	shapes such as straight wires, closed circular loops, conductive slabs, or solenoids. b. Derive the magnitude of the magnetic field for certain current-carrying conductors using Ampère's law and symmetry arguments. c. Derive the expression for the magnetic field of an ideal solenoid (length dimension is much larger than the radius of the solenoid) using Ampère's law. d. Describe the conclusions that can be made about the magnetic field at a particular point in space if the line integral in Ampère's law is equivalent to zero.	analogous to Gauss's law for electrostatics and is a fundamental law that allows for an easier approach to determining some magnetic fields of certain symmetries or shapes of current-carrying conductors. The law is always true but not always useful. **CNV-8.C.1.ii:** The law can only be applied when the symmetry of the magnetic field can be exploited. Circular loops, long, straight wires, conductive slabs with current density, solenoids, and other cylindrical conductors containing current are the types of shapes for which Ampère's law can be useful.	
	CNV-8: There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge. **CNV-8.D:** Describe the relationship of the magnetic field as a function of distance for various configurations of current-carrying cylindrical conductors with either a single current or multiple currents, at points inside and outside of the conductors.	**CNV-8.D.1:** Ampère's law can be used to determine magnetic-field relationships at different locations in cylindrical current-carrying conductors.	29.3, pp. 779–782
	CNV-8: There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge. **CNV-8.E:** a. Describe the direction of a magnetic field at a point in space due to various combinations of conductors, wires, cylindrical conductors, or	**CNV-8.E.1:** The principle of superposition can be used to determine the net magnetic field at a point in space due to various combinations of current-carrying conductors, loops, segments, or cylindrical conductors. Ampère's law can be used to determine individual field magnitudes. The principle of superposition can be used to add those individual fields.	29.3, pp. 779–782

	loops. b. Calculate the magnitude of a magnetic field at a point in space due to various combinations of conductors, wires, cylindrical conductors, or loops.		

Unit 5: Electromagnetism

AP® Exam Weighting: 11 class periods

- **Big Idea 1:** Interactions produce changes in motion.
- **Big Idea 2:** Forces characterize interactions between objects or systems.
- **Big Idea 3:** Fields predict and describe interactions.
- **Big Idea 4**: Conservation laws constrain interactions.

Topic	Enduring Understanding and Learning Objective	Essential Knowledge	Text Section(s)
Topic 5.1: Electromagnetism: Electromagnetic Induction (Including Faraday's Law and Lenz's Law)	**CNV-9:** There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing a magnetic field. **CNV-9.A:** a. Calculate the magnetic flux through a loop of regular shape with an arbitrary orientation in relation to the magnetic-field direction. b. Calculate the magnetic flux of the field due to a current-carrying, long, straight wire through a rectangular-shaped area that is in the plane of the wire and oriented perpendicularly to the field. c. Calculate the magnetic flux of a non-uniform magnetic field that may have a magnitude that varies over one coordinate through a specified rectangular loop that is oriented perpendicularly to the field.	**CNV-9.A.1:** Magnetic flux is the scalar product of the magnetic-field vector and the area vector over the entire area contained by the loop. The definition of flux is: $\Phi_B = \int \vec{B} \cdot d\vec{A}$	30.1, pp. 798–801
	FIE-6: A changing magnetic field over time can induce current in conductors. **FIE-6.A:** a. Describe which physical situations with a changing magnetic field and a conductive loop will create an induced current in the	**FIE-6.A.1:** Induced currents arise in a conductive loop (or long wire) when there is a change in magnetic flux occurring through the loop. This change is defined by Faraday's law: $\varepsilon_i = -N\dfrac{d\phi_B}{dt}$ where ε_i is the induced EMF and *N* is number of turns. (In a coil or solenoid, the *N* refers to the	30.1, pp. 798–801 30.2, pp. 801–803 30.3, pp. 805–808 30.4, pp. 808–

	loop. b. Describe the direction of an induced current in a conductive loop that is placed in a changing magnetic field. c. Describe the induced current magnitudes and directions for a conductive loop moving through a specified region of space containing a uniform magnetic field. d. Calculate the magnitude and direction of induced EMF and induced current in a conductive loop (or conductive bar) when the magnitude of either the field or area of loop is changing at a constant rate. e. Calculate the magnitude and direction of induced EMF and induced current in a conductive loop (or conductive bar) when a physical quantity related to magnetic field or area is changing with a specified non-linear function of time. f. Derive expressions for the induced EMF (or current) through a closed conductive loop with a time-varying magnetic field directed either perpendicularly through the loop or at some angle oriented relative to the magnetic-field direction g. Describe the relative magnitude and direction of induced currents in a conductive loop with a time-varying magnetic field.	number of turns of coil or conductive loops in the solenoid.) **FIE-6.A.1.i:** The negative sign in the expression embodies Lenz's law and is an important part of the relationship. **FIE-6.A.1.ii:** Lenz's law is the relationship that allows the direction of the induced current to be determined. The law states that any induced EMF and current induced in a conductive loop will create an induced current and induced magnetic field to oppose the direction change in external flux. **FIE-6.A.1.iii:** Lenz's law is essentially a law relating to conservation of energy in a system and has mechanical consequences.	810
	ACT-4: Induced forces (arising from magnetic interactions) that are exerted on objects can change the kinetic energy of an object. **ACT-4.A:**	**ACT-4.A.1:** When an induced current is created in a conductive loop, the current will interact with the already-present magnetic field, creating induced forces acting on the loop. The magnitude and directions of these induced forces can be calculated using the definition of force on a current-carrying wire	30.3, pp. 805–808

	a. Determine if a net force or net torque exists on a conductive loop in a region of changing magnetic field. b. Justify if a conductive loop will change its speed as it moves through different regions of a uniform magnetic field.		
	ACT-4: Induced forces (arising from magnetic interactions) that are exerted on objects can change the kinetic energy of an object. **ACT-4.B:** a. Calculate an expression for the net force on a conductive bar as it is moved through a magnetic field. b. Write a differential equation and calculate the terminal velocity for the motion of a conductive bar (in a closed electrical loop) falling through a magnetic field or moving through a field due to other physical mechanisms. c. Describe the mechanical consequences of changing an electrical property (such as resistance) or a mechanical property (such as length/area) of a conductive loop as it moves through a uniform magnetic field. d. Derive an expression for the mechanical power delivered to a conductive loop as it moves through a magnetic field in terms of the electrical characteristics of the conductive loop.	**ACT-4.B.1:** Newton's second law can be applied to a moving conductor as it experiences a flux change. **ACT-4.B.1.i:** The force on the conductor is proportional to the velocity of the conductor. **ACT-4.B.1.ii:** A differential equation of velocity can be written for these physical situations. **ACT-4.B.1.iii:** This will lead to an exponential relationship with the changing velocity of the conductor. **ACT-4.B.1.iv:** Using calculus, the expressions for velocity, induced force, and power can all be expressed with these exponential relationships.	30.2, pp. 801–805
Topic 5.2 Electromagnetism:	**CNV-10:** In a closed circuit containing inductors and resistors, energy and charge are	**CNV-10.A.1:** By applying Faraday's law to an inductive electrical device, a variation on the law can be determined to relate the definition of	31.1, pp. 825–826

Inductance (Including LR Circuits)	conserved. **CNV-10.A:** a. Derive the expression for the inductance of a long solenoid. b. Calculate the magnitude and the sense of the EMF in an inductor through which a changing current is specified. c. Calculate the rate of change of current in an inductor with a transient current.	inductance to the properties of the inductor: $\varepsilon_i = -L\dfrac{dI}{dt}$ where L is defined as the inductance of the electrical device. **CNV-10.A.1.i:** The very nature of the inductor is to oppose the change in current occurring in the inductor.	
	CNV-10: In a closed circuit containing inductors and resistors, energy and charge are conserved. **CNV-10.B:** Calculate the stored electrical energy in an inductor that has a steady-state current.	**CNV-10.B.1:** The stored energy in an inductor is defined by: $U_L = \dfrac{1}{2}LI^2$	31.3, pp. 830–832
	CNV-10: In a closed circuit containing inductors and resistors, energy and charge are conserved. **CNV-10.C:** a. Calculate initial transient currents and final steady-state currents through any part of a series or parallel circuit containing an inductor and one or more resistors. b. Calculate the maximum current in a circuit that contains only a charged capacitor and an inductor.	**CNV-10.C.1:** The electrical characteristics of an inductor in a circuit are the following: **CNV-10.C.1.i:** At the initial condition of closing or opening a switch with an inductor in a circuit, the induced voltage will be equal in magnitude and opposite in direction of the applied voltage across the branch containing the inductor. **CNV-10.C.1.ii:** In a steady-state condition, the ideal inductor has a resistance of zero and therefore will behave as a bare wire in a circuit. **CNV-10.C.1.iii:** In circuits containing only a charged capacitor and an inductor, the maximum current through the inductor can be determined by applying conservation of energy within the circuit and the two circuit elements that can store energy.	31.1–31.2, pp. 825–830 31.3, pp. 830–832
	CNV-10: In a closed circuit containing inductors and resistors, energy and charge are conserved. **CNV-10.D:** a. Derive a differential equation for the current as	**CNV-10.D.1:** Kirchhoff's rules can be applied to a series LR circuit. The result of applying Kirchhoff's rules in this case will be a differential equation in current for the loop. **CNV-10.D.1.i:** The solution of this equation will yield the fundamental models for the LR circuit (in turning on the circuit and turning off the circuit).	31.5, pp. 834–837, 844

	a function of time in a simple LR series circuit. b. Derive a solution to the differential equation for the current through the circuit as a function of time in the cases involving the simple LR series circuit.		
	CNV-10: In a closed circuit containing inductors and resistors, energy and charge are conserved. **CNV-10.E:** Describe currents or potential differences with respect to time across resistors or inductors in a simple circuit containing resistors and an inductor, either in series or a parallel arrangement.	**CNV-10.E.1:** Using Kirchhoff's rules and the general model for an LR circuit, general current characteristics can be determined in an LR circuit in a series or parallel arrangement.	31.5, pp. 834–837, 844
Topic 5.3 Electromagnetism: Maxwell's Equation	**FIE-7:** Electric and magnetic fields that change over time can mutually induce other electric and magnetic fields. **FIE-7.A:** a. Explain how a changing magnetic field can induce an electric field. b. Associate the appropriate Maxwell's equation with the appropriate physical consequence in a physical system containing a magnetic or electric field.	**FIE-7.A.1:** Maxwell's laws completely describe the fundamental relationships of magnetic and electric fields in steady-state conditions, as well as in situations in which the fields change in time.	33.2, pp. 876–878

