Randolph Township Schools
Randolph High School
AP Physics C Curriculum

“Nothing happens until something moves.”
- Albert Einstein

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AP Physics C Curriculum

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Mission Statement

We commit to inspiring and empowering all students in Randolph schools to reach their full potential as unique, responsible and educated members of a global society.

Affirmative Action Statement
Equality and Equity in Curriculum

The Randolph Township School district ensures that the district's curriculum and instruction are aligned to the state's standards. The curriculum provides equity in instruction, educational programs and provides all students the opportunity to interact positively with others regardless of race, creed, color, national origin, ancestry, age, marital status, affectional or sexual orientation, gender, religion, disability or socioeconomic status.

N.J.A.C. 6A:7-1.7(b): Section 504, Rehabilitation Act of 1973; N.J.S.A. 10:5; Title IX, Education Amendments of 1972

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EDUCATIONAL GOALS
VALUES IN EDUCATION

The statements represent the beliefs and values regarding our educational system. Education is the key to self-actualization, which is realized through achievement and self-respect. We believe our entire system must not only represent these values, but also demonstrate them in all that we do as a school system.

We believe:

- The needs of the child come first
- Mutual respect and trust are the cornerstones of a learning community
- The learning community consists of students, educators, parents, administrators, educational support personnel, the community and Board of Education members
- A successful learning community communicates honestly and openly in a non-threatening environment
- Members of our learning community have different needs at different times. There is openness to the challenge of meeting those needs in professional and supportive ways
- Assessment of professionals (i.e., educators, administrators and educational support personnel) is a dynamic process that requires review and revision based on evolving research, practices and experiences
- Development of desired capabilities comes in stages and is achieved through hard work, reflection and ongoing growth

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Introduction

AP Physics C is an elective course in the STEM department. It is taught as a second-year calculus-based course for juniors and seniors who have completed AP Physics 1 & Pre-Calculus. This course covers both the mechanics half and electricity and magnetism half of the AP Physics C curriculum. The mechanics portion of the course will apply calculus to topics in kinematics, dynamics, energy, momentum, circular and rotational motion. The electricity and magnetism portion of this course will introduce students to electrostatics, electric circuits, magnetic fields, and electromagnetism. The course provides students with the opportunity to earn AP college credit. The course makes use of both technology and traditional methods to collect and analyze data. Details of the New Jersey Student Learning Standards for Science can be found at Science NJSLS 2020 (June).

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Curriculum Pacing Chart

SUGGESTED TIME ALLOTMENT	UNIT NUMBER	CONTENT - UNIT OF STUDY
2 weeks	**I**	**Kinematics**
2 weeks	**II**	**Dynamics and Newton's Laws of Motion**
1 week	**III**	**Work, Energy, and Power**
2 weeks	**IV**	**Systems of Particles and Linear Momentum**
2 weeks	**V**	**Rotation**
1 week	**VI**	**Oscillations**
3 weeks	**VII**	**Gravitation**
3 weeks	**VIII**	**Electrostatics**
2 weeks	**IX**	**Conductors, Capacitors, Dielectrics**
4 weeks	**X**	**Electric Circuits**
3 weeks	**XI**	**Magnetic Fields**
3 weeks	**XII**	**Electromagnetism**
4 weeks	**XIII**	**Exam Preparation and Review**
4 weeks	**XIV**	**Extension and Enrichment**

36 weeks is the average

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Unit I: Kinematics

TRANSFER: The motion of an object can be described by mathematical equations, graphs and diagrams, and through words.		
STANDARDS / GOALS: **AP Physics C Big Idea 1: Change -** Interactions produce changes in motion. (*Essential Knowledge:* 1.A.1, 1.B.1, 1.C.1, 2.A.1, 2.B.1, 2.C.1, 2.D.1) **NJSLS Disciplinary Core Ideas** PS2.A: Forces and Motion HS-ETS1-1, HS-ETS1-2 **NJSLS Science & Engineering Practices** Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information	**ENDURING UNDERSTANDINGS**	**ESSENTIAL QUESTIONS**
	There are relationships among the vector quantities of position, velocity, and acceleration for the motion of a particle along a straight line. (CHA-1)	• In which ways can we describe "how" objects move in nature? • How does distance differ from displacement?
	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 forces. (CHA-2)	• How do the formulas for position, velocity, and acceleration relate? • How do the graphs for position, velocity, and acceleration relate?
	<u>KNOWLEDGE</u> **Students will know:**	**<u>SKILLS</u>** **Students will be able to:**
	The kinematic relationships for an object accelerating uniformly in one dimension are: $x = x_0 + v_{x_0} t + \frac{1}{2} a_x t^2$ $v_x = v_{x_0} + a_x t$ $v_x^2 = v_{x_0}^2 + 2a_x (x - x_0)$ • The constant velocity model can be derived from the above relationships.	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. Calculate unknown variables of motion such as acceleration, velocity, or positions for an object undergoing uniformly accelerated motion in one dimension.

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Unit I: Kinematics

NJSLS Crosscutting Concepts Patterns Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change	• The average velocity and acceleration models can also be derived from the above relationships. (CHA-1.A.1)	Calculate values such as average velocity or minimum or maximum velocity for an object in uniform acceleration. (CHA-1.A)
	Differentiation and integration are necessary for determining functions that relate position, velocity, and acceleration for an object with nonuniform acceleration. $v_x = \frac{dx}{dt}$ $a_x = \frac{dv_x}{dt}$ • These functions may include trigonometric, power, or exponential functions of time. • They may also include a velocity-dependent acceleration function (such as a resistive force). (CHA-1.B.1)	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)
	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. • These functions may include trigonometric, power, exponential functions (of time) or velocity-dependent functions. (CHA-1.C.1)	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)

Unit I: Kinematics

	All kinematic quantities are vector quantities and can be resolved into components (on a given coordinate system). • Vector addition and subtraction are necessary to properly determine changes in quantities. • The position, average velocity, and average acceleration can be represented in the following vector notation: (CHA-2.A.1) $\vec{r} = \vec{x} + \vec{y} + \vec{z}$ $\vec{v}_{avg} = \frac{\Delta \vec{r}}{\Delta t}$ $\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$	Calculate the components of a velocity, position, or acceleration vector in two dimensions. Calculate a net displacement of an object moving in two dimensions. Calculate net change in velocity of an object moving in two dimensions. Calculate average acceleration vector for an object moving in two dimensions. Calculate velocity vector for an object moving relative to another object (or frame of reference) that moves with a uniform velocity. Describe the velocity vector for one object relative to a second object with respect to its frame of reference. (CHA-2.A)
	Differentiation and integration are necessary for determining functions that relate position, velocity, and acceleration for an object in each dimension. $v_x = \frac{dx}{dt}$ $a_x = \frac{dv_x}{dt}$	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)

	• The accelerations may be different in each direction and may be nonuniform. • The resultant vector of a given quantity such as position, velocity, or acceleration is the vector sum of the components of each quantity. (CHA-2.B.1)	
	Motion in two dimensions can be analyzed using the kinematic equations if the motion is separated into vertical and horizontal components. • Projectile motion assumes negligible air resistance and therefore constant horizontal velocity and constant vertical acceleration (earth's gravitational acceleration). • These kinematic relationships only apply to constant (uniform) acceleration situations and can be applied in both x and y directions. (CHA-2.C.1) $x = x_0 + v_{x_0} t + \frac{1}{2} a_x t^2$ $v_x = v_{x_0} + a_x t$ $v_x^2 = v_{x_0}^2 + 2a_x (x - x_0)$	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)

	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. (CHA-2.D.1)	Describe the motion of an object in two-dimensional motion in terms of the consistency that exists between position and time, velocity and time, and acceleration and time. (CHA-2.D)
	VOCABULARY: kinematics, position, displacement, speed, velocity & average velocity, acceleration & average acceleration, magnitude, direction, scalar, vector, component vector, vector addition, resultant vector, unit vector, translation, relative velocity, derivative, integral, projectile, trajectory, motion, system, uniform & nonuniform, linear, quadratic, exponential, trigonometric, slope, intercept, asymptote, simultaneous, turning point, free fall	

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Unit I: Kinematics

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Selecting and plotting appropriate kinematic data; linearizing or determining a best fit line or curve.
- Identifying patterns and trends in data or a graph of motion (such as freefall, inclined plane, etc.).
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation.
- Making and justifying a scientific claim with evidence.
- Determining the relationship between kinematic variables within an equation when an existing variable changes.
- Extracting quantities from narratives or mathematical relationships to solve kinematics problems.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph motion in one- and two-dimensions.
  - Suggestions: Constant Velocity Buggy, Inclined Plane, Freefall, Falling Coffee Filters Lab, Projectile Motion (Angle, range, hang-time, initial velocity)
- Problem-Solving Techniques
  - Suggestions: Defining variables, Solving algebraic- and calculus-based equations, Vectors and Vector Addition Activity, Unit analysis, Clarifying connection between slopes & derivatives and area & integrals

SUGGESTED TIME ALLOTMENT	2 weeks
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 1 – 4 Workbook Topics 1 – 4 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit II: Dynamics and Newton's Laws of Motion

TRANSFER: Forces can change the motion of an object.		
STANDARDS / GOALS: **AP Physics C Big Idea 2: Force Interactions** - Forces characterize interactions between objects or systems. (*Essential Knowledge:* 1.A.1, 1.B.1, 1.C.1, 1.D.1, 1.E.1, 1.F.1, 1.G.1, 1.H.1, 1.J.1, 2.A.1, 2.B.1, 2.C.1, 2.D.1, 2.E.1, 3.A.1, 3.B.1) **NJSLS Disciplinary Core Ideas** PS2.A: Forces and Motion HS-PS2-1 PS2.B: Types of Interactions HS-PS2-5 PS2.C: Stability & Instability in Physical Systems HS-ETS1-1 , HS-ETS1-2 **NJSLS Science & Engineering Practices** Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data	**ENDURING UNDERSTANDINGS**	**ESSENTIAL QUESTIONS**
	A net force will change the translational motion of an object. (INT-1)	• How do forces affect motion?
	The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. (INT-2)	• How can forces cause circular motion?
	There are force pairs with equal magnitude and opposite directions between any two interacting objects. (INT-3)	• Can a force exist by itself?
	<u>KNOWLEDGE</u> **Students will know:**	**<u>SKILLS</u>** **Students will be able to:**
	Newton's second law can be applied to an object in accelerated motion or in a state of equilibrium. (INT-1.A.1)	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)

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Unit II: Dynamics and Newton's Laws of Motion

Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Stability and Change Structure and Function	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: $\sum F_x = 0$ $\sum F_y = 0$ • Forces can be resolved into components and these components can be separately added in their respective directions. (INT-1.B.1)	Explain Newton's first law in qualitative terms and apply the law to many different physical situations. Calculate a force of unknown magnitude acting on an object in equilibrium. (INT-1.B)
	The appropriate use of Newton's second law is one of the fundamental skills in mechanics. $\vec{a} = \frac{\sum \vec{F}}{m}$ • 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.	Calculate the acceleration of an object moving in one dimension when a single constant force (or a net constant force) acts on the object during a known interval of time. Calculate the average force acting on an object moving in a plane with a velocity vector that is changing over a specified time interval.

	• Forces acting parallel to the velocity vector have the capacity to change the speed of the object. • Forces acting in the perpendicular direction have the capacity to change the direction of the velocity vector. (INT-1.C.1)	Describe the trajectory of a moving object that experiences a constant force in a direction perpendicular to its initial velocity vector. Derive an expression for the net force on an object in translational motion. 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). (INT-1.C)
	Using appropriate relationships derived from a Newton's second law analysis, unknown forces (or accelerations) can be determined from the given known physical characteristics. (INT-1.D.1)	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)
	The relationship for the frictional force acting on an object on a rough surface is: (INT-1.E.1) $\left\|\vec{F}_{f_s}\right\| \leq \mu_s \left\|\vec{F}_N\right\|$ $\left\|\vec{F}_{f_k}\right\| = \mu_k \left\|\vec{F}_N\right\|$	Describe the relationship between frictional force and the normal force for static friction and for kinetic friction. 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)

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	The direction of friction can be determined by the relative motion between surfaces in kinetic frictional cases. • 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. (INT-1.F.1)	Describe the direction of frictional forces (static or kinetic) acting on an object under various physical situations. (INT-1.F)
	The maximum value of static friction has a precise relationship: $\left\lvert\vec{F}_{f_s}\right\rvert = \mu_s \left\lvert\vec{F}_N\right\rvert$ • This relationship can be used to determine values such as, "The maximum angle of incline at which the block will not slip." (INT-1.G.1)	Derive expressions that relate mass, forces, or angles of inclines for various slipping conditions with friction. 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)
	The standard "resistive force" in this course is defined as a velocity-dependent force in the opposite direction of velocity, for example: (INT-1.H.1) $\vec{F}_r = -k\vec{v}$ or $\left\lvert\vec{F}_r\right\rvert = kv^2$	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). (INT-1.H) 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)

Unit II: Dynamics and Newton's Laws of Motion

	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. (INT-1.I.1)	Calculate the terminal velocity of an object moving vertically under the influence of a resistive force of a given relationship. (INT-1-I)
	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: $$\frac{dv}{dt} = -\frac{k}{m}v$$ • Using the method of separation of variables, the velocity can be determined from relationships by correctly integrating over the proper limits of integration. • The acceleration or position can be determined using methods of calculus once a function for velocity is determined. (INT-1.J.1)	Derive a differential equation for an object in motion subject to a specified resistive force. 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). Derive expressions for the acceleration or position of an object moving under the influence of a given resistive force. (INT-1.J)

Unit II: Dynamics and Newton's Laws of Motion

	Centripetal acceleration is defined by: $$a_c = \frac{v^2}{r}$$ or defined using angular velocity: $$a_c = \omega^2 r$$ • Uniform circular motion is defined as an object moving in a circle with a constant speed. • The net force acting in the radial direction can be determined by applying Newton's second law in the radial direction. (INT-2.A.1)	Calculate the velocity of an object moving in a horizontal circle with a constant speed, when subject to a known centripetal force. Calculate relationships among the radius of a circle, the speed of an object (or period of revolution), and the magnitude of centripetal acceleration for an object moving in uniform circular motion. (INT-2.A)
	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. (INT-2.B.1)	Explain how a net force in the centripetal direction can be modeled as a single force, more than one force, or even components of forces that are acting on an object moving in circular motion. Describe forces that are exerted on objects undergoing horizontal circular motion, vertical circular motion, or horizontal circular motion on a banked curve. Describe forces that are acting on different objects traveling in different circular paths. (INT-2.B)

Unit II: Dynamics and Newton's Laws of Motion

	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. • 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. (INT-2.C.1)	Describe the direction of the velocity and acceleration vector for an object moving in two dimensions, circular motion, or uniform circular motion. Calculate the resultant acceleration for an object that changes its speed as it moves in a circular path. (INT-2.C)
	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. • The maximum speed occurs at the bottom of the circle and is related to all of the vertical forces acting on the object. (INT-2.D.1)	Derive expressions relating centripetal force to the minimum speed or maximum speed of an object moving in a vertical circular path. (INT-2.D)
	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. (INT-2.E.1)	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)

Unit II: Dynamics and Newton's Laws of Motion

	The forces exerted between objects are equal in magnitude and opposite in direction. • Third law force pairs are always internal to the system of the two objects that are interacting. • Each force in the pair is always the same type of force. (INT-3.A.1)	Describe the forces of interaction between two objects (Newton's third law). Describe pairs of forces that occur in a physical system due to Newton's third law. 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)
	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 simultaneous linear equations. (INT-3.B.1)	Derive expressions that relate the acceleration of multiple connected masses moving in a system (e.g., Atwood machines) connected by light strings with tensions (and pulleys). (INT-3.B)

	VOCABULARY: physical system, motion (translational vs circular), interacting objects, mass, inertia, force (contact & long-range), net force, vector sum, superposition, free body diagram, Newton's laws, force-pair, equilibrium (dynamic and static), component (of a vector), magnitude (of a force, or other vector), quantitative and qualitative, kinetic and static friction, coefficient of friction, normal force, gravitational force (weight), tension force, spring force, sliding/slipping, drag and resistive force, terminal velocity, centripetal/radial (acceleration and velocity), Atwood machine, incline plane, banked curve, differential equation, separation of variables, uniform circular motion, radial, critical speed, system of equations, period, frequency, radians & degrees, angular displacement, angular velocity, angular acceleration	

ASSESSMENT EVIDENCE: Students will show their learning by:
- Identifying a system and describe the changes to the system due to external forces.
- Making observations or collecting data from representations of laboratory setups or results.
- Representing features of a model or the behavior of a physical system using appropriate graphing techniques, scales, and units.
- Applying Newton's Laws of Motion to describe a physical situation, and appropriately using mathematical relationships among dynamic variables.
- Making a scientific claim, supported by evidence from experimental data or physical representations of dynamic systems, with justification applying Newton's Laws.

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Unit II: Dynamics and Newton's Laws of Motion

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigations to measure and graph motion and forces.
  - Suggestions: Inclined Planes, Banked Curves, Atwood's Machine, Hooke's Law, Circular Motion
- Problem-Solving Techniques
  - Suggestions: Defining Systems, Free Body Diagrams, Solving Systems of Equations, Applying Newton's Laws both translationally and radially/centripetally, Analyzing and evaluating graphs

SUGGESTED TIME ALLOTMENT	**2 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 5 – 8 Workbook Topics 5 - 8 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit III: Work, Energy, and Power

<table>
<tr><td colspan="3">TRANSFER: Energy cannot be created nor destroyed, only transformed into various types of energy, or transferred between systems.</td></tr>
<tr><td>STANDARDS / GOALS:</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td rowspan="6">AP Physics C Big Idea 2: Force Interactions - Forces characterize interactions between objects or systems. (Essential Knowledge: 4.A.1, 4.B.1, 4.C.1)

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions.
(Essential Knowledge: 1.A.1, 1.B.1, 1.C.1, 1.D.1, 1.E.1, 1.F.1, 2.A.1, 2.B.1, 2.C.1, 2.D.1, 3.A.1)

NJSLS Disciplinary Core Ideas
PS2.C: Stability & Instability in Physical Systems
PS3.A: Definitions of Energy
HS-PS3-2
PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-3
PS3.C: Relationship Between Energy & Forces</td><td>When a force is exerted on an object, and the energy of the object changes, then work was done on the object.</td><td>• What is meant by “work”?</td></tr>
<tr><td>Conservative forces internal to the system can change the potential energy of that system.</td><td>• How do conservative and non-conservative forces affect a system?</td></tr>
<tr><td>The energy of a system can transform from one form to another without changing the total amount of energy in the system.</td><td>• What does it mean for energy to transform and transfer?
• How can conservation laws be applied to energy?</td></tr>
<tr><td>The energy of an object or a system can be changed at different rates.</td><td>• How can we apply rates of change to energy?</td></tr>
<tr><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>The area under the curve of a force versus position graph is equivalent to the work done on the object or system. (INT-4.B.1)</td><td>Calculate a value for work done on an object from a force versus position graph. (INT-4.B)</td></tr>
</table>

Unit III: Work, Energy, and Power

HS-ETS1-1, HS-ETS1-2 **NJSLS Science & Engineering Practices** Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology	The component of the displacement that is parallel to the applied force is used to calculate the work. • The work done on an object by a force can be calculated using: $$W = \int_a^b \vec{F}(r) \cdot d\vec{r}$$ • Work is a scalar value that can be positive, negative, or zero. • The definition of work can be applied to an object when that object can be modeled as a point-like object. (INT-4.A.1)	Calculate work done by a given force (constant or as a given function F(x)) on an object that undergoes a specified displacement. Describe the work done on an object as the result of the scalar product between force and displacement. Explain how the work done on an object by an applied force acting on an object can be negative or zero. (INT-4.A)
	The net work done on an (point-like) object is equal to the object's change in the kinetic energy. $$W_{net} = \Delta K$$ • This is defined as the work-energy theorem. The work-energy theorem can be used when an object or system can be modeled as a point-like particle (i.e., nondeformable and not having the capacity for internal energy).	Calculate the change in kinetic energy due to the work done on an object or a system by a single force or multiple forces. Calculate the net work done on an object that undergoes a specified change in speed or change in kinetic energy. Calculate changes in an object's kinetic energy or changes in speed that result from the application of specified forces. (INT-4.C)

Influence of Engineering, Technology, and Science on Society and the Natural World	• The definition for kinetic energy is: $K=\frac{1}{2}mv^2$ • 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). (INT-4.C.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. • The work done by a conservative force will be zero if the object undergoes a displacement that completes a complete closed path. • Common dissipative forces discussed in this course are friction, resistive forces, or externally applied forces from some object external to the system. (CON-1.A.1)	Compare conservative and dissipative forces. Describe the role of a conservative force or a dissipative force in a dynamic system. (CON-1.A)

	A definition that relates conservative forces internal to the system to the potential energy function of the system is: $$\Delta U = -\int_a^b \vec{F}_{cf} \cdot d\vec{r}$$ • The differential version (in 1-D) of this relationship is: (CON-1.B.1) $$F_x = -\frac{dU(x)}{dx}$$	Explain how the general relationship between potential energy functions and conservative forces is used to determine relationships between the two physical quantities. 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)
	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 (e.g., slopes, area under the curve, intercepts, etc.). (CON-1.C.1)	Describe the force within a system and the potential energy of a system. (CON-1.C)
	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”: $$\vec{F}_s = -k\Delta\vec{x}$$	Derive the expression for the potential energy function of an ideal spring. Derive an expression for the potential energy function of a nonideal spring that has a nonlinear relationship with position. (CON-1.D)

	• Using the general relationship between conservative force and potential energy, the potential energy for an ideal spring can be shown as: $$U_s = \frac{1}{2}k(\Delta x)^2$$ • 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. (CON-1.D.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: (CON-1.E.1) $$\Delta U_g = mg\Delta h$$	Calculate the potential energy of a system consisting of an object in a uniform gravitational field. (CON-1.E)
	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: $$U_G = -\frac{Gm_1m_2}{r}$$ • The potential energy of the Earth-mass system is defined to be zero at an infinite distance from the Earth. (CON-1.F.1)	Derive an expression for the gravitational potential energy of a system consisting of a satellite or large mass and the Earth at a great distance from the Earth. (CON-1.F)

	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. • Total mechanical energy is defined as the sum of potential and kinetic energy: $E = U_g + K + U_s$ • When nonconservative forces are acting on the system, the work they do changes the total energy of the system as follows: (CON-2.A.1) $W_{nc} = \Delta E$	Describe physical situations in which mechanical energy of an object in a system is converted to other forms of energy in the system. Describe physical situations in which the total mechanical energy of an object in a system changes or remains constant. (CON-2.A)
	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." • Some common systems that are frequently analyzed in this way are systems such as pendulum systems, ball/rollercoaster track, frictionless ramps or tracks, or the mass-spring oscillator. (CON-2.B.1)	Describe kinetic energy, potential energy, and total energy in relation to time (or position) for a "conservative" mechanical system. (CON-2.B)

	The application of the conservation of total mechanical energy can be used in many physical situations. (CON-2.C.1)	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 an Atwood machine, masses connected with pulley/ string combinations, or the masses in a modified Atwood machine. Calculate unknown quantities, such as speed or positions of an object that is under the influence of an ideal spring. 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.C)
	Power is defined by the following expressions: (CON-3.A.1) $P = \frac{dE}{dt}$ $P = \vec{F} \cdot \vec{v}$	Derive an expression for the rate at which a force does work on an object. Calculate the amount of power required for an object to maintain a constant acceleration. Calculate the amount of power required for an object to be raised vertically at a constant rate. (CON-3.A)

	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 the 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. (CON-2.D.1)	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)
	VOCABULARY: physical system & environment, work, energy, dot-product, work-energy theorem, kinetic energy, potential energy, joule, equilibrium, total mechanical energy, conservative force, restoring force, dissipating force, elastic potential, energy transfer, transform, gravity, gravitational potential energy, power, systems of equations, differential equation, integral	

Unit III: Work, Energy, and Power

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of energy representations of the same physical situation.
- Selecting relevant features of a representation to answer a question or solve a problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Making observations or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph motion and forces with relation to energy principles.
    - Suggestions: Hooke's Law (springs in series/parallel), Friction Lab
- Problem-Solving Techniques
    - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Unit analysis, Analyzing and evaluating graphs

SUGGESTED TIME ALLOTMENT	**1 week**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 10 – 11 Workbook Topics 10 - 11 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

Randolph Township Schools
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AP Physics C Curriculum
Unit IV: Systems of Particles and Linear Momentum

<table>
<tr><td colspan="3">TRANSFER: Momentum cannot be created nor destroyed, only transferred between objects within a system and with the environment.</td></tr>
<tr><td rowspan="6">STANDARDS / GOALS:

AP Physics C Big Idea 1: Changes - Interactions produce changes in motion. (Essential Knowledge: 3.A.1, 3.B.1, 3.C.1)

AP Physics C Big Idea 2: Force Interactions - Forces characterize interactions between objects or systems. (Essential Knowledge: 5.A.1, 5.B.1, 5.C.1, 5.D.1, 5.E.1)

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions. (Essential Knowledge: 4.A.1, 4.B.1, 4.C.1, 4.D.1, 4.E.1, 4.F.1)

NJSLS Disciplinary Core Ideas
PS22.B: Types of Interactions
HS-PS2.2, HS-PS2.3</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td>The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.</td><td>• How can we predict and describe the motion of a multi-body system?</td></tr>
<tr><td>An impulse exerted on an object will change the linear momentum of the object.</td><td>• How can we quantize a change in momentum?
• What effect does a net external force have on the momentum of a system?</td></tr>
<tr><td>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.</td><td>• What does it mean when momentum is conserved in a system?
• How can conservation laws be applied to momentum?</td></tr>
<tr><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>A symmetrical, regular solid of uniform mass density has a center of mass at its geometric center.</td><td>Calculate the center of mass of a system of point masses or a system of regular symmetrical objects.</td></tr>
</table>

Unit IV: Systems of Particles and Linear Momentum

PS2.C: Stability & Instability in Physical Systems PS3.B: Conservation of Energy and Energy Transfer HS-PS3-1, HS-PS3-3 PS3.C: Relationship Between Energy & Forces HS-ETS1-1, HS-ETS1-2, HS-ETS1-3, HS-ETS1-4 **NJSLS Science & Engineering Practices** Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information	• For a nonuniform solid that can be considered as a collection of regular masses or for a system of masses: (CHA-3.A.1) $x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$ • The calculus definition is: $x_{cm} = \frac{\int x\,dm}{\int dm}$	Calculate the center of mass of a thin rod of nonuniform density using integration. (CHA-3.A)
	If there is no net force acting on an object or a system, the center of mass does not accelerate; therefore, the velocity of the center of mass remains unchanged. • A system of multiple objects can be represented as one single mass with a position represented by the center of mass. • The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. (CHA-3.B.1)	Describe the motion of the center of the mass of a system for various situations. (CHA-3.B)

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Unit IV: Systems of Particles and Linear Momentum

NJSLS Crosscutting Concepts Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	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 location being a different location than the center of mass. (CHA-3.C.1)	Explain the difference between 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. (CHA-3.C)
	For a single object moving with some velocity, momentum is defined as: $\vec{p} = m\vec{v}$ • The total momentum of the system is the vector sum of the momenta of the individual objects. The rate of change of momentum is equal to the net external force. (INT-5.A.1) $\vec{F} = \frac{d\vec{p}}{dt}$	Calculate the total momentum of an object or a system of objects. Calculate relationships between mass, velocity, and linear momentum of a moving object. (INT-5.A)

Unit IV: Systems of Particles and Linear Momentum

	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-5.B.1) $$\int \vec{F}\,dt=\Delta\vec{p}=\vec{J}$$	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)
	A collection of objects with individual momenta can be described as one system with one center of mass velocity. (INT-5.C.1)	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)
	Impulse is equivalent to the area under a force versus time graph. (INT-5.D.1)	Calculate the momentum change in a collision using a force versus time graph for a collision. (INT-5.D)
	Momentum changes can be calculated using the calculus relationship for impulse: (INT-5.E.1) $$\vec{J}=\Delta\vec{p}=\int \vec{F}\,dt$$	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)
	Total momentum is conserved in the system and momentum is conserved in each direction in the absence of an external force. (CON-4.A.1)	Calculate the velocity of one part of a system after an explosion or a collision of the system. Calculate energy changes in a system that undergoes a collision or an explosion. (CON-4.A)

Unit IV: Systems of Particles and Linear Momentum

	In the absence of an external force, momentum is always conserved. • Kinetic energy is only conserved in elastic collisions. • In an inelastic collision, some kinetic energy is transferred to internal energy of the system. (CON-4.B.1)	Calculate the changes of momentum and kinetic energy as a result of a collision between two objects. (CON-4.B)
	Momentum is a vector quantity. • Momentum in each dimension is conserved in the absence of a net external force exerted on the object or system. • Kinetic energy is conserved only if the collision is totally elastic. (CON-4.C.1)	Describe the quantities that are conserved in a collision. (CON-4.C)
	Forces internal to a system do not change the momentum of the center of mass. (CON-4.D.1)	Calculate the speed of the center of mass of a system. (CON-4.D)
	Conservation of momentum states that the momentum of a system remains constant when there are no external forces exerted on the system. • Momentum is a vector quantity. • An elastic collision is defined as a system where the total kinetic energy is conserved in the collision. (CON-4.E.1)	Calculate the change in speed, change in velocity, change in kinetic energy, or change in momentum of objects in all types of collisions (elastic or inelastic) in one dimension, given initial conditions. Derive expressions for the conservation of momentum for a particular collision in one dimension. (CON-4.E)

Unit IV: Systems of Particles and Linear Momentum

	In the absence of a net external force during an interaction, linear momentum is conserved. • Momentum is a vector quantity. The momenta in each dimension (horizontal and vertical) are also conserved. • Using momentum components can be useful in this approach. (CON-4.F.1)	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. Derive expressions for the conservation of momentum for a particular two-dimensional collision of two objects. (CON-4.F)
	VOCABULARY: center of mass, system & environment, center of gravity, density (linear, areal, volumetric), momentum, impulse, force, motion, component vectors, conservation, elastic collision, inelastic collision, perfectly inelastic collision	

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Unit IV: Systems of Particles and Linear Momentum

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of momentum representations of the same physical situation.
- Selecting relevant features of a representation to answer a question or solve a problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigations to measure and graph motion in terms of momentum principles.
  - Suggestions: Center of Mass Lab, Ball bouncing off ground/wall (Force-Plate measurement), Cart collisions (elastic, inelastic, perfectly inelastic), Ballistic-Pendulum.
- Problem-Solving Techniques
  - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyzing and evaluating graphs

SUGGESTED TIME ALLOTMENT	**2 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapter 9 Workbook Topic 9 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

Randolph Township Schools
Randolph High School
AP Physics C Curriculum
Unit V: Rotation

TRANSFER: The motion of a rotating object can be described by mathematical equations, graphs and diagrams, and through words.

STANDARDS / GOALS:	ENDURING UNDERSTANDINGS	ESSENTIAL QUESTIONS
AP Physics C Big Idea 1: Changes - Interactions produce changes in motion. (*Essential Knowledge:* 4.A.1, 4.B.1) **AP Physics C Big Idea 2: Force Interactions -** Forces characterize interactions between objects or systems. (*Essential Knowledge:* 6.A.1, 6.B.1, 6.C.1, 6.D.1, 6.E.1, 7.A.1, 7.B.1, 7.C.1, 7.D.1, 7.E.1) **AP Physics C Big Idea 4: Conservation -** Conservation laws constrain interactions. (*Essential Knowledge:* 5.A.1, 5.B.1, 5.C.1, 5.D.1) **NJSLS Disciplinary Core Ideas** PS2.A: Forces and Motion HS-PS2-1 PS2.B: Types of Interactions PS2.C: Stability & Instability in Physical Systems	When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition.	• What does it mean for an object to be in equilibrium?
	There are relationships among the physical properties of angular velocity, angular position, and angular acceleration.	• How can we describe the motion of a rotating system?
	A net torque acting on a rigid extended body will produce rotational motion about a fixed axis.	• What causes the motion of a rotating system to change?
	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.	• What does it mean for angular momentum to be conserved? • How can conservation laws be applied to rotating systems?

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Unit V: Rotation

<table>
<tr><td rowspan="3">PS3.A: Definitions of Energy
HS-PS3-2
PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-3
PS3.C: Relationship Between Energy & Forces
HS-ETS1-1, HS-ETS1-2, HS-ETS1-4

NJSLS Science & Engineering Practices
Asking Questions & Defining Problems
Developing & Using Models
Planning and Carrying Out Investigations
Analyzing & Interpreting Data
Using Mathematical and Computational Thinking
Constructing Explanations and Designing Solutions
Engaging in Argument from Evidence
Obtaining, Evaluating, and Communicating Information

NJSLS Crosscutting Concepts
Patterns
Cause and Effect</td><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>The definition of torque is:
$\vec{\tau} = \vec{r} \times \vec{F}$
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.
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. (INT-6.A.1)</td><td>Calculate the magnitude and direction of the torque associated with a given force acting on a rigid body system.

Calculate the torque acting on a rigid body due to the gravitational force. (INT-6.A)</td></tr>
<tr><td>The two conditions of equilibrium are:
$\sum \vec{F} = 0$
$\sum \vec{\tau} = 0$
Both conditions must be satisfied for an extended rigid body to be in equilibrium. (INT-6.B.1)</td><td>Describe the two conditions of equilibrium for an extended rigid body.

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)</td></tr>
</table>

Unit V: Rotation

Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	The general definition of moment of inertia is: (INT-6.C.1) $I = \sum m_i r_i^2$	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. Calculate by what factor an object's rotational inertia will change when a dimension of the object is changed by some factor. Calculate the moment of inertia of point masses that are located in a plane about an axis perpendicular to the plane. (INT-6.C)
	The calculus definition of moment of inertia is: $I = \int r^2 dm$ • The differential mass *dm* must be determined from the linear mass density of the rod or object. (INT-6.D.1)	Derive the moment of inertia, using calculus, of a thin rod of uniform density about an arbitrary axis perpendicular to the rod. Derive the moment of inertia, using calculus, of a thin rod of nonuniform density about an arbitrary axis perpendicular to the rod. 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 of coaxial shells (e.g., annular ring). (INT-6.D)

	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. (Int-6.E.1) $I' = I_{cm} + Md^2$	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)
	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. • The appropriate unit for angular position is radians. • The general calculus kinematic linear relationships have analogous representations in rotational motion, such as: (CHA-4.A.1) $\omega = \frac{d\theta}{dt}$	Explain how the angular kinematic relationships for uniform angular acceleration are directly analogous to the relationships for uniformly and linearly accelerated motion. Calculate unknown quantities such as angular positions, displacement, angular speeds, or angular acceleration of a rigid body in uniformly accelerated motion, given initial conditions. 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)

Unit V: Rotation

	For objects that are rolling without slipping on a surface, the angular motion is related to the linear translational motion by the following relationships: (CHA-4.B.1) $v = r\omega$ $a = r\alpha$ $\Delta x = r\Delta\theta$	Explain the use of the relationships that connect linear translational motion to rotational motion in appropriate physical situations. Calculate the translational kinematic quantities from an object's rotational kinematic quantities for objects that are rolling without slipping. Calculate the (tangential) linear acceleration of a point on a rotating object given the object's angular acceleration. (CHA-4.B)
	The rotational analog to Newton's second law is: $\vec{\alpha} = \frac{\sum \vec{\tau}}{I}$ • 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. (INT-7.A.1)	Describe the complete analogy between fixed axis rotation and linear translation for an object subject to a net torque. Calculate unknown quantities such as net torque, angular acceleration, or moment of inertia for a rigid body undergoing rotational acceleration. Calculate the angular acceleration of an extended rigid body, of known moment of inertia, about a 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)

	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. • The rigid body diagram is helpful in applying the rotational Newton's second law to a rotating body. (INT-7.B.1)	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. 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)
	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. • The rotational characteristics may be related to the linear motion characteristics with the relationships listed in section CHA-4.A1 and CHA-4.B.1. • 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. (INT-7.C.1)	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 rolling (or rotating on a fixed axis) without slipping, and rotating and sliding simultaneously. (INT-7.C)

	The definition of rotational kinetic energy is: $$K_R = \frac{1}{2} I \omega^2$$ • Total kinetic energy of a rolling body or a body with both forms of motion is the sum of each kinetic energy term. • The definition of work also has an analogous form in rotational dynamics: (INT-7.D.1) $$W = \int \tau \, d\theta$$	Calculate the rotational kinetic energy of a rotating rigid body. Calculate the total kinetic energy of a rolling body or a body that has both translational and rotational motion. Calculate the amount of work done on a rotating rigid body by a specified force applied to the rigid over a specified angular displacement. (INT-7.D)
	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. (INT-7.E.1)	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)

	The definition of angular momentum of a rotating rigid body is: $\vec{L} = I\vec{\omega}$ • Angular impulse is equivalent to the change in angular momentum. The definition of this relationship is: $\int \vec{\tau}\, dt = \Delta\vec{L}$ • The differential equation is: (CON-5.A.1) $\vec{\tau} = \frac{d\vec{L}}{dt}$	Calculate the angular impulse acting on a rotating rigid body given specified angular properties or forces acting over time intervals. Calculate the angular momentum vector of a rotating rigid body in cases in which the vector is parallel to the angular velocity vector. (CON-5.A)
	The angular momentum of a linearly translating particle can be defined about some arbitrary point of reference or origin. The definition is: $\vec{L} = \vec{r} \times \vec{p}$ • The direction of this particle's angular momentum is determined by the vector product (cross-product). (CON-5.B.1)	Calculate the angular momentum vector of a linearly translating particle about a defined stationary point of reference. (CON-5.B)

	In the absence of external torques acting on a rotating body or system, the total angular momentum of the system is a constant. (CON-5.C.1)	Describe the conditions under which a rotating system's angular momentum is conserved. 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)
	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. • 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. • 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. (CON-5.D.1)	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). Calculate the increase or decrease in angular momentum of a rigid body when a point mass particle has a collision with the rigid body. 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)

	VOCABULARY: torque, force, radius (moment arm), vector-/cross-product, right-hand rule, extended rigid body, system, moment of inertia, center of mass, parallel-axis theorem, equilibrium, translational motion, rotational motion, angular displacement, angular velocity, angular acceleration, angular kinetic energy, angular momentum, conservation, rolling without slipping, rolling constraint, rolling friction	

ASSESSMENT EVIDENCE: Students will show their learning by:

- Selecting relevant features of a graph to answer a question or solve a problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve rotational kinematic problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph
    - Suggestions: Ball Rolling down Incline (Rolling Energy), Moment of Inertia of a Pulley, Rotational Dynamics (angular kinematics & torque), Angular Momentum (textbooks and office chair)
- Problem-Solving Techniques
    - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyzing and evaluating graphs

Randolph Township Schools
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Unit V: Rotation

SUGGESTED TIME ALLOTMENT	**2 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 12 Workbook Topics 12 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

Randolph Township Schools
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Unit VI: Oscillations

TRANSFER: Motion can be periodic; it can be described using mathematical equations, conservation principles, graphs and diagrams, and through words.

STANDARDS / GOALS:	**ENDURING UNDERSTANDINGS**	**ESSENTIAL QUESTIONS**
AP Physics C Big Idea 2: **Force Interactions** - Forces characterize interactions between objects or systems. (*Essential Knowledge:* 8.A.1, 8.B.1, 8.C.1, 8.D.1, 8.E.1, 8.F.1, 8.G.1, 8.H.1, 8.I.1, 8.J.1, 8.K.1) **NJSLS Disciplinary Core Ideas** PS2.A: Forces and Motion HS-PS2-1 PS2.C: Stability & Instability in Physical Systems PS3.A: Definitions of Energy HS-PS3-2 PS3.B: Conservation of Energy and Energy Transfer HS-PS3-1, HS-PS3-3 PS3.C: Relationship Between Energy & Forces HS-ETS1-2, HS-ETS1-4	There are certain types of forces that cause objects to repeat their motions with a regular pattern.	• How do restorative forces bound the motion and energy of a system? • How can calculus concepts apply to simple harmonic motion?
	KNOWLEDGE **Students will know:**	**SKILLS** **Students will be able to:**
	The general relationship for SHM is given by the following relationship: $x = x_{max}\cos(\omega t + \varphi)$ where 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. (INT-8.A.1)	Describe the general behavior of a spring-mass system in SHM in qualitative terms. Describe the relationship between the phase angle and amplitude in an SHM system. (INT-8.A)
	The period of SHM is related to the angular frequency by the following relationship: $T = \frac{2\pi}{\omega} = \frac{1}{f}$	Describe the displacement in relation to time for a mass-spring system in SHM. Identify the period, frequency, and amplitude of the SHM in a mass-spring system from the features of a plot. (INT-8.B)

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Unit VI: Oscillations

NJSLS Science & Engineering Practices Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Influence of Engineering, Technology, and Science on Society and the Natural World	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. (INT-8.C.1)	Describe each of the three kinematic characteristics of a spring-mass system in SHM in relation to time (displacement, velocity, and acceleration). For a spring-mass system in SHM, describe the general features of the motion, and identify the places on a graph where these values. (INT-8.C)
	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. (INT-8.D.1)	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)
	All of the characteristics of motion in SHM can be determined by using the general relationship listed in section INT-8.A.1 and calculus relationships. (INT-8.E.1)	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)

Unit VI: Oscillations

	The period can be derived from the characteristic differential equation. The following types of SHM systems can be explored (INT-8.F.1): • Mass oscillating on spring in vertical orientation • Mass oscillating on spring in horizontal orientation • Mass-spring system with springs in series or parallel • Simple pendulum • Physical pendulum • Torsional pendulum	Derive the expression for the period of oscillation for various physical systems oscillating in SHM. (INT-8.F)
	Potential energy can be calculated using the spring constant and the displacement from equilibrium of a mass-spring system: $U_s = \frac{1}{2}k(\Delta x)^2$ • Mechanical energy is always conserved in an ideal oscillating spring-mass system. • 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.	Calculate the mechanical energy of an oscillating system. Show that this energy is conserved in an ideal SHM spring-mass system. (INT-8.G)

Unit VI: Oscillations

	• These energy relationships are true in the following three types of SHM systems: Mass-spring in horizontal orientation, Mass-spring in vertical orientation, Simple pendulum (INT-8.G.1)	
	Total energy of a spring-mass system is proportional to the square of the amplitude. $E_{total} = \frac{1}{2}kA^2 = \frac{1}{2}kx_{max}^2$ • The total energy is composed of the two contributing mechanical energies of the spring-mass system. (INT-8.H.1) $E_{total} = K + U_s$	Describe the effects of changing the amplitude of a spring-mass system. (INT-H.8)
	The total mechanical energy of a system in SHM is conserved (INT-8.H.1). The potential energy of the spring-mass system is: $U_s = \frac{1}{2}k(\Delta x)^2$ and the kinetic energy of the system is: (INT-8.I.1) $K = \frac{1}{2}mv^2$	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. (INT-8.I)

Unit VI: Oscillations

	Any physical system that creates a linear restoring force will exhibit the characteristics of SHM. (INT-8.J.1)	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)
	The period of a system oscillating in SHM is: $T_s = 2\pi\sqrt{\frac{m}{k}}$ (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. (INT-8.K.1) $T_p = 2\pi\sqrt{\frac{l}{g}}$	Describe a linear relationship between the period of a system oscillating in SHM and physical constants of the system. (INT-8.K)
	VOCABULARY: simple harmonic motion, oscillation, hertz, amplitude, period, frequency, time constant, angular frequency, phase & phase constant, position, velocity, acceleration, restorative force, mass-spring system, simple pendulum, energy conservation, differential equation, dampening, resonance, driven oscillation	

Unit VI: Oscillations

ASSESSMENT EVIDENCE: Students will show their learning by:

- Selecting relevant features of a graph to answer a question or solve a problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph oscillatory motion.
  - Suggestions: Mass-spring system, Simple Pendulum to determine *g*

- Problem-Solving Techniques
  - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs

SUGGESTED TIME ALLOTMENT	**1 week**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapter 14 Workbook Topic 14 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit VII: Gravitation

<table>
<tr><td colspan="3">TRANSFER: Fields are necessary to understand gravitational interactions among massive objects that are not in contact.</td></tr>
<tr><td rowspan="6">STANDARDS / GOALS:

AP Physics C Big Idea 3: Fields – Fields predict and describe interactions.
(Essential Knowledge: 1.A.1, 1.B.1, 1.C.1)

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions.
(Essential Knowledge: 6.A.1, 6.B.1, 6.C.1, 6.D.1, 6.E.1, 6.F.1, 6.G.1, 6.H.1, 6.I.1)

NJSLS Disciplinary Core Ideas
PS2.A: Forces and Motion
HS-PS2-1
PS2.B: Types of Interactions
HS-PS2-4, HS-ESS1-4
PS2.C: Stability & Instability in Physical Systems
PS3.A: Definitions of Energy
HS-PS3-2
PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-3</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td>Objects of large mass will cause gravitational fields that create an interaction at a distance with other objects with mass.</td><td>• How can objects interact when not in contact with each other?
• How do fields relate to conservative forces?</td></tr>
<tr><td>Angular momentum and total mechanical energy will not change for a satellite in an orbit.</td><td>• How can we apply conservation laws to gravitation and orbits?</td></tr>
<tr><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>The magnitude of the gravitational force between two masses can be determined by using Newton’s universal law of gravitation. (FLD-1.A.1)</td><td>Calculate the magnitude of the gravitational force between two large spherically symmetrical masses. (FLD-1.A)</td></tr>
<tr><td>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: (FLD-1.B.1)
$$g = \frac{GM_e}{r^2}$$</td><td>Calculate the value for g or gravitational acceleration on the surface of the Earth (or some other large planetary object) and at other points outside of the Earth. (FLD-1.B)</td></tr>
</table>

Unit VII: Gravitation

<table>
<tr>
<td rowspan="3">PS3.C: Relationship Between Energy & Forces
HS-ETS1-1, HS-ETS1-2, HS-ETS1-4

NJSLS Science & Engineering Practices
Asking Questions & Defining Problems
Developing & Using Models
Planning and Carrying Out Investigations
Analyzing & Interpreting Data
Using Mathematical and Computational Thinking
Constructing Explanations and Designing Solutions
Engaging in Argument from Evidence
Obtaining, Evaluating, and Communicating Information

NJSLS Crosscutting Concepts
Patterns
Cause and Effect
Scale, Proportion, and Quantity
Systems and System Models
Energy and Matter
Stability and Change</td>
<td>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 non-uniform. (FLD-1.C.1)</td>
<td>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 larger than the Earth’s radius. (FLD-1.C)</td>
</tr>
<tr>
<td>The centripetal force acting on a satellite is provided by the gravitational force between satellite and planet.
• 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. (CON-6.A.1)</td>
<td>Calculate quantitative properties (such as period, speed, radius of orbit) of a satellite in circular orbit around a planetary object. (CON-6.A)</td>
</tr>
<tr>
<td>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.
• With proper substitutions, this can be reduced to expressing the period’s dependence on orbital distance as Kepler’s third law shows: (CON-6.B.1)
$T^2 = \frac{4\pi^2}{GM} r^3$</td>
<td>Derive Kepler’s third law for the case of circular orbits. (CON-6.B)</td>
</tr>
</table>

Unit VII: Gravitation

Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	Verifying Kepler's third law with actual data provides experimental verification of the law. (CON-6.C.1)	Describe a linear relationship to verify Kepler's third law. (CON-6.C)
	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: $U_g = -\frac{Gm_e m_{sat}}{r}$ • 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. (CON-6.D.1)	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)
	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. (CON-6.E.1)	Derive the relationship of total mechanical energy of a satellite/Earth system as a function of radial position. (CON-6.E)
	In ideal situations, the energy in a planet/ satellite system is a constant. • The gravitational potential energy of a 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.	Derive an expression for the escape speed of a satellite using energy principles. 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)

Unit VII: Gravitation

	• 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. (CON-6.F.1)	
	In ideal non-orbiting cases, a satellite's physical characteristics of motion can be determined using the conservation of energy. (CON-6.G.1)	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)
	The derivation of Kepler's third law is only required for a satellite in a circular orbit. (CON-6.H.1)	Describe elliptical satellite orbits using Kepler's three laws of planetary motion. (CON-6.H)
	In all cases of orbiting satellites, the total angular momentum of the satellite is a constant. • 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. (CON-6.I.1)	Calculate the orbital distances and velocities of a satellite in elliptical orbit using the conservation of angular momentum. Calculate the speeds of a satellite in elliptical orbit at the two extremes of the elliptical orbit (perihelion and aphelion).

Unit VII: Gravitation

	VOCABULARY: field, gravity, volume & surface density, mass, radius, period, speed, centripetal force, kinetic energy, gravitational potential energy, work, conservation of energy, Kepler's Laws, elliptical orbit, angular momentum, escape speed, gravitational constant, satellite	

ASSESSMENT EVIDENCE: Students will show their learning by:

- Selecting relevant features of a graph or diagram to answer a question or solve a problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph satellite motion.
    - Suggestions: Satellite Motion (PhET, CLEA - Jupiter's Moons)
- Problem-Solving Techniques
    - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs

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Unit VII: Gravitation

SUGGESTED TIME ALLOTMENT	**3 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapter 13 Workbook Topic 13 College Board Course Description - Mechanics College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit VIII: Electrostatics

<table>
<tr><td colspan="3">TRANSFER: Fields are necessary to understand electrostatic interactions among charged objects that are not in contact.</td></tr>
<tr><td>STANDARDS / GOALS:</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td rowspan="5">AP Physics C Big Idea 2: Force Interactions – Forces characterize interactions between objects or systems.
(Essential Knowledge: 1.A.1, 1.B.1, 1.C.1, 1.D.1)

AP Physics C Big Idea 3: Fields - Fields predict and describe interactions.
(Essential Knowledge: 1.A.1, 1.B.1, 1.C.1, 1.D.1, 1.E.1, 1.F.1, 1.G.1)

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions.
(Essential Knowledge: 1.A.1, 1.B.1, 1.C.1, 1.D.1, 1.E.1. 1.F.1, 2.A.1, 2.B.1, 2.C.1, 2.D.1, 2.E.1. 2.F.1, 3.A.1, 3.B.1, 3.C.1)

NJSLS Disciplinary Core Ideas
PS2.A: Forces and Motion
HS-PS2-1
PS2.B: Types of Interactions</td><td>Objects with an electric charge will interact with each other by exerting forces on each other. (ACT-1)</td><td>• What is charge?
• How do objects with excess charge interact?</td></tr>
<tr><td>Objects with an electric charge will create an electric field. (FIE-1)</td><td>• What is a field?
• What is an electric field?
• How do fields relate to forces?</td></tr>
<tr><td>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)</td><td>• How can conservation laws apply to systems with charge?</td></tr>
<tr><td>There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. (CNV-2)</td><td>• How does symmetry help solve a problem?
• How can we model charges and fields mathematically?</td></tr>
<tr><td>There are laws that use calculus and symmetry to derive mathematical relationships that can be applied to electrostatic-charge distributions. (CNV-3)</td><td>• How can models be used to help solve complex problems?</td></tr>
</table>

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Unit VIII: Electrostatics

<table>
<tr>
<td rowspan="4">HS-PS2-4
PS2.C: Stability & Instability in Physical Systems
HS-PS2-6
PS3.A: Definitions of Energy
HS-PS3-2
PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-3
PS3.C: Relationship Between Energy & Forces
HS-PS3-5, HS-ETS1-2

NJSLS Science & Engineering Practices
Asking Questions & Defining Problems
Developing & Using Models
Planning and Carrying Out Investigations
Analyzing & Interpreting Data
Using Mathematical and Computational Thinking
Constructing Explanations and Designing Solutions
Engaging in Argument from Evidence
Obtaining, Evaluating, and Communicating Information</td>
<td><u>KNOWLEDGE</u>
Students will know:</td>
<td><u>SKILLS</u>
Students will be able to:</td>
</tr>
<tr>
<td>Particles and objects may contain electrostatic charges. The Law of Electrostatics states that like charges repel and unlike charges attract through electrostatic interactions. (ACT-1.A.1)</td>
<td>Describe behavior of charges or system of charged objects interacting with each other. (ACT-1.A)</td>
</tr>
<tr>
<td>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.
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. (ACT-1.B.1)</td>
<td>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)</td>
</tr>
<tr>
<td>Point charge is defined as a charged object where the object is of negligible mass and size and takes up virtually no space.
The magnitude of electrostatic force between two-point charges is given by Coulomb's Law:
$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$$ Net force can be determined by superposition of all forces acting on a point charge due to the vector sum of other point charges. (ACT-1.C.1)</td>
<td>Calculate the net electrostatic force on a single point charge due to other point charges.

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)</td>
</tr>
</table>

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Unit VIII: Electrostatics

NJSLS Crosscutting Concepts Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	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. (ACT-1.D.1)	Determine the motion of a charged object of specified charge and mass under the influence of an electrostatic force. (ACT-1.D)
	The definition of electric field is defined as $\vec{E} = \frac{\vec{F}_E}{q}$ where q is defined as a “test charge.” • A test charge is a small positively charged object of negligible size and mass. • The direction of an electric field is the direction in which a test charge would move if placed in the field. (FIE-1.A.1)	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)
	The electric field of a single point charge can be determined by using the definition of the electric field and Coulomb’s Law. (FIE-1.B.1) $\left\|\vec{F}_E\right\| = \frac{1}{4\pi\varepsilon_0}\left\|\frac{q_1 q_2}{r^2}\right\|$	Describe and calculate the electric field due to a single point charge. (FIE-1.B)

Unit VIII: Electrostatics

	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. (FIE-1.C.1)	Describe and calculate the electric field due to a dipole or a configuration of two or more static-point charges. (FIE-1.C)
	Electric field lines have properties that show the relative magnitude of the electric field strength and the direction of the electric field vector at any position in the diagram. (FIE-1.D.1)	Explain or interpret an electric field diagram of a system of charges. (FIE-1.D)
	Using the properties of electric field diagrams, a general field line diagram can be drawn for static-charged situations. (FIE-1.E.1)	Sketch an electric-field diagram of a single point charge, a dipole, or a collection of static-point charges. (FIE-1.E)
	A charged particle in a uniform electric field will be subjected to a constant electrostatic force. (FIE-1.F.1)	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)
	The trajectory of a charged particle can be determined when placed in a known uniform electric field. • The initial conditions of motion are necessary to provide a complete description of the trajectory. • The force acting on the particle will be a constant force. (FIE-1.G.1)	Sketch the trajectory of a known charged particle placed in a known uniform electric field. (FIE-1.G)

	The definition of electric potential at a particular location due to a single point charge is: $$V = \frac{1}{4\pi\varepsilon_o}\frac{q}{r}$$ • 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: $$V = \frac{1}{4\pi\varepsilon_o}\sum_i \frac{q_i}{r_i}$$ • The electric potential is defined to be zero at an infinite distance from the point charge. (CNV-1.A.1)	Calculate the value of the electric potential in the vicinity of one or more point charges. (CNV-1.A)
	The definition for stored electrostatic potential energy in an electrostatic system of a point charge and a known electric field is: (CNV-1.B.1) $$\Delta U = q\Delta V$$	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)

Unit VIII: Electrostatics

	The electrostatic potential energy of two point charges near each other is defined in this way: $$U_E = \frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r}$$ • 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. (CNV-1.C.1)	Calculate the electrostatic potential energy of a collection of two or more point charges held in a static configuration. Calculate the amount of work needed to assemble a configuration of point charges in some known static configuration. (CNV-1.C)
	The work done in moving a test charge between two points in a uniform electric field can be calculated. • Use the definition of electric potential difference and the definition of a conservative field to determine the difference in electric potential in this case. (CNV-1.D.1)	Calculate the potential difference between two points in a uniform electric field and determine which point is at the higher potential. (CNV-1.D)
	An electrostatic configuration or field is a conservative field, and the work done in an electric field in moving a known charge through a 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.E.1)	Calculate the work done or changes in kinetic energy (or changes in speed) of a charged particle when it is moved through some known potential difference. (CNV-1.E)

	The characteristics and direction of an electric field can be determined from the characteristics of equipotential lines. • The relative magnitude of an electric field can be determined by the gradient of the potential lines. • The direction of the electric field is defined to be perpendicular to an equipotential line and pointing in the direction of the decreasing potential. (CNV-1.F.1)	Describe the relative magnitude and direction of an electrostatic field given a diagram of equipotential lines. Describe characteristics of a set of equipotential lines given in a diagram of an electric field. Describe the general relationship between electric field lines and a set of equipotential lines for an electrostatic field. (CNV-1.F)
	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: (CNV-1.G.1) $$E_x = -\frac{dV}{dx}$$	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. Use integration techniques to calculate a potential difference between two points on a line given the electric field as a function of position on that line. (CNV-1.G)
	The general definition of electric flux is: • The definition for the total flux through a geometric closed surface is defined by the "surface integral" defined as: $$\Phi = \int \vec{E} \cdot d\vec{A}$$	State and apply the general definition of electric flux. Calculate the electric flux through an arbitrary area or through a geometric shape (e.g., cylinder, sphere).

Unit VIII: Electrostatics

	• The sign of the flux is given by the dot product between the electric field vector and the area vector. $$\varphi_{surface} = \oint \vec{E} \cdot d\vec{A}$$ • The area vector is defined to be perpendicular to the plane of the surface and directed outward from a closed surface. (CNV-2.A.1)	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)
	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.1)	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. (CNV-2.B)
	Gauss's Law in integral form is: (CNV-2.C.1) $$\oint \vec{E} \cdot dA = \frac{q_{enclosed}}{\varepsilon_o}$$	State and use Gauss's Law in integral form to derive unknown electric fields for planar, spherical, or cylindrically symmetrical charge distributions. (CNV-2.C)
	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. (CNV-2.D.1)	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. Use Gauss's Law to calculate an unknown charge density or total charge on surface in

Unit VIII: Electrostatics

		terms of the electric field near the surface. (CNV-2.D)
	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. (CNV-2.E.1) $$\oint \vec{E}\cdot d\vec{A}=\frac{Q}{\varepsilon_0}=\Phi_E$$	Qualitatively describe electric fields around symmetrically (spherically, cylindrically, or planar) charged distributions. Describe the general features of an electric field due to symmetrically shaped charged distributions. (CNV-2.E)
	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. (CNV-2.F.1) $$\oint \vec{E}\cdot d\vec{A}=\frac{Q}{\varepsilon_0}=\Phi_E$$	Describe the general features of an unknown charge distribution given other features of the system. (CNV-2.F)
	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: $$d\vec{E}=\frac{1}{4\pi\varepsilon_0}\frac{dq}{r^2}\hat{r}$$ If this is applied appropriately and evaluated over the appropriate limits, the electric fields	Derive expressions for the electric field of specified charge distributions using integration and the principle of superposition. Analyze examples of charge distributions including a uniformly charged wire, a thin ring of charge (along the axis of the ring), and a semicircular or part of a semicircular arc. (CNV-3.A)

Unit VIII: Electrostatics

	of the stated charge distributions can be determined as a function of position. The following charge distributions can be explored using this method: • An infinitely long, uniformly charged wire or cylinder determine field at distances along perpendicular bisector • A thin ring of charge (along the axis of the ring) • A semicircular or part of a semicircular arc • A field due to a finite wire or line charge at a distance that is collinear with the line charge (CNV-3.A.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: • Electric fields with planar symmetry, infinite sheets of charge, combinations of infinite sheets of charge, or oppositely charged plates • Linearly charged wires or charge distributions • Spherically symmetrical charge distributions on spheres or spherical shells of charge (CNV-3.B.1)	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. Describe an electric field as a function of distance for the different types of symmetrical charge distributions. (CNV-3.B)

	Other distributions of charge that can be deduced using Gauss's Law or the principle of superposition. (CNV-3.B.2)	
	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: • A uniformly charged wire • A thin ring of charge (along the axis of the ring) • A semicircular arc or part of a semicircular arc • A uniformly charged disk (CNV-3.C.1)	Derive expressions for the electric potential of a charge distribution using integration and the principle of superposition. Describe electric potential as a function of distance for the different types of symmetrical charge distributions. 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)

Unit VIII: Electrostatics

	VOCABULARY: charge, electric force, attract/repel, physical system, energy, electrostatic, particle, Law of Electrostatics, interaction, neutral (charge), polarization, charging by conduction, charging & discharging, grounding, point charge, Coulomb's Law, superposition, vector sum, electric field, test charge, Coulomb's Law, electrostatic equilibrium, electric dipole, electric field, electric field line, permissivity constant, electric-field diagram, uniform electric field, electric potential, electrostatic potential energy, work, vector/scalar sum, conservative field, kinetic/potential energy, potential difference, equipotential lines, gradient, surface integral, electric flux, area vector, Gauss's Law, Gaussian surface/shape, charge density (linear,surface,volume), symmetry (planar, cylindrical, spherical), perpendicular bisector	

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Describing the physical meaning of a representation (such as Gauss’s Law).
- Selecting relevant features of a graph or diagram to answer a question or solve an electrostatic problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

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Unit VIII: Electrostatics

<table>
<tr><td colspan="2">KEY LEARNING EVENTS AND INSTRUCTION:

Design and perform laboratory investigation to measure and graph.
Suggestions: Electroscope, discovery activity conduction/induction, Coulomb’s Law, Electric Potential between charged plates (3D landscape), Electric Fields.
Problem-Solving Techniques
Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs, Drawing and evaluating electric field lines and equipotential maps, Drawing and applying Gaussian surfaces
</td></tr>
<tr><td>SUGGESTED TIME ALLOTMENT</td><td>3 weeks</td></tr>
<tr><td>SUPPLEMENTAL UNIT RESOURCES</td><td>Textbook: Chapter 25-29
Workbook Topics 25-29
College Board Course Description - Electricity and Magnetism
College Board - AP Classroom
Learn AP Physics - Practice Problems
PhET - Lab Simulations
Flipping Physics - Video Lessons
See Appendix A for additional resources</td></tr>
</table>

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Unit IX: Conductors, Capacitors, Dielectrics

TRANSFER: The physical properties of materials affect the motion of charge and storage of electrical energy.

STANDARDS / GOALS:	ENDURING UNDERSTANDINGS	ESSENTIAL QUESTIONS
AP Physics C Big Idea 2: Force Interactions – Forces characterize interactions between objects or systems. (*Essential Knowledge: 2*.A.1, 2.B.1, 2.C.1, 2.D.1, 2.E.1, 3.A.1, 3.B.1)	Excess charge on an insulated conductor will spread out on the entire conductor until there is no more movement of the charge. (ACT-2)	• How does charge behave on/in a conductor?
AP Physics C Big Idea 3: Fields - Fields predict and describe interactions. (*Essential Knowledge:* 2.A.1, 2.B.1, 2.C.1, 2.D.1)	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)	• How does electric potential explain how a charge behaves?
AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions. (*Essential Knowledge:* 4.A.1, 4.B.1, 4.C.1, 4.D.1, 4.E.1. 4.F.1, 4.G.1, 4.H.1, 4.I.1)	There are electrical devices that store and transfer electrostatic potential energy. (CNV-4)	• How does energy relate to electronics?
NJSLS Disciplinary Core Ideas PS1.A: Structure and Properties of Matter PS2.A: Forces and Motion HS-PS2-1	An insulator has different properties (than a conductor) when placed in an electric field. (FIE-2)	• What would happen if we placed an insulator in an electric behave? • How does charge behave on/in an insulator?

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<table>
<tr><td rowspan="3">PS2.B: Types of Interactions
PS2.C: Stability & Instability in Physical Systems
HS-PS2-6
PS3.A: Definitions of Energy
HS-PS3-2
PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-3
PS3.C: Relationship Between Energy & Forces
HS-PS3-5, HS-ETS1-2

NJSLS Science & Engineering Practices:
Asking Questions & Defining Problems
Developing & Using Models
Planning and Carrying Out Investigations
Analyzing & Interpreting Data
Using Mathematical and Computational Thinking
Constructing Explanations and Designing Solutions
Engaging in Argument from Evidence</td><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>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 nonuniform shapes).
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. (ACT-2.A.1)</td><td>Recognize that the excess charge on a conductor in electrostatic equilibrium resides entirely on the surface of a conductor.

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)</td></tr>
<tr><td>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).
The equipotential condition on a conductor remains, even if the conductor is placed in an external electric field. (ACT-2.B.1)</td><td>Explain why a conducting surface must be an equipotential surface.

Describe the consequences of a conductor being an equipotential surface.

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)</td></tr>
</table>

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Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	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. (ACT-2.C.1)	Describe the process of charging a conductor by induction. Describe the net charge residing on conductors during the process of inducing a charge on an electroscope/conductor. (ACT-2.C)
	A conductor can be completely polarized in the presence of an electric field. • The complete polarization of the conductor is a consequence of the conductor remaining an equipotential in the presence of an external electric field. (ACT-2.D.1)	Explain how a charged object can attract a neutral conductor. (ACT-2.D)
	Electrostatic shielding is the process of surrounding an area by a completely closed conductor to create a region free of an electric field. (ACT-2.E.1)	Describe the concept of electrostatic shielding. (ACT-2.E)
	The electric field has a value of zero within a spherical conductor. • 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. (ACT-3.A.1)	For charged conducting spheres or spherical shells, describe the electric field with respect to position. For charged conducting spheres or spherical shells, describe the electric potential with respect to position. (ACT-3.A)

	The net charge in a system must remain constant. The entire system of connected spheres must be at the same potential. • Charges will redistribute on two connected spheres until the two conditions above are met. (ACT-3.B.1)	Calculate the electric potential on the surfaces of two charged conducting spheres when connected by a conducting wire. (ACT-3.B)
	The general definition of capacitance is given by the following relationship: (CNV-4.A.1) $C = \frac{Q}{\Delta V}$	Apply the general definition of capacitance to a capacitor attached to a charging source. Calculate unknown quantities such as charge, potential difference, or capacitance for physical system with a charged capacitor. (CNV-4.A)
	The energy stored in a capacitor is determined by the following relationship: $U_E = \frac{1}{2}C(\Delta V)^2$ (or an equivalent expression) (CNV-4.B.1)	Use the relationship for stored electrical potential energy for a capacitor. Calculate quantities such as charge, potential difference, capacitance, and potential energy of a physical system with a charged capacitor. (CNV-4.B)
	The conservation of charge and energy can be applied to a closed physical system containing charge, capacitors, and a source of potential difference. (CNV-4.C.1)	Explain how a charged capacitor, which has stored energy, may transfer that energy into other forms of energy. (CNV-4.C)

Unit IX: Conductors, Capacitors, Dielectrics

	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: $$C=\frac{\varepsilon_0 A}{d}$$ 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. (CNV-4.D.1)	Derive an expression for a parallel-plate capacitor in terms of the geometry of the capacitor and fundamental constants. 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. 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. Explain how a change in the geometry of a capacitor will affect the capacitance value. (CNV-4.D)
	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: • The electric field is constant in magnitude and is independent of the geometry of the capacitor. • The electric field is proportional to the surface-charge density of the charge on one plate. (CNV-4.E.1)	Apply the relationship between the electric field between the capacitor plates and the surface-charge density on the plates. (CNV-4.E)

Unit IX: Conductors, Capacitors, Dielectrics

	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. (CNV-4.F.1)	Derive expressions for the energy stored in a parallel-plate capacitor or the energy per volume of the capacitor. (CNV-4.F)
	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 with 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. (CNV-4.G.1)	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. 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)
	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. (CNV-4.H.1)	Derive expressions for a cylindrical capacitor or a spherical capacitor in terms of the geometry of the capacitor and fundamental constants. (CNV-4.H)

	The properties of capacitance still hold for all types of capacitors (spherical or cylindrical). (CNV-4.I.1)	Calculate physical quantities such as charge, potential difference, electric field, surface area, and distance of separation for a physical system that contains a charged capacitor. (CNV-4.I)
	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. (FIE-2.A.1)	Describe and/or explain the physical properties of an insulating material when the insulator is placed in an external electric field. (FIE-2.A)
	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. (FIE-2.B.1)	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)

	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. (FIE-2.C.1)	Use the definition of the capacitor to describe changes in the capacitance value when a dielectric is inserted between the plates. (FIE-2.C)
	The initial condition of the capacitor system can determine which relationship to use when attempting to calculate unknown quantities in a capacitor system. (FIE-2.D.1)	Calculate changes in energy, charge, or potential difference when a dielectric is inserted into an isolated charge capacitor. 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)
	VOCABULARY: conductivity, conductor, insulator, charging by induction, charging/discharging, battery, emf, capacitance, induced electric field, polarization, dielectric, dielectric constant, charge density, electroscope, electrostatic shielding, parallel-plate capacitor, Gauss' Law	

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Unit IX: Conductors, Capacitors, Dielectrics

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Describing the physical meaning of a representation (such as current density, dielectric medium in capacitors, etc.).
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure & graph.
  - Suggestions: Electroscope, Van de Graaf machine, Capacitor Lab (with dielectric)
- Problem-Solving Techniques
  - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs, Drawing and applying Gaussian surfaces

SUGGESTED TIME ALLOTMENT	**2 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 25 & 29 Workbook Topics 25 & 29 College Board Course Description - Electricity and Magnetism College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit X: Electric Circuits

TRANSFER: Conservation laws can be used a mathematical tool to describe electrical circuits.

STANDARDS / GOALS:	ENDURING UNDERSTANDINGS	ESSENTIAL QUESTIONS
AP Physics C Big Idea 3: Fields - Fields predict and describe interactions. (*Essential Knowledge:* 3.A.1, 3.B.1, 3.C.1, 3.D.1, 3.E.1, 3.F.1) **AP Physics C Big Idea 4: Conservation** - Conservation laws constrain interactions. (*Essential Knowledge:* 5.A.1, 5.A.1, 5.B.1, 6.A.1, 6.A.2, 6.B.1, 6.C.1, 6.D.1, 6.E.1, 6.F.1, 6.G.1, 7.A.1, 7.B.1, 7.C.1, 7.D.1, 7.E.1, 7.F.1, 7.G.1) **NJSLS Disciplinary Core Ideas** PS1.A: Structure and Properties of Matter PS2.A: Forces and Motion PS2.B: Types of Interactions PS2.C: Stability & Instability in Physical Systems HS-PS2-6 PS3.A: Definitions of Energy HS-PS3-2	The rate of charge flow through a conductor depends on the physical characteristics of the conductor. (FIE-3)	• What quantities in physics are "rates of change?" • What does "rate of change" mean? • What factors influence the motion of charge in a conductor?
	There are electrical devices that convert electrical potential energy into other forms of energy. (CNV-5)	• How does a circuit do "work"?
	Total energy and charge are conserved in a circuit containing resistors and a source of energy. (CNV-6)	• How can conservation laws be applied to circuits with only resistors?
	Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. (CNV-7)	• How can conservation laws be applied to RC circuits?

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Unit X: Electric Circuits

PS3.B: Conservation of Energy and Energy Transfer HS-PS3-1, HS-PS3-3 PS3.C: Relationship Between Energy & Forces HS-PS3-5, HS-ETS1-2 **NJSLS Science & Engineering Practices** Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models	**KNOWLEDGE** **Students will know:**	**SKILLS** **Students will be able to:**
	The definition of current is: $I = \frac{dQ}{dt}$ Conventional current is defined as the direction of positive charge flow. (FIE-3.A.1)	Calculate unknown quantities relating to the definition of current. Describe the relationship between the magnitude and direction of current to the rate of flow of positive or negative charge. (FIE-3.A)
	Ohm's Law is defined as: (FIE-3.B.1) $I = \frac{\Delta V}{R}$	Describe the relationship between current, potential difference, and resistance of a resistor using Ohm's Law. Apply Ohm's Law in an operating circuit with a known resistor or resistances. (FIE-3.B)
	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. (FIE-3.C.1)	Explain how the properties of a conductor affect resistance. Compare resistances of conductors with different geometries or material. Calculate the resistance of a conductor of known resistivity and geometry. (FIE-3.C)
	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. (FIE-3.D.1)	Describe the relationship between the electric field strength through a conductor and the current density within the conductor. (FIE-3.D)

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Unit X: Electric Circuits

Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	The definition of current in a conductor is: $$I = Nev_d A$$ where N is the number of charge carriers per unit volume, e is the charge on electron, A is the cross-sectional area, and v_d is the drift velocity of electrons. (FIE-3.E.1)	Using the microscopic definition of current in a conductor, describe the properties of the conductor and the idea of "drift velocity." (FIE-3.E)
	The definition of resistance can be derived using the microscopic definition of current and the relationship between electric field and current density. (FIE-3.F.1)	Derive the expression for resistance of a conductor of uniform cross-sectional area in terms of its dimensions and resistivity. (FIE-3.F)
	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. (CNV-5.A.1)	Derive expressions that relate current, voltage, and resistance to the rate at which heat is produced in a resistor. Calculate different rates of heat production for different resistors in a circuit. (CNV-5.A)
	The total amount of heat energy transferred from electrical potential energy to heat can be determined using the definition of power. (CNV-5.B.1)	Calculate the amount of heat produced in a resistor given a known time interval and the circuit characteristics. (CNV-5.B)
	Series arrangement of resistors is defined as resistors arranged one after the other, creating one possible branch for charge flow. (CNV-6.A.1) Parallel arrangement of resistors is defined as resistors attached to the same two points (electrically) creating multiple pathways for charge flow. (CNV-6.A.2)	Identify parallel or series arrangement in a circuit containing multiple resistors. Describe a series or a parallel arrangement of resistors. (CNV-6.A)

Unit X: Electric Circuits

	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: (CNV-6.B.1) $$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$$	Calculate equivalent resistances for a network of resistors that can be considered a combination of series and parallel arrangements. (CNV-6.B)
	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. • The potential difference is the same value across multiple branches of resistors or branches that are in parallel. • The reduction of a circuit containing a network of resistors in parallel and series arrangement is necessary to determine the current through the battery. • Once the current through the battery is known, other quantities can be determined more easily. • Ohm's Law can be applied for every resistor in the circuit and for every branch in the circuit. (CNV-6.C.1)	Calculate voltage, current, and power dissipation for any resistor in a circuit containing a network of known resistors with a single battery or energy source. 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). (CNV-6.C)

Unit X: Electric Circuits

	Conventional circuit symbols and circuit-diagramming technique should be used in order to properly represent appropriate circuit characteristics. (CNV-6.D.1)	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)
	In a nonideal 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. (CNV-6.E.1)	Calculate the terminal voltage and the internal resistance of a battery of specified EMF and known current through the battery. Calculate the power and distribution of a circuit with a nonideal batter (i.e., power loss due to the battery's resistance versus the total power supplied by the battery). (CNV-6.E)
	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. • According to Kirchoff's current rule, 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. • According to Kirchoff'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.F.1)	Calculate a single unknown current, potential difference, or resistance in a multi-loop circuit using Kirchhoff's Rules. Set up simultaneous equations to calculate at least two unknowns (currents or resistance values) in a multi-loop circuit. Explain why Kirchoff's Rules are valid in terms of energy conservation and charge conservation around a circuit loop. Identify when conventional circuit-reduction methods can be used to analyze a circuit and when Kirchoff's Rules must be used to analyze a circuit. (CNV-6.F)

	An ideal ammeter has a resistance that is close to zero (negligible), and an ideal voltmeter has a resistance that is very large (infinite). • 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 parallel arrangement with the circuit element being measured. (CNV-6.G.1)	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. Describe the effect on measurements made by voltmeters or ammeters that have nonideal resistances. (CNV-6.G)
	The equivalent capacitance of capacitors arranged in series can be determined by the following relationship: $\frac{1}{C_s}=\sum_i \frac{1}{C_i}$ • The equivalent capacitance of capacitors arranged in parallel can be determined by the following relationship: $C_p=\sum_i C_i$ • The system of capacitors will behave as if the one equivalent capacitance were connected to the voltage source.	Calculate the equivalent capacitance for capacitors arranged in series or parallel, or a combination of both, in steady-state situations. Calculate the potential differences across specified capacitors arranged in a series in a circuit. Calculate the stored charge in a system of capacitors and on individual capacitors arranged in series or in parallel. (CNV-7.A)

Unit X: Electric Circuits

	• 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. • 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.A.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. (CNV-7.B.1)	Calculate the potential difference across a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions. 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)
	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. (CNV-7.C.1)	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)
	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 the transient time interval.	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

	• The general model for the charging or discharging of a capacitor in an RC circuit contains a factor of e^{t-RC}. (CNV-7.D.1)	resistor in an RC circuit when charging or discharging a capacitor. Recognize the model of charging or discharging a capacitor in an RC circuit, and apply the model to a new RC circuit. (CNV-7.D)
	The time constant ($\tau = RC$) is a significant feature on the sketches for transient behavior in an RC circuit. • 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 (e.g., final stored charge). • The initial conditions of the circuit will be represented on the sketch by the vertical intercept of the graph (e.g., initial current). • The capacitor in a circuit behaves as a "bare wire" with zero resistance at a time immediately after t = 0 seconds. • 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. (CNV-7.E.1)	Describe stored charge or potential difference across a capacitor or current, or potential difference of a resistor in a transient RC circuit. 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)

Unit X: Electric Circuits

	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. (CNV-7.F.1)	Calculate expressions that determine electrical potential energy stored in a capacitor as a function of time in a transient RC circuit. (CNV-7.F)
	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. (CNV-7.G.1)	Describe the energy transfer in charging or discharging a capacitor in an RC circuit. Calculate expressions that account for the energy transfer in charging or discharging a capacitor. (CNV-7.G)
	VOCABULARY: current, ampere, charge carrier, drift speed, current density, circuit diagram, circuit loop, circuit components, battery, capacitor, resistor, Kirchoff's Junction Rule, junction/node, Kirchoff's Loop Rule, potential difference (voltage), volt, resistivity, resistance, ohm, Ohm's Law, series/parallel, equivalent resistance, internal resistance, ideal wire, load, ammeter, voltmeter, short circuit, RC circuit, open circuit (infinite resistance), bare wire (zero resistance), time constant, charge/discharge, steady-state, transient, electric potential energy	

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Unit X: Electric Circuits

<table>
<tr><td colspan="2">

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Describing the physical meaning of a representation (such as Circuit Diagrams).
- Selecting and analyzing relevant features of a graph or diagram to answer a question or solve a circuit problem.
- Selecting an appropriate conservation law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve circuit problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph .
  - Suggestions: Resistivity Lab, Ohm's Law lab, Internal Resistance of a Battery, Resistors in Series & Parallel, RC Circuits
- Problem-Solving Techniques
  - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Applying conservation laws, Analyze and evaluate graphs, Drawing and evaluating circuit diagrams

</td></tr>
<tr><td>SUGGESTED TIME ALLOTMENT</td><td>4 weeks</td></tr>
<tr><td>SUPPLEMENTAL UNIT RESOURCES</td><td>Textbook: Chapters 30-31
Workbook Topics 30 & 31

College Board Course Description - Electricity and Magnetism
College Board - AP Classroom
Learn AP Physics - Practice Problems
PhET - Lab Simulations
Flipping Physics - Video Lessons
See Appendix A for additional resources</td></tr>
</table>

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Unit XI: Magnetic Fields

<table>
<tr><td colspan="3">TRANSFER: Magnetic fields and forces cause macroscopic and microscopic interactions.</td></tr>
<tr><td>STANDARDS / GOALS:</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td rowspan="6">AP Physics C Big Idea 1: Change - Interactions produce changes in motion. (Essential Knowledge: 1.A.1, 1.B.1, 1.C.1, 1.D.1, 1.E.1

AP Physics C Big Idea 3: Fields - Fields predict and describe interactions. (Essential Knowledge: 4.A.1, 4.B.1, 4.C.1, 5.A.1, 5.B.1, 5.C.1)

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions. (Essential Knowledge: 8.A.1, 8.B.1, 8.C.1, 8.D.1, 8.E.1)

Disciplinary Core Ideas
PS2.A: Forces and Motion
HS-PS2-1
PS2.B: Types of Interactions
HS-PS2-5, HS-PS3-5, HS-ETS1-2
PS2.C: Stability & Instability in Physical Systems</td><td>Charged particles moving through a magnetic field may change the direction of their motion. (CHG-1)</td><td>• What happens when a charged particle interacts with a magnetic field?</td></tr>
<tr><td>A magnetic field can interact with a straight conducting wire with current. (FIE-4)</td><td>• What happens when current interacts with a magnetic field?</td></tr>
<tr><td>Current-carrying conductors create magnetic fields that allow them to interact at a distance with other magnetic fields. (FIE-5)</td><td>• How do current-carrying conductors interact with other objects?</td></tr>
<tr><td>There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charges. (CNV-8)</td><td>• How can we mathematically model a system of moving charges?</td></tr>
<tr><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>The magnetic force of interaction between a moving charged particle and a uniform magnetic field is defined by the following expression:
$\vec{F}_M = q(\vec{v} \times \vec{B})$</td><td>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.</td></tr>
</table>

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Unit XI: Magnetic Fields

HS-PS2-6 **NJSLS Science & Engineering Practices**: Asking Questions & Defining Problems Developing & Using Models Planning and Carrying Out Investigations Analyzing & Interpreting Data Using Mathematical and Computational Thinking Constructing Explanations and Designing Solutions Engaging in Argument from Evidence Obtaining, Evaluating, and Communicating Information **NJSLS Crosscutting Concepts** Patterns Cause and Effect Scale, Proportion, and Quantity Systems and System Models Energy and Matter Stability and Change Structure and Function Interdependence of Science, Engineering, and Technology	• The direction of the magnetic force is determined by the cross-product or can be determined by the appropriate right-hand rule. • 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. • The charged particle must have a velocity to interact with the magnetic field. (CHG-1.A.1)	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. 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)
	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). (CHG-1.B.1)	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)
	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. • 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. (CHG-1.C.1)	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)

Unit XI: Magnetic Fields

Influence of Engineering, Technology, and Science on Society and the Natural World	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. (CHG-1.D.1)	Explain why the magnetic force acting on a moving charge particle does not work on the moving charged particle. (CHG-1.D)
	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. (CHG-1.E.1)	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)
	The definition of the magnetic force acting on a straight-line segment of a current-carrying conductor in a uniform magnetic field is: $\vec{F}_M = \int I\left(d\vec{\ell}\times\vec{B}\right)$ • The direction of the force can be determined by the cross-product or by the appropriate right-hand rule. (FIE-4.A.1)	Calculate the magnitude of the magnetic force acting on a straight-line segment of a conductor with current in a uniform magnetic field. Describe the direction of the magnetic force of interaction on a segment of a straight current-carrying conductor in a specified uniform magnetic field. (FIE-4.A)

Unit XI: Magnetic Fields

	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. • Depending on the orientation of the loop and the field, the forces may result in a torque that acts on the loop. (FIE-4.B.1)	Describe or indicate the direction of magnetic forces acting on a complete conductive loop with current in a region of uniform magnetic field. Describe the mechanical consequences of the magnetic forces acting on a current-carrying loop of wire. (FIE-4.B)
	The definition of torque can be applied to the loop to determine a relationship between the torque, field, current, and area of the loop. (FIE-4.C.1)	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)
	It can be shown or experimentally verified that the magnetic field of a long, straight, current-carrying conductor is: $B = \frac{\mu_0 I}{2\pi r}$ • The magnitude of the field is proportional to the inverse of the distance from the wire. • The magnetic-field vector is always mutually perpendicular to the position vector and the direction of the conventional current.	Calculate the magnitude and direction of a magnetic field produced at a point near a long, straight, current-carrying wire. Apply the right-hand rule for magnetic field of a straight wire (or correctly use the Biot–Savart Law found in CNV-8.A.1) to deduce the direction of a magnetic field near a long, straight, current-carrying wire. (FIE-5.A)

	• 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. • The magnetic field inside a solenoid can be determined using: (FIE-5.A.1) $B=\mu_0 nI$	
	The principle of superposition can be used to determine the net magnetic field at a point due to multiple long, straight, current-carrying wires. (FIE-5.B.1)	Describe the direction of a magnetic-field vector at various points near multiple long, straight, current-carrying wires. Calculate the magnitude of a magnetic field at various points near multiple long, straight, current-carrying wires. 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)
	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. • The direction of the force can be determined from the cross-product definition or from the appropriate right-hand rule. (FIE-5.C.1)	Calculate the force of attraction or repulsion between two long, straight, current-carrying wires. Describe the consequence (attract or repel) when two long, straight, current-carrying wires have known current directions. (FIE-5.C)

Unit XI: Magnetic Fields

	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: (CNV-8.A.1) $$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\left(d\vec{\ell}\times\hat{r}\right)}{r^2}$$	Describe the direction of the contribution to the magnetic field made by a short (differential) length of straight segment of a current-carrying conductor. Calculate the magnitude of the contribution to the magnetic field due to a short (differential) length of straight segment of a current-carrying conductor. (CNV-8.A)
	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. (CNV-8.B.1)	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. 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. (CNV-8.B)
	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: $$\oint \vec{B}\cdot d\vec{\ell} = \mu_0 I$$ where *I* in this case is the enclosed current by the Amperian loop.	Explain Ampère's Law and justify the use of the appropriate Amperian loop for current-carrying shapes such as straight wires, closed circular loops, conductive slabs, or solenoids. Derive the magnitude of the magnetic field for certain current-carrying conductors using Ampère's Law and symmetry arguments. 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.

Unit XI: Magnetic Fields

	• Ampère's Law for magnetism is 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. • 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.C.1)	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. (CNV-8.C)
	Ampère's Law can be used to determine magnetic-field relationships at different locations in cylindrical current-carrying conductors. (CNV-8.D.1)	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)
	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.	Describe the direction of a magnetic field at a point in space due to various combinations of conductors, wires, cylindrical conductors, or loops.

Unit XI: Magnetic Fields

	Ampère's Law can be used to determine individual field magnitudes. The principle of superposition can be used to add those individual fields. (CNV-8.E.1)	Calculate the magnitude of a magnetic field at a point in space due to various combinations of conductors, wires, cylindrical conductors, or loops. (CNV-8.E)
	VOCABULARY: north pole, south pole, ferromagnetic, permanent magnet, magnetic dipole, induced magnetic dipole, magnetic dipole moment, magnetic material, magnetic force, superposition, right-hand rule, vector-/cross-product, magnetic field, tesla, magnetic field lines, Biot-Savart Law, permeability constant, conductive loop, line integral, Ampere's Law, uniform magnetic field, solenoid, charge/mass ratio	

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Describing the physical meaning of a representation (such as Ampere's Law and Bio-Savart Law).
- Selecting relevant features of a graph or diagram to answer a question or solve a magnetism problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

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Unit XI: Magnetic Fields

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph magnetic fields.
  - Suggestions: Magnetic Field Discovery Activity, Magnetic Field Line mapping, Measuring Earth's Magnetic Field, Attractive/Repulsive Wires, Magnetic Field of Solenoid/Slinky
- Problem-Solving Techniques
  - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs, Applying the Right-Hand Rule, Drawing and applying Gaussian surfaces for magnetic fields

SUGGESTED TIME ALLOTMENT	**3 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapter 32 Workbook Topic 32 College Board Course Description - Electricity and Magnetism College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit XII: Electromagnetism

TRANSFER: Electricity and magnetism are intrinsically related.

STANDARDS / GOALS:	ENDURING UNDERSTANDINGS	ESSENTIAL QUESTIONS
AP Physics C Big Idea 2: Force Interactions – Forces characterize interactions between objects or systems. (*Essential Knowledge:* 4.A.1, 4.B.1) **AP Physics C Big Idea 3: Fields -** Fields predict and describe interactions. (*Essential Knowledge:* 6.A.1, 7.A.1,) **AP Physics C Big Idea 4: Conservation -** Conservation laws constrain interactions. (*Essential Knowledge:* 9.A.1, 10.A.1, 10.B.1, 10.C.1, 10.D.1, 10.E.1) **Disciplinary Core Ideas** PS2.A: Forces and Motion PS2.B: Types of Interactions HS-PS2-5, HS-PS3-5, HS-ETS1-2 PS2.C: Stability & Instability in Physical Systems HS-PS2-6	There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing a magnetic field. (CNV-9)	• How can we mathematically model magnetic fields?
	A changing magnetic field over time can induce current in conductors. (FIE-6)	• How does magnetism and electricity relate?
	Induced forces (arising from magnetic interactions) that are exerted on objects can change the kinetic energy of an object. (ACT-4)	• How can magnetic forces do “work”?
	In a closed circuit containing inductors and resistors, energy and charge are conserved. (CNV-10)	• How can conservation laws apply to LR circuits?
	Electric and magnetic fields that change over time can mutually induce other electric and magnetic fields. (FIE-7)	• How does magnetism and electricity relate?

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Unit XII: Electromagnetism

<table>
<tr><td rowspan="3">PS3.B: Conservation of Energy and Energy Transfer
HS-PS3-1, HS-PS3-2

NJSLS Science & Engineering Practices
Asking Questions & Defining Problems
Developing & Using Models
Planning and Carrying Out Investigations
Analyzing & Interpreting Data
Using Mathematical and Computational Thinking
Constructing Explanations and Designing Solutions
Engaging in Argument from Evidence
Obtaining, Evaluating, and Communicating Information

NJSLS Crosscutting Concepts
Patterns
Cause and Effect
Scale, Proportion, and Quantity
Systems and System Models
Energy and Matter
Stability and Change
Structure and Function</td><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>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 magnetic flux is: (CNV-9.A.1)
$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$</td><td>Calculate the magnetic flux through a loop of regular shape with an arbitrary orientation in relation to the magnetic-field direction.
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.
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)</td></tr>
<tr><td>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:
$$\varepsilon_i = -N\frac{d\phi_B}{dt}$$
where ε is the induced EMF and N is number of turns. (In a coil or solenoid, the N refers to the number of turns of coil or conductive loops in the solenoid.)</td><td>Describe which physical situations with a changing magnetic field and a conductive loop will create an induced current in the loop.
Describe the direction of an induced current in a conductive loop that is placed in a changing magnetic field.
Describe the induced current magnitudes and directions for a conductive loop moving through a specified region of space containing a uniform magnetic field.</td></tr>
</table>

Unit XII: Electromagnetism

Interdependence of Science, Engineering, and Technology Influence of Engineering, Technology, and Science on Society and the Natural World	• The negative sign in the expression embodies Lenz's Law and is an important part of the relationship. • 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. • Lenz's Law is essentially a law relating to conservation of energy in a system and has mechanical consequences. (FIE-6.A.1)	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. 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. 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. Describe the relative magnitude and direction of induced currents in a conductive loop with a time-varying magnetic field. (FIE-6.A)
	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. (ACT-4.A.1)	Determine if a net force or net torque exists on a conductive loop in a region of changing magnetic field. Justify if a conductive loop will change its speed as it moves through different regions of a uniform magnetic field. (ACT-4.A)

	Newton's second law can be applied to a moving conductor as it experiences a flux change. • The force on the conductor is proportional to the velocity of the conductor. • A differential equation of velocity can be written for these physical situations. • This will lead to an exponential relationship with the changing velocity of the conductor. • Using calculus, the expressions for velocity, induced force, and power can be all expressed with these exponential relationships. (ACT-4.B.1)	Calculate an expression for the net force on a conductive bar as it is moved through a magnetic field. 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. 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. 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)

Unit XII: Electromagnetism

	By applying Faraday's Law to an inductive electrical device, a variation on the law can be determined to relate the definition of inductance to the properties of the inductor: $$\varepsilon_i = -L\frac{dI}{dt}$$ where L is defined as the inductance of the electrical device. • The very nature of the inductor is to oppose the change in current occurring in the inductor. (CNV-10.A.1)	Derive the expression for the inductance of a long solenoid. Calculate the magnitude and the sense of the EMF in an inductor through which a changing current is specified. Calculate the rate of change of current in an inductor with a transient current. (CNV-10.A)
	The stored energy in an inductor is defined by: (CNV-10.B.1) $$U_L = \frac{1}{2}LI^2$$	Calculate the stored electrical energy in an inductor that has a steady-state current. (CNV-10.B)
	The electrical characteristics of an inductor in a circuit are the following: • 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.	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. Calculate the maximum current in a circuit that contains only a charged capacitor and an inductor. (CNV-10.C)

	• In a steady-state condition, the ideal inductor has a resistance of zero and therefore will behave as a bare wire in a circuit. • 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. (CNV-10.C.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. • The solution of this equation will yield the fundamental models for the LR circuit (in turning on the circuit and turning off the circuit). (CNV-10.D.1)	Derive a differential equation for the current as a function of time in a simple LR series circuit. 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.D)
	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. (CNV-10.E.1)	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)

Unit XII: Electromagnetism

	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. (CNV-10.F.1)	Explain how a changing magnetic field can induce an electric field. Associate the appropriate Maxwell's equation with the appropriate physical consequence in a physical system containing a magnetic or electric field. (CNV-10.F)
	VOCABULARY: electromagnetic induction, induced current, motional emf, eddy current, magnetic field vector, area vector, magnetic flux, weber, Faraday's Law, Lenz's Law, induced emf, induced electric field, inductance, henry, inductor, LC circuit, LR circuit, time constant, Maxwell's Laws	

ASSESSMENT EVIDENCE: Students will show their learning by:

- Describing the relationship between different types of representations of the same physical situation.
- Describing the physical meaning of a representation (such as Maxwell's Equations).
- Selecting relevant features of a graph or diagram to answer a question or solve a magnetism problem.
- Selecting an appropriate law, definition, mathematical relationship, or model to describe a physical situation and using correct computational techniques.
- Extracting quantities from narratives or mathematical relationships to solve problems.
- Making predictions, observations, or collecting data from representations of laboratory setups or results and discussing potential sources of experimental error.

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Unit XII: Electromagnetism

KEY LEARNING EVENTS AND INSTRUCTION:

- Design and perform laboratory investigation to measure and graph electromagnetic relationships.
    - Suggestions: Faraday's Law Induction Lab, LR Circuit, A/C motor/generator
- Problem-Solving Techniques
    - Suggestions: Defining variables and systems, Solving algebraic- and calculus-based equations, Analyze and evaluate graphs, Applying Right-Hand Rule, Drawing and applying Gaussian surfaces

SUGGESTED TIME ALLOTMENT	**4 weeks**
SUPPLEMENTAL UNIT RESOURCES	Textbook: Chapters 33 & 34 Workbook Topics 33 & 34 College Board Course Description - Electricity and Magnetism College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit XIII: Exam Review

TRANSFER: Physics concepts are not in isolation, they all combine together to explain the universe around us.

STANDARDS / GOALS:	ENDURING UNDERSTANDINGS	ESSENTIAL QUESTIONS
AP Physics C Big Idea 1: Change – Interactions produce changes in motion. **AP Physics C Big Idea 2: Force Interactions –** Forces characterize interactions between objects or systems. **AP Physics C Big Idea 3: Fields -** Fields predict and describe interactions. **AP Physics C Big Idea 4: Conservation -** Conservation laws constrain interactions. **Disciplinary Core Ideas** HS-PS1 – Matter and its Interactions HS-PS2 – Motion and Stability: Forces and Interactions HS-PS3 – Energy **NJSLS Science & Engineering Practices** Obtaining, Evaluating, and Communicating Information	Physical phenomena typically encapsulate many different aspects of physics and are not restricted to only one topic of physics.	• What steps does one take in solving a problem?
	Physics involves the concepts of change, force, fields, and conservation and how they all combine.	• What "big ideas" are involved in answering a certain problem?
	<u>KNOWLEDGE</u> **Students will know:**	**<u>SKILLS</u>** **Students will be able to:**
	The necessary physics concepts for the AP Physics C Mechanics Exam and the AP Physics C Electricity and Magnetism Exam.	Take the AP Physics C Mechanics Exam and AP Physics C Electricity and Magnetism Exam.
	Common themes create connections throughout the curriculum.	Apply their knowledge of physics to solve problems that require principles from different units of physics to be applied at the same time.
	VOCABULARY: see previous units.	

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Unit XIII: Exam Review

NJSLS Crosscutting Concepts Influence of Engineering, Technology, and Science on Society and the Natural World		

ASSESSMENT EVIDENCE: Students will show their learning by:

- Answering practice problems for the AP Physics C exams – both multiple choice and free response.

KEY LEARNING EVENTS AND INSTRUCTION:

- Practice AP style problems (Practice Exams from College Board and Practice Problems from AP Classroom) – both multiple choice and free response.

SUGGESTED TIME ALLOTMENT	**4 weeks**
SUPPLEMENTAL UNIT RESOURCES	College Board Course Description - Mechanics College Board Course Description - Electricity and Magnetism College Board - AP Classroom Learn AP Physics - Practice Problems PhET - Lab Simulations Flipping Physics - Video Lessons See Appendix A for additional resources

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Unit XIV: Extensions and Enrichment

<table>
<tr><td colspan="3">TRANSFER: Physics has many real-world applications.</td></tr>
<tr><td rowspan="6">STANDARDS / GOALS:

AP Physics C Big Idea 1: Change – Interactions produce changes in motion.

AP Physics C Big Idea 2: Force Interactions – Forces characterize interactions between objects or systems.

AP Physics C Big Idea 3: Fields - Fields predict and describe interactions.

AP Physics C Big Idea 4: Conservation - Conservation laws constrain interactions.

Disciplinary Core Ideas
HS-PS1 – Matter and its Interactions
HS-PS2 – Motion and Stability: Forces and Interactions
HS-PS3 – Energy

NJSLS Science & Engineering Practices
Obtaining, Evaluating, and Communicating Information</td><td>ENDURING UNDERSTANDINGS</td><td>ESSENTIAL QUESTIONS</td></tr>
<tr><td>Forces cause changes in motion.</td><td>• Where can we identify and analyze physical phenomena in our daily lives?</td></tr>
<tr><td>Conservation laws are universal and apply to many topics – energy, momentum, charge, etc.</td><td>• How can conservation laws be applied to a real-world situation?</td></tr>
<tr><td>Fields are a means for objects to interact without contact.</td><td>• How can we communicate complex physics concepts to our peers?</td></tr>
<tr><td><u>KNOWLEDGE</u>
Students will know:</td><td><u>SKILLS</u>
Students will be able to:</td></tr>
<tr><td>At least one, specific, real-world application of physics.

VOCABULARY: see previous units</td><td>Demonstrate a thorough understanding of the application of skills and concepts of physics to a real-world situation.</td></tr>
</table>

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Unit XIV: Extensions and Enrichment

NJSLS Crosscutting Concepts Influence of Engineering, Technology, and Science on Society and the Natural World		

ASSESSMENT EVIDENCE: Students will show their learning by:

- Creating their own presentation that demonstrates a mastery of knowledge and extension to the real world.
  - Suggestions: Presentation, Project, Paper, etc.

KEY LEARNING EVENTS AND INSTRUCTION:

- Compile resources in various media related to chosen topic.
- Develop a well-organized presentation of knowledge to their peers.

SUGGESTED TIME ALLOTMENT	**4 weeks**
SUPPLEMENTAL UNIT RESOURCES	See Appendix A for possible resources

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APPENDIX A

Textbook:

Physics for Scientists and Engineers
Authors: Knight, Randall
ISBN13: 978-0-132-83212-0
ISBN10: 0-132-83212-7 (High School binding)
Copyright 2013 Pearson Education, Inc.

Technology:

- Vernier LoggerPro software and data collection system
- Spreadsheet software, such as Excel
- Word processor software, such as Word
- Presentation software, such as PowerPoint
- Graphing Calculator

Supplemental Resources:

PhET – Lab Simulations
Flipping Physics – Video Lessons
Bozeman Science AP Physics Video Lessons
Dan Fullerton (A-Plus Physics) - Video Lessons
TwuPhysics Video Lessons & Problem Solutions
Doc Schuster's Video Lessons
LearnAPPhysics – Practice Problems
Mr. Roger's AP Physics C Course Resources
Mr. Levine's AP Physics Video Lessons

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APPENDIX B

Opportunities exist for interdisciplinary units with courses such as Calculus, and various science electives.