Summit High School
Summit, NJ

AP Physics C Curriculum

Developed 2011
Revised 2017, 2022

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Course Description

Advanced Placement Physics C is designed for students with exceptional aptitude for and interest in mathematics and the physical sciences. We utilize guided inquiry and student-centered learning to engage the development of critical and analytical thinking skills. The course will address all of the basic topics and concepts covered in the first part of the regular level physics course but to a depth equal to that of a first year college course for students majoring in engineering or the physical sciences. The first part of the course (approx 18 weeks) covers mechanics, while the second part (approx 14 weeks) covers electricity and magnetism.

Topics covered are in keeping with the suggested syllabus of the College Board. Students will understand how physics principles and concepts are developed from observations and data and, whenever possible, will develop these principles on the basis of experimentation. The Mechanics portion of the course covers classical Newtonian mechanics: kinematics, dynamics, work & energy, momentum, rotational motion, oscillations and gravitation. The Electricity & Magnetism part covers classical electrodynamics up to Maxwell: electrostatics, electronic devices, circuits, magnetostatics, and electromagnetism. Descriptive physics is included in the study of these areas and serves to help the students understand how ordinary physical phenomena are included in everyday activities. After the AP examination students will study special topics and projects, such as special relativity, a design challenge, and/or a science book report.

AP Physics C utilizes mathematics at the first-year Calculus level. To support success, students should be simultaneously enrolled in an AP Calculus course. Calculus skills such as differentiation, integration, and solving first-order separable differential equations are frequently used in lessons and problem solving throughout the year.

This curriculum revision (2022) incorporates the NJSLS “Standards in Action: Climate Change” recommendations for all NJ students. Here we focus on standards related to engineering solutions for climate change and analyzing empirical data related to climate change. Climate change themes are integrated in two places in this course: 1) in the Dynamics unit focusing on air resistance, driving speed, and driving efficiency; 2) in the Circuits unit where solar cells can be studied and used in experiments. Potential opportunities for climate change learning are not limited to these applications.

About this document

What follows is a guide to the course content and practices. Included are “Big Ideas”, “Essential Questions”, “Enduring Understandings”, “Proficiencies”, and Examples of Outcomes and Assessments as they appear in the classroom. Although this course is not officially aligned with the New Jersey Student Learning Standard for Science (NJSLS-S) or Next Generation Science Standards (NGSS), we have included relevant standards within the document to reflect areas of coverage. Big Ideas, Enduring Understandings, Course Proficiencies, and Essential Knowledge come directly from the AP Physics C Course Descriptions. Suggestions for supplementary topics, Global Perspectives, Technology Integration, and lab activities and other assessments are also included.

Please note that it is impossible to cover everything that is listed in any given year, as time and schedule constraints require teachers to pick and choose. Rather, what follows can be thought of as a list of potential topics, activities, and assessments from which to choose for a successful school year.

Course Pacing Guide

Timeframe	Unit	Key Topics
Summer assignment	Kinematics review	1-D Motion, equations of kinematics, calculus applications, motion graphs, freefall
Weeks 1-3	Kinematics	Vectors, Projectiles, 2-D Motion, uniform and nonuniform circular motion Relative Motion
Weeks 4-6	Dynamics	Newton's Laws, Friction, Applications, Centripetal force, Air Drag
Weeks 7-11	Energy and Momentum	Work and energy, energy conservation, Power, Momentum and impulse, momentum conservation, center of mass
Weeks 12-15	Rotation	Angular kinematics, dynamics, moment of inertia, rotational energy, angular momentum and conservation
Weeks 16-18	Oscillations and Gravitation	Simple harmonic motion, harmonic oscillators, pendulums, Universal gravitation, Kepler's Laws, gravitational potential energy and orbital applications
Weeks 19-23	Electrostatics,	Charging methods, Gauss's Law, electric potential, conductors in equilibrium, conductors and applications,
Weeks 24-26	Conductors, capacitors, dielectrics & Electric Circuits	Capacitors in series and parallel, dielectric properties, Current, Power, series and parallel circuits, complex circuits, Kirchoff's Laws and applications, RC circuits, Solar Cells and Climate Change Mitigation
Weeks 27-30	Magnetic fields and Electromagnetism	Lorentz forces, Hall effect, Ferromagnetism, Magnetism of current carrying wires and loops, solenoids, Ampere's Law and applications, Faraday and Lenz's Law, induction and applications, Maxwell's equations
Weeks 31-32	AP Exam Review	
Weeks 33-34	AP Exams	

Weeks 35-39	Post-AP exam	e.g. Special relativity, design projects, book reports

Laboratory work

Students spend a significant amount of time performing hands-on laboratory exercises in this course. According to the College Board, approximately 25% of class time should be centered on lab work and discussions about that lab work. Lab work supplements textbook learning and supports conceptual understanding. Most laboratories are inquiry based, so that students can design their own experiments to investigate relevant phenomena in each unit. Appropriate equipment is available for flexible approaches to different experiments. Students are encouraged to communicate the results of their investigations orally or in formal written reports. In this college level class, measurement techniques and statistical analysis are explicitly addressed, and students are expected to consider not only the results of their experiments, but sources of error and calculations of measurement uncertainty. In each unit of this document, lists of possible laboratories are included. There is not sufficient time to include all during the course of the year, so teachers and students can choose labs based on interest and need.

Part 1: Newtonian Mechanics

Unit 1
Kinematics

<table>
<tr><th colspan="2">NJSLS Standards: N/A</th></tr>
<tr><td colspan="2">Big Ideas:
BIG IDEA 1: CHANGE
Interactions produce changes in motion.</td></tr>
<tr><th>Essential Questions
What provocative questions will foster inquiry, understanding, and transfer of learning?</th><th>Enduring Understandings
What will students understand about the big ideas?</th></tr>
<tr><td>How would you quantitatively describe the motion of a fighter jet landing on a carrier deck in a way that would help designers and pilots?

How would you estimate the arrival time of your commute with knowledge of the different speed limits and starts and stops along the way?

As the space shuttle lands and slows to a stop, is it accurate to say that it is “accelerating”?

When fragments of rock are ejected from a volcano, what factors determine which will land farthest from the volcano?

What information would a bee need to specify to tell other bees the location of a flowerbed?

Why must a sailboat “tack” back and forth across the wind during a journey and how is it able to move against the wind?

How did film crews achieve the effect of weightlessness in scenes of “Apollo 13”?

When descending a hill on your bike, why do you roll faster the farther you go?</td><td>There are relationships among the vector quantities of position, velocity, and acceleration for the motion of a particle along a straight line

There are multiple simultaneous relationships among the quantities of position, velocity, and acceleration for the motion of a particle moving in more than one dimension with or without net forces
<hr>From AP Physics C Essential Knowledge
Students will understand…

The kinematic relationships for an object accelerating uniformly in one dimension

The constant velocity model can be derived from the kinematic relationships

The average velocity and acceleration models can also be derived from the above relationships

Differentiation and integration are necessary for determining functions that relate position,</td></tr>
</table>

Why should you throw a stone higher if you want it to go farther?	velocity, and acceleration for an object with nonuniform acceleration. 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). 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. a. These functions may include trigonometric, power, exponential functions (of time) or velocity-dependent functions. Differentiation and integration are necessary for determining functions that relate position, velocity, and acceleration for an object in each dimension. 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. 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. 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

Areas of Focus: Proficiencies (Cumulative Progress Indicators)	Examples, Outcomes, Assessments
From AP Physics C Learning Objectives Students can… 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. Calculate values such as average velocity or minimum or maximum velocity for an object in uniform acceleration. Determine functions of position, velocity, and acceleration that are consistent with each other, for the motion of an object with a nonuniform acceleration. Describe the motion of an object in terms of the consistency that exists between position and time, velocity and time, and acceleration and time 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 a net change in velocity of an object moving in two dimensions. Calculate an average acceleration vector for an object moving in two dimensions. Calculate a velocity vector for an object moving relative to another object (or frame of reference) that moves with a uniform velocity.	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests ● Measurement techniques and error analysis ● Calculus applications ● Preparation for AP exam **Sample Assessments:** ● Daily assignments and homework quizzes ● Collaborative projects ● Multiple choice items from textbook test banks and released AP exams ● Free response problems from released AP exams ● Unit Exam ● Lab: Graph matching (calculus focus) ● Lab: Galileo and the Inclined Plane ● Lab: Projectile launch challenge ● Lab: Non uniform acceleration (falling chain) **Instructional Strategies:** **Interdisciplinary Connections** ● Astronomy: Relative distances and velocities. ● History: Knowledge of velocity, distance and time allowed the ancient Greeks to accurately estimate the circumference of the Earth ● History: biographical sketch of Galileo ● Mathematics: algebraic manipulation of single variable equations (average speed, wave equation); arithmetic calculations ● Math: Calculations of energies, velocities, forces at various points in a roller coaster. ● Math: Numerical integration of kinematic data to yield physical constants. ● Math: Numerical integration of a force and time graph to yield impulse.

Describe the velocity vector for one object relative to a second object with respect to its frame of reference. 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 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 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.	● Forensic Science: determining initial speeds and positions of vehicles before an automobile collision. **Technology Integration** ● Use of computer spreadsheet software programs (Excel, Graphical Analysis, etc) to analyze data graphically ● Using infrared photogate timing devices to measure velocity ● Use computers to collect data on fast moving objects ● Use motion sensors, photo gates, and video cameras to record motion data ● Use computers to store motion data, and calculate velocities and acceleration **Media Literacy Integration** ● Often our metal images of famous scientists are formed from information presented in classroom movies. Sometimes this information is inaccurate or misleading. ● We need to consider the credentials of the “experts” who speak in educational media. **Global Perspectives** ● Explore travel distances and velocities of various modes of transportation. ● Explore travel distances and velocities of peoples from various societies today and in the past. ● Explore travel direction, distances and velocities of oil from the 2010 Gulf Oil Spill. ● Explore the concept of planetary travel to the Moon, Mars, and beyond.

Unit 2
Dynamics

NJSLS standards:
HS-PS2-1 Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration. **HS-ESS3-6** Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity (i.e., climate change).
Big Ideas: ● **BIG IDEA 2: FORCE INTERACTIONS** Forces characterize interactions between objects or systems.

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
How is it possible for a single person to support the vertical weight of an airship and what property makes it impossible to abruptly change its horizontal motion? When a horse pulls a buggy, and the action force of the horse pulling on the buggy is equal to the reaction force of the buggy pulling on the horse, how is it possible for the system to move at all? Why is it possible to juggle when riding in a moving airplane? How could an airplane passenger determine the rate of acceleration down the runway with only a shoelace, a wedding ring, and a camera? What factors determine how fast a car can go around a corner without skidding? How do airplanes receive lift? What factors determine the maximum falling speed of a skydiver?	A net force will change the translational motion of an object. The motion of some objects is constrained so that forces acting on the object cause it to move in a circular path. There are force pairs with equal magnitude and opposite directions between any two interacting objects. --- *From AP Physics C Essential Knowledge: Students will understand…* Newton's second law can be applied to an object in accelerated motion or in a state of equilibrium. 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. Forces can be

How does driving speed impact fuel efficiency, carbon emissions, and climate change? Why does the swirling motion continue after you've stopped stirring a cup of coffee or tea? If you apply the same amount of "push" to a car as you would a shopping cart, why doesn't it move? Why will the sun set tomorrow in nearly the same place that it set today? Why must you push backward to make a skateboard move forward?	resolved into components and these components can be separately added in their respective directions. The appropriate use of Newton's second law is one of the fundamental skills in mechanics. 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. 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. Using appropriate relationships derived from Newton's second law analysis, unknown forces (or accelerations) can be determined from the given known physical characteristics. The relationships for the frictional force acting on an object on a rough surface The direction of friction can be determined by the relative motion between surfaces in kinetic frictional cases. a. 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. The maximum value of static friction has a precise relationship: a. This relationship can be used to determine values such as, "The maximum angle of incline at which the block will not slip." The standard "resistive force" in this course is defined as a velocity-dependent force. 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.

	Because the resistive force is a function of velocity, applying Newton's second law correctly will lead to a differential equation for velocity 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. 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. 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. 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. 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. a. The maximum speed occurs at the bottom of the circle and is related to all of the vertical forces acting on the object. 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.

	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. 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.
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From NJSLS DCI: **PS2.A: Forces and Motion** • Newton's second law accurately predicts changes in the motion of macroscopic objects. (HS-PS2-1) **ESS3.D: Global Climate Change** ● Through computer simulations and other studies, important discoveries are still being made about how the ocean, the atmosphere, and the biosphere interact and are modified in response to human activities. ______________________________ From AP Physics C Objectives Students can… 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). 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.	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests ● Measurement techniques and error analysis ● Calculus applications ● Preparation for AP exam **Sample Assessments:** ● Daily assignments and homework quizzes ● Collaborative projects ● Multiple choice: items from textbook test banks and released AP exams ● Free response problems from released AP exams ● Unit Exam ● Lab: Connected bodies ● Lab: Measuring static/kinetic friction coefficients ● Lab: Whirligig (uniform circular motion) ● Lab: Increasing mass lab (Newton's 2nd law) ● Lab: Coffee filters dropping (air resistance) **Instructional Strategies:** **Interdisciplinary Connections**

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. 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). 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.). Describe the relationship between frictional force and the normal force for static friction and for kinetic friction. b. Explain when to use the static frictional relationship versus the kinetic frictional relationship in different physical situations (e.g., object sliding on surface or object not slipping on incline). Describe the direction of frictional forces (static or kinetic) acting on an object under various physical situations. Derive expressions that relate mass, forces, or angles of inclines for various slipping conditions with friction. b. Calculate the value for the static frictional force for an object in various dynamic situations (e.g., an object at rest on a truck bed, an object at rest on an incline, or an object pinned to a horizontal surface).	● History: to put Isaac Newton's 1687 magnum opus, *The Principia*, into its historical context ● Biology: Discuss the maximum boundaries of acceleration on the human body, particularly in roller coasters, airplanes, and spaceships. ● Biological basis of roller coaster design constraints – g-forces. **Technology Integration** ● Collect force data using computer based lab probeware ● Use motion and force sensors to determine frictional forces. ● Use of computer spreadsheet software programs (Sheets, Graphical Analysis, etc) to analyze data graphically **Media Literacy Integration** ● Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. ● Scientifically literate students should be able to identify the critical difference between the two types of media. **Global Perspectives** ● The laws of mechanics—equivalent throughout the universe—transcend geographical and cultural borders. ● Inertia and relative motion as a reference frame phenomena--metaphor for Point of View ● Historical background of Newton's life and work ● Climate change: how driving faster increases air drag quadratically, contributing more to carbon emissions and climate change

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). 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). Calculate the terminal velocity of an object moving vertically under the influence of a resistive force of a given relationship. 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. 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. Explain how a net force in the centripetal direction can be a single force, more than one force, or even components of forces that are acting on an object moving in circular motion. 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. 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. Derive expressions relating centripetal force to the minimum speed or maximum speed of an object moving in a vertical circular path. 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. 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). 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).	

Unit 3
Energy and Momentum

NJSLS Standards:

HS-PS3-1 Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known

HS-PS3-2 Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative position of particles (objects).

HS-PS3-3 Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.

HS-PS2-2 Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.

HS-PS2-3 Apply science and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.

Big Ideas:

- **BIG IDEA 1: CHANGE**
  Interactions produce changes in motion.
- **BIG IDEA 2: FORCE INTERACTIONS**
  Forces characterize interactions between objects or systems.
- **BIG IDEA 4: CONSERVATION**
  Conservation laws constrain interactions

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
When a pole-vaulter springs over the bar, what energy transformations are involved? Why do “fish ladders” help salmon in their journey over a dam? In the carnival “Ring the Bell” attraction, what is the best strategy to win the game? When a high diver dives into the water, what energy transformations are involved?	When a force is exerted on an object, and the energy of the object changes, then work is done on the object. Conservative forces internal to the system can change the potential energy of that system. The energy of a system can transform from one form to another without changing the total amount of energy in the system.

How does energy conservation help roller coaster designers know how high up the cars must be when they start their descent to negotiate a loop-the-loop? What is more dangerous: being tackled by a lightweight football player moving quickly or by a player with twice the mass moving half as fast? What principles govern the behavior of rockets? Do golfers benefit from more massive clubs? Why does an airbag protect passengers during a car crash? Why is no work done when you push against a wall, but work is done when you coast down a hill? Why does a stretched rubber band return to its original length? Why is it easier to walk up a flight of steps, rather than run, when the gravitational potential energy of the system is the same? Why do pictures hung on a wall sometimes tilt forward? Why will you fall if you lean too far over a banister or ledge? Why does water move a ship forward when its propellers push water backward? Why are cannon barrels so much longer and heavier than cannonballs?	The energy of an object or a system can be changed at different rates. The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. An impulse exerted on an object will change the linear momentum of the object. 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. --- *From the AP Physics C Essential Knowledge: Students will understand…* 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. 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. The area under the curve of a force versus position graph is equivalent to the work done on the object or system. The net work done on an (point-like) object is equal to the object's change in the kinetic energy. 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., non-deformable and not having the capacity for internal energy).. 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). 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. For conservative forces, a derivative/integral relationship exists between potential energy and force. 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.). 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:" F=-kx. Using the general relationship between conservative force and potential energy, the potential energy for an ideal spring can be shown as: 0.5 kx^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. The definition of the gravitational potential energy of a system consisting of the Earth and an object of mass m near the surface of the Earth can be derived. Using the relationship between the conservative force and potential energy, it can be shown that the gravitational potential energy of the object-Earth system can be derived. The potential energy of the Earth-mass system is defined to be zero at an infinite distance from the Earth. 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. When nonconservative forces are acting on the system, the work they do changes the total energy of the system. 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. The application of the conservation of total mechanical energy can be used in many physical situations. 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. Power is defined as the rate of change of work. A symmetrical, regular solid of uniform mass density has a center of mass at its geometric center. 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.

	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. For a single object moving with some velocity, momentum is defined as p=mv. 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. Impulse is defined as the average force acting over a time interval. Impulse is also equivalent to the change in momentum of the object receiving the impulse. A collection of objects with individual momenta can be described as one system with one center of mass velocity. Impulse is equivalent to the area under a force versus time graph. Momentum changes can be calculated using the calculus relationship for impulse. Total momentum is conserved in the system and momentum is conserved in each direction in the absence of an external force. 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. 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. Forces internal to a system do not change the momentum of the center of mass. 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. 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.
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From the NJSLS *DCI's:* **PS3.A: Definitions of Energy** • Energy is a quantitative property of a system that depends on the motion and interactions of matter and radiation within that system. That there is a single quantity called energy is due to the fact that a system's total energy is conserved, even as, within the system, energy is continually transferred from one object to another and between its various possible forms. (HS-PS3-1),(HS-PS3-2) • At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy. (HS-PS3-2) (HS-PS3-3) • These relationships are better understood at the microscopic scale, at which all of the different manifestations of energy can be modeled as a combination of energy associated with the motion of particles and energy associated with the	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests ● Measurement techniques and error analysis ● Calculus applications ● Preparation for AP exam **Sample Assessments:** ● Daily assignments and homework quizzes ● Collaborative projects ● Multiple choice: items from textbook test banks and released AP exams ● Free response problems from released AP exams ● Unit Exam ● Lab: Spring constant of projectile launcher and/or motion cart

configuration (relative position of the particles). In some cases the relative position energy can be thought of as stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space. (HS-PS3-2) **PS3.B: Conservation of Energy and Energy Transfer** • Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. (HS-PS3-1) • Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4) • Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g. relative positions of charged particles, compression of a spring) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. (HS-PS3-1) • The availability of energy limits what can occur in any system. (HS-PS3-1) • Uncontrolled systems always evolve toward more stable states—that is, toward more uniform energy distribution (e.g., water flows downhill, objects hotter than their surrounding environment cool down). (HS-PS3-4) **PS3.C: Relationship Between Energy and Forces** • When two objects interacting through a field change relative position, the energy stored in the field is changed. (HS-PS3-5) **PS3.D: Energy in Chemical Processes** • Although energy cannot be destroyed, it can be converted to less useful forms—	• Lab: Ballistic pendulum • Lab: Cut pendulum • Lab: Inelastic Collisions • Lab: 2-D Elastic collisions • Lab: Impulse of a falling chain **Instructional Strategies:** **Interdisciplinary Connections** • Math: Calculations of energies, velocities, forces at various points in a roller coaster. • Math: Numerical integration of kinematic data to yield physical constants. • Social studies: how does the existence of high concentrations of potential energy (oil) affect global politics? • Astronomy: Supernova and other explosions. • Biology: energy transfers and effects in biological systems and ecosystems • Sports: Analysis of Dale Earnhardt's fatal 2001 crash **Technology Integration** • Use computer simulations to observe and create unique energy transfer systems. • Use of computer spreadsheet software programs (Excel, Graphical Analysis, etc) to analyze data graphically • Mining internet for data on worldwide energy use and savings • Collection of lab data through computerized probeware • Collection of force, impulse, and momentum data with computers and probeware • Use of precision timing photogates • Simulations of idealized collision events **Media Literacy Integration** • Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. • Scientifically literate students should be able to identify the critical difference between the two types of media.

for example, to thermal energy in the surrounding environment. (HS-PS3-3),(HS-PS3-4) **PS2.A: Forces and Motion** • Momentum is defined for a particular frame of reference; it is the mass times the velocity of the object. (HS-PS2-2) • If a system interacts with objects outside itself, the total momentum of the system can change; however, any such change is balanced by changes in the momentum of objects outside the system. (HS-PS2-2),(HS-PS2-3) *From AP Physics C Learning Objectives* Students can... 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. Calculate a value for work done on an object from a force versus position graph. 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. Compare conservative and dissipative forces. b. Describe the role of a conservative force or a dissipative force in a dynamic system. Explain how the general relationship between potential energy functions and conservative forces is used to determine relationships between the two	**Global Perspectives** ● Compare and contrast classroom energy transformations with those within our solar system, our galaxy, and the universe. ● Investigate the geopolitical effects of energy policy ● Energy as a unifying concept ● Explore the concept of planetary travel to the Moon, Mars, and beyond using concepts of impulse and momentum. ● Momentum conservation as a universal law

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. Describe the force within a system and the potential energy of a system. 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. Calculate the potential energy of a system consisting of an object in a uniform gravitational field. Derive an expression for the gravitational potential energy of a system consisting of a satellite or large mass (e.g., an asteroid) and the Earth at a great distance from the Earth. Describe physical situations in which mechanical energy of an object in a system is converted to other forms of energy in the system. b. Describe physical situations in which the total mechanical energy of an object in a system changes or remains constant. Describe kinetic energy, potential energy, and total energy in relation to time (or position) for a "conservative" mechanical system. 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 non-constant one dimensional force. Derive expressions such as positions, heights, angles, and speeds for an object in vertical circular motion or a pendulum motion in an arc. 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. Calculate the center of mass of a system of point masses or a system of regular symmetrical objects. Calculate the center of mass of a thin rod of nonuniform density using integration. Describe the motion of the center of the mass of a system for various situations. 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. Calculate the total momentum of an object or a system of objects. Calculate relationships between mass, velocity, and linear momentum of a moving object. 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. Describe relationships between a system of objects’ individual momenta and the velocity of the center of mass of the system of objects.	

Calculate the momentum change in a collision using a force versus time graph for a collision. Calculate the change in momentum of an object given a nonlinear function, F(t), for a net force acting on the object. 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. Calculate the changes of momentum and kinetic energy as a result of a collision between two objects. Describe the quantities that are conserved in a collision. Calculate the speed of the center of mass of a system. Calculate the changes in speeds, changes in velocities, changes in kinetic energy, or changes in momenta of objects in all types of collisions (elastic or inelastic) in one dimension, given the initial conditions of the objects. Derive expressions for the conservation of momentum for a particular collision in one dimension. 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.	

Unit 4
Rotation

NJSLS Standards: N/A	
Big Ideas: • **BIG IDEA 1: CHANGE** Interactions produce changes in motion. • **BIG IDEA 2: FORCE INTERACTIONS** Forces characterize interactions between objects or systems • **BIG IDEA 4: CONSERVATION** Conservation laws constrain interactions	
Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
Why must CD/DVD players adjust their speed depending on what track is being used at the time? How could you design a bowling ball return that stops the ball's rotation? How does a rotating merry-go-round speed up when the riders move toward the center? In what sense do different parts of a bicycle wheel move at different speeds? How can a gymnast, figure skater, or acrobat change their rotational speed without touching the ground? When dying stars become pulsars, how do they obtain such great rotational speeds? Why does a curveball take less time to reach the plate than a fastball? Why is it easier to balance a bicycle when it's in motion? Why does pumping your legs increase your swing on a swing set without being pushed?	When a physical system involves an extended rigid body, there are two conditions of equilibrium—a translational condition and a rotational condition. There are relationships among the physical properties of angular velocity, angular position, and angular acceleration. A net torque acting on a rigid extended body will produce rotational motion about a fixed axis. 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. --- *From the AP Physics C Essential Knowledge: Students will understand…*

	Torque is a vector product and it has a direction that can be determined by 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. Both conditions of equilibrium must be satisfied for an extended rigid body to be in equilibrium. Moment of inertia is defined with a formula, either a system of particles or, using calculus, for an extended object. 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. There are angular kinematic relationships for objects experiencing a uniform angular acceleration. Other relationships can be derived from the above two relationships. a. The appropriate unit for angular position is radians. For objects that are rolling without slipping on a surface, the angular motion is related to the linear translational motion 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. 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.

	If a rigid body is defined as "rolling," this implies (in the ideal case) that the frictional force does no net 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. The angular momentum of a linearly translating particle can be defined about some arbitrary point of reference or origin. In the absence of external torques acting on a rotating body or system, the total angular momentum of the system is constant. 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. a. 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. b. 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.
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From the NJSLS *DCI's:* **PS3.B: Conservation of Energy and Energy Transfer** • Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. (HS-PS3-1) • Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4) • Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g. relative positions of charged particles,	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests ● Measurement techniques and error analysis ● Calculus applications ● Preparation for AP exam

compression of a spring) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. (HS-PS3-1)

- The availability of energy limits what can occur in any system. (HS-PS3-1)
- Uncontrolled systems always evolve toward more stable states—that is, toward more uniform energy distribution (e.g., water flows downhill, objects hotter than their surrounding environment cool down). (HS-PS3-4)

PS3.D: Energy in Chemical Processes

- Although energy cannot be destroyed, it can be converted to less useful forms—for example, to thermal energy in the surrounding environment. (HS-PS3-3),(HS-PS3-4)

From AP Physics C Objectives
Students can...

Relate the radius of the circle and the speed or rate of revolution of the particle to the magnitude of the centripetal acceleration; describe the direction of the particle's velocity and acceleration at any instant during the motion; determine the components of the velocity and acceleration vectors at any instant, and sketch or identify graphs of these quantities; analyze motion in a horizontal circle; analyze motion in a vertical circle

Calculate the magnitude and direction of the torque associated with a given force; calculate the torque on a rigid object due to gravity

State the conditions for translational and rotational equilibrium and apply these conditions in analyzing the equilibrium of a rigid object under the combined influence of a number of coplanar forces applied at different locations

Sample Assessments:

- Daily assignments and homework quizzes
- Collaborative projects
- Multiple choice: items from textbook test banks and released AP exams
- Free response problems from released AP exams
- Unit Exam
- Lab: the Rolling Projectile (measuring rotational energy)
- Lab: Moment of inertia of Rod and Point masses (Vernier rotation sensor)
- Lab: Rotational Collision (Vernier rotation sensor)
- Lab: (Statics) Weight on meter-stick supported by two force sensors

Instructional Strategies:

Interdisciplinary Connections

- Biology: Discuss rotational motion and schemes of artificial gravity in space travel.

Technology Integration

- Computer and probeware collection of data in rotational laboratory experiments
- Use of computer spreadsheet software programs (Excel, Graphical Analysis, etc) to analyze data graphically

Media Literacy Integration

- Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals.
- Scientifically literate students should be able to identify the critical difference between the two types of media.

Global Perspectives

- Rotating space stations with simulated gravity as unified international effort
- Dynamics of the rotation and revolution of Earth in space

Determine by inspection which of a set of symmetrical objects of equal mass has the greatest rotational inertia; determine by what factor an object's rotational inertia changes if all its dimensions are increased by the same factor Find the rotational inertia of a collection of point masses lying in a plane perpendicular to the plane, a thin rod of uniform density, about an arbitrary axis perpendicular to it, and a thin cylindrical shell about its axis or an object that might be viewed as being made up of coaxial shells 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. Apply the parallel axis theorem Write and apply relations among the angular acceleration, angular velocity, and angular displacement of an object that rotates about a fixed axis with constant angular acceleration Use the right hand rule for angular velocities 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. Write down, justify, and apply the relation between linear and angular velocity and acceleration for an objecting rolling without slipping; apply the	

equations of translational and rotational motion simultaneously; calculate the total kinetic energy of an object that is undergoing both translational and rotational motion and apply energy conservation Calculate the torque of a specified force about an arbitrary origin; calculate the angular momentum vector for a moving particle; calculate the angular momentum vector for a rotating rigid object in simple cases where this vector lies parallel to the angular velocity vector Describe the complete analogy between fixed axis rotation and linear translation for an object subject to a net torque. 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 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. 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). Calculate the angular momentum vector of a linearly translating particle about a defined stationary point of reference. 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). 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.	

Unit 5
Oscillations and Gravitation

NJSLS Standards:

HS-PS2-4 Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

HS-ESS1-4 Use mathematical or computational representations to predict the motion of orbiting objects in the solar system

Big Ideas:

- **BIG IDEA 2: FORCE INTERACTIONS**
  Forces characterize interactions between objects or systems.
- **BIG IDEA 3: FIELDS**
  Fields predict and describe interactions.
- **BIG IDEA 4: CONSERVATION**
  Conservation laws constrain interactions

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
If the pendulum in a mechanical clock reduces the amplitudes of its oscillations, how does it continue to keep good time? What causes horizontal ridges along dirt roads? If the gravitational attraction on the moon is stronger than the Sun than the Earth, why does the Moon orbit the Earth? How did the Tacoma Narrows bridge collapse? How is a falling apple like the Moon? Why do space shuttle astronauts feel "weightless"? What factors determine whether dying stars become white dwarfs, neutron stars, or black holes?	There are certain types of forces that cause objects to repeat their motions with a regular pattern. Objects of large mass will cause gravitational fields that create an interaction at a distance with other objects with mass. Angular momentum and total mechanical energy will not change for a satellite in an orbit. --- *From the AP Physics C Essential Knowledge: Students will understand…* The general relationship for SHM.

How does the presence of restoring forces predict and lead to harmonic motion? How does the moon stay in orbit despite its great distance from the Earth? Why is navigation technology dependent on the orbits of Earth's artificial satellites?	The period of SHM is related to the angular frequency 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. Using Newton's second law, the following characteristic differential equation of SHM can be derived The physical characteristics of the spring mass system (or pendulum) can be determined from the differential relationship. All of the characteristics of motion in SHM can be determined by using the general relationship The period can be derived from the characteristic differential equation. The following types of SHM systems can be explored: a. Mass oscillating on spring in vertical orientation b. Mass oscillating on spring in horizontal orientation c. Mass-spring system with springs in series or parallel d. Simple pendulum e. Physical pendulum f. Torsional pendulum 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. These energy relationships are true in the following three types of SHM systems: i. Mass-spring in horizontal orientation ii. Mass-spring in vertical orientation iii. Simple pendulum Total energy of a spring-mass system is proportional to the square of the amplitude.

	The total mechanical energy of a system in SHM is conserved. Any physical system that creates a linear restoring force will exhibit the characteristics of SHM. The period of a system oscillating in SHM can be derived. The magnitude of the gravitational force between two masses can be determined by using Newton's universal law of gravitation. Using Newton's laws it can be shown that the value for gravitational acceleration at the surface of the Earth The gravitational force is proportional to the inverse of distance squared; therefore, the acceleration of an object under the influence of this type of force will be nonuniform. The centripetal force acting on a satellite is provided by the gravitational force between satellite and planet. In a circular orbit, Newton's second law analysis can be applied to the satellite to determine the orbital velocity relationship for a satellite of mass m about a central body of mass M. Verifying Kepler's third law with actual data provides experimental verification of the law. 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. 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 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. 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. In ideal non orbiting cases, a satellite's physical characteristics of motion can be determined using the conservation of energy. The derivation of Kepler's third law is only required for a satellite in a circular orbit. 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.
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From the NJSLS DCI's: **PS2.B: Types of Interactions** • Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. (HS-PS2-4) • Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields. (HS-PS2-4),(HS-PS2-5) **ESS1.B: Earth and the Solar System**	**Instructional Focus:** • Mathematical derivation of key formulas and concepts • Problem solving techniques and strategies • Hands-on exploration of unit topics • Comparison of theoretical simplifications to real-world complexities • Real-world applications and connections to individual student interests • Measurement techniques and error analysis • Calculus applications • Preparation for AP exam **Sample Assessments:** • Daily assignments and homework quizzes • Collaborative projects • Multiple choice: items from textbook test banks and released AP exams

• Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. (HS-ESS1-4) *From AP Physics C Learning Objectives* Students can… 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. 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. Describe each of the three kinematic characteristics of a spring-mass system in SHM in relation to time (displacement, velocity, and acceleration) Derive a differential equation to describe Newton's second law for a spring-mass system in SHM or for the simple pendulum. 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. Derive the expression for the period of oscillation for various physical systems oscillating in SHM. Calculate the mechanical energy of an oscillating system. Show that this energy is conserved in an ideal SHM spring-mass system. Describe the effects of changing the amplitude of a spring-mass system.	• Free response problems from released AP exams • Unit Exam • Lab: Galileo's Pendulum • Lab: Physical Pendulums • Lab: Mass on a spring • Lab: Using astronomical data of Mercury's orbit to show Kepler's 3 laws **Instructional Strategies:** **Interdisciplinary Connections** • History: Galileo's use of a pendulum to measure time enabled much more accurate naval navigation and exploration. • Historical background of Kepler's life and works and relationship with Tycho Brahe **Technology Integration** • Computer/probeware of data collection in pendulum and spring experiments • Use of computer spreadsheet software programs (Excel, Graphical Analysis, etc) to analyze data graphically • Use of real current Mercury orbit data from NASA online • Computer simulations of orbits **Media Literacy Integration** • Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. • Scientifically literate students should be able to identify the critical difference between the two types of media. **Global Perspectives** • Space exploration as an international cooperative effort • The laws of mechanics—equivalent throughout the universe—transcend geographical and cultural borders

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. Explain how the model of SHM can be used to determine characteristics of motion for other physical systems that can exhibit this behavior. Describe a linear relationship between the period of a system oscillating in SHM and physical constants of the system. Calculate the magnitude of the gravitational force between two large spherically symmetrical masses. 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. 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. Calculate quantitative properties (such as period, speed, radius of orbit) of a satellite in circular orbit around a planetary object. Derive Kepler's third law for the case of circular orbits. Describe a linear relationship to verify Kepler's third law. 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. Derive the relationship of total mechanical energy of a satellite/earth system as a function of radial position.	

Derive an expression for escape speed of a satellite. Use energy principles to describe the motion of a satellite launched straight up. 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. Describe elliptical satellite orbits using Kepler's three laws of planetary motion. Calculate the orbital distances and velocities of a satellite in elliptical orbit using the conservation of angular momentum. b. Calculate the speeds of a satellite in elliptical orbit at the two extremes of the elliptical orbit (perihelion and aphelion).	

Part 2: Electricity and Magnetism

Unit 6
Electrostatics

NJSLS Standards:

HS-PS2-4 Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.

Big Ideas:

BIG IDEA 2: FORCE INTERACTIONS
Forces characterize interactions between objects or systems.
BIG IDEA 3: FIELDS
Fields predict and describe interactions.
BIG IDEA 4: CONSERVATION
Conservation laws constrain interactions.

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
What electrical properties of water make it a good solvent? How can modern electronics in an operating room cause bacterial contamination? How do lightning rods work? How are thunderclouds similar to rubbing your socks on your carpet and receiving a shock? In what real-world situations are electric shocks dangerous? What caused some burn-victim hospital unit gurneys to catch fire? Why does your hair stand up after brushing it with a plastic comb? How does a charged rubber rod bend a stream of water?	Objects with an electric charge will interact with each other by exerting forces on each other. Objects with an electric charge will create an electric field. 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. There are laws that use symmetry and calculus to derive mathematical relationships that can be applied to physical systems containing electrostatic charge. There are laws that use calculus and symmetry to derive mathematical relationships that can be applied to electrostatic-charge distributions.

How is the kinematics of charged particles used in old televisions? Why is it sometimes necessary to shield against electric fields? How are maps of voltage and topographical maps related? Why can a bird land on a high voltage wire and not be electrocuted?	*From the AP Physics C Essential Knowledge: Students will understand…* Particles and objects may contain electrostatic charges. The Law of Electrostatics states that like charges repel and unlike charges attract through electrostatic interactions. 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. a. 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. 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 Net force can be determined by superposition of all forces acting on a point charge due to the vector sum of other point charges. 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. The definition of electric field. A test charge is a small positively charged object of negligible size. The direction of an electric field is the direction in which a test charge would move if placed in the field. The electric field of a single point charge can be determined by using the definition of the electric field and Coulomb's Law.

	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. 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. Using the properties of electric field diagrams, a general field line diagram can be drawn for static-charged situations. A charged particle in a uniform electric field will be subjected to a constant electrostatic force. The trajectory of a charged particle can be determined when placed in a known uniform electric field. a. The initial conditions of motion are necessary for a complete description b. The force acting on the particle will be a constant force. The definition of electric potential at a particular location due to a single point charge The potential due to multiple point charges can be determined by the principle of superposition in scalar terms of the charges The definition for stored electrostatic potential energy in an electrostatic system of a point charge and a known electric field The electrostatic potential energy of two point charges near each other 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. The work done in moving a test charge between two points in a uniform electric field can be calculated. a. Use the definition of electric potential difference and the definition of a conservative field

	to determine the difference in electric potential in this case. 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. 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 general definition of potential difference that can be used in most cases The general definition of electric flux 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. 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. 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. 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. If this is applied appropriately and evaluated over the appropriate limits, the electric fields of the stated charge distributions can be determined as a function of position. The following charge distributions can be explored

	using this method: a. An infinitely long, uniformly charged wire or cylinder determines a field at distances along perpendicular bisector b. A thin ring of charge (along the axis of the ring) c. A semicircular or part of a semicircular arc d. A field due to a finite wire or line charge at a distance that is collinear with the line charge. 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: a. Electric fields with planar symmetry, infinite sheets of charge, combinations of infinite sheets of charge, or oppositely charged plates b. Linearly charged wires or charge distributions c. Spherically symmetric charge distributions Other distributions of charge that can be deduced using Gauss's Law or the principle of superposition. The integral definition of the electric potential due to continuous charge distributions is defined as: 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. A uniformly charged wire b. A thin ring of charge (along the axis of the ring) c. A semicircular arc or part of a semicircular arc d. A uniformly charged disk
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From the NJSLS DCI's: **PS2.B: Types of Interactions** • Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. (HS-PS2-4)	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests

• Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields. (HS-PS2-4),(HS-PS2-5) **PS3.B: Conservation of Energy and Energy Transfer** • Conservation of energy means that the total change of energy in any system is always equal to the total energy transferred into or out of the system. (HS-PS3-1) • Energy cannot be created or destroyed, but it can be transported from one place to another and transferred between systems. (HS-PS3-1),(HS-PS3-4) • Mathematical expressions, which quantify how the stored energy in a system depends on its configuration (e.g. relative positions of charged particles, compression of a spring) and how kinetic energy depends on mass and speed, allow the concept of conservation of energy to be used to predict and describe system behavior. (HS-PS3-1) • The availability of energy limits what can occur in any system. (HS-PS3-1) • Uncontrolled systems always evolve toward more stable states—that is, toward more uniform energy distribution (e.g., water flows downhill, objects hotter than their surrounding environment cool down). (HS-PS3-4) **PS3.C: Relationship Between Energy and Forces** • When two objects interacting through a field change relative position, the energy stored in the field is changed. (HS-PS3-5) *From AP Physics C Learning Objectives* Students can…	• Measurement techniques and error analysis • Calculus applications • Preparation for AP exam **Sample Assessments:** • Daily assignments and homework quizzes • Collaborative projects • Multiple choice: items from textbook test banks and released AP exams • Free response problems from released AP exams • Unit Exam • Lab: Static Electricity Stations lab • Lab: Electroscopes • Lab: Electric Field Mapping (Pasco, metal ink) • Virtual Lab: Electric fields around charges • Virtual Lab: Electric field hockey • Lab: Electrophorus • Lab: Van de Graaff conductor demonstrations **Instructional Strategies:** **Interdisciplinary Connections** • Social studies: historical and cultural context of Franklin, Coulomb, Volta, Ampere • Engineering: operation of grounds, lightning rods, etc. • Meteorology: electrodynamics of thunderstorms • Health: physiological effects of electrical charge • Math: Calculus integration methods for solving capacitance and potential of common capacitor geometries • Math: application of Gauss's law to justify physics of conducting bodies **Technology Integration** • Computer/probeware of data collection in electric charge experiments • Use of computer spreadsheet software programs (Excel, Graphical Analysis, etc) to analyze data graphically • Internet-based research of electric charge in thunderstorms and lightning •

Describe behavior of charges or system of charged objects interacting with each other. Explain and/or describe the behavior of a neutral object in the presence of a charged object or a system of charges. 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. Determine the motion of a charged object of specified charge and mass under the influence of an electrostatic force. 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. Describe and calculate the electric field due to a single point charge. Describe and calculate the electric field due to a dipole or a configuration of two or more static-point charges. Explain or interpret an electric field diagram of a system of charges. Sketch an electric-field diagram of a single point charge, a dipole, or a collection of static-point charges. Determine the qualitative nature of the motion of a charged particle of specified charge and mass placed in a uniform electric field. Sketch the trajectory of a known charged particle placed in a known uniform electric field.	**Media Literacy Integration** ● Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. ● Scientifically literate students should be able to identify the critical difference between the two types of media. **Global Perspectives** ● Association of lightning and associated electrical phenomena with intercontinental weather systems ● International historical context of 18^{th} and 19^{th} century electricians ● Ancient understanding of electrical forces, from which the word “electron” is derived ● Importance of electronics to modern global economy

Calculate the value of the electric potential in the vicinity of one or more point charges. 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. 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. Calculate the potential difference between two points in a uniform electric field and determine which point is at the higher potential. 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. 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. 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. 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). 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 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. State and use Gauss's Law in integral form to derive unknown electric fields for planar, spherical, or cylindrically symmetrical charge distributions. 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 a surface in terms of the electric field near the surface. 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. Describe the general features of an unknown charge distribution, given other features of the system. Derive expressions for the electric field of specified charge distributions using integration and the principle of superposition. Examples of such charge distributions include a uniformly charged wire, a thin ring of charge (along the axis of the ring), and a semicircular or part of a semicircular arc	

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. 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.	

Unit 7
Conductors, Capacitors, Dielectrics & Electrical Circuits

NJSLS Standards:

HS-ESS3-4 Evaluate or refine a technological solution that reduces impacts of human activities on climate change and other natural systems.

Big Ideas:

BIG IDEA 2: FORCE INTERACTIONS
Forces characterize interactions between objects or systems.
BIG IDEA 3: FIELDS
Fields predict and describe interactions.
BIG IDEA 4: CONSERVATION
Conservation laws constrain interactions.

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
Why does a flashlight dim over time? Where should you go when caught outdoors during a thunderstorm? If individual electrons drift through a conducting wire very slowly, why do light bulbs come on immediately when the switch is thrown? How do you jumpstart a car battery? How do computers work? What are solar cells, and how can they be used to reduce climate change? How do car airbags know when to inflate? How does a camera flash work? How does a defibrillator work? Why is the electric potential in the conductor connecting two resistors in series constant? Why is the electric field everywhere perpendicular to surfaces of constant electric potential?	Excess charge on an insulated conductor will spread out on the entire conductor until there is no more movement of the charge. 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. There are electrical devices that store and transfer electrostatic potential energy. An insulator has different properties (than a conductor) when placed in an electric field. The rate of charge flow through a conductor depends on the physical characteristics of the conductor. There are electrical devices that convert electrical potential energy into other forms of energy. Total energy and charge are conserved in a circuit containing resistors and a source of energy.

Why does water in a microwave oven become warm while aluminum foil sparks? Why are capacitors used as circuit elements shaped like cylinders? How does the wiring design for a house allow for electricity to still be on in some rooms when others have none due to a circuit breaker being flipped? Why do warming light bulbs take several minutes to shine bright? Why doesn't the electric company charge for electrons used? How does touching a conductor to a capacitor before removing it from a circuit protect you?	Total energy and charge are conserved in a circuit that includes resistors, capacitors, and a source of energy. --- *From AP Essential Knowledge:* 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. 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. 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. 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. Electrostatic shielding is the process of surrounding an area by a completely closed conductor to create a region free of an electric field. 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. 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. The general definition of capacitance The energy stored in a capacitor The conservation of charge and energy can be applied to a closed physical system containing charge, capacitors, and a source of potential difference. 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 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: a. The electric field is constant in magnitude and is independent of the geometry of the capacitor. b. The electric field is proportional to the surface-charge density of the charge on one plate. 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. 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. 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. The properties of capacitance still hold for all types of capacitors (spherical or cylindrical). 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. 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 plates and therefore a reduction in the potential difference between the plates. The capacitance of a parallel-plate capacitor with a dielectric material inserted between the plates can be calculated. The initial condition of the capacitor system can determine which relationship to use when attempting to calculate unknown quantities in a capacitor system. The definition of current.

	Conventional current is defined as the direction of positive charge flow. Ohm's Law formula. The definition of resistance in terms of the properties of the conductor The relationship that defines current density (current per cross-sectional area) in a conductor The definition of resistance can be derived using the microscopic definition of current and the relationship between electric field and current density The definition of power or the rate of heat loss through a resistor The total amount of heat energy transferred from electrical potential energy to heat can be determined using the definition of power. Series arrangement of resistors is defined as resistors arranged one after the other, creating one possible branch for charge flow. Parallel arrangement of resistors is defined as resistors attached to the same two points (electrically), creating multiple pathways for charge flow. The rule for equivalent resistance for resistors arranged in series; The rule for equivalent resistance for resistors arranged in parallel 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. Conventional circuit symbols and circuit diagramming techniques should be used in order to properly represent appropriate circuit characteristics.

	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. 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. An ideal ammeter has a resistance that is close to zero (negligible), and an ideal voltmeter has a resistance that is very large (infinite) The equivalent capacitance of capacitors arranged in series; The equivalent capacitance of capacitors arranged in parallel 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. Under transient conditions for $t = 0$ to $t = \infty$ for steady-state conditions, the time constant in an RC circuit is equal to the product of equivalent resistance and the equivalent capacitance. 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. The time constant ($\tau = RC$) is a significant feature on the sketches for transient behavior in an RC circuit. The electrical potential energy stored in a capacitor 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.

Areas of Focus: Proficiencies (Cumulative Progress Indicators)	Examples, Outcomes, Assessments
From the *NJSLS* DCI's: **PS3.A: Definitions of Energy** • "Electrical energy" may mean energy stored in a battery or energy transmitted by electric currents. *(secondary to HS-PS2-5)* **ESS3.C: Human Impacts on Earth Systems** • Scientists and engineers can make major contributions by developing technologies that produce less pollution and waste and that preclude ecosystem degradation. *From AP Physics C Learning Objectives* Students can… 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). 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. 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. Explain how a charged object can attract a neutral conductor. Describe the concept of electrostatic shielding. For charged conducting spheres or spherical shells, describe the electric field with respect to position. b.	**Instructional Focus:** • Mathematical derivation of key formulas and concepts • Problem solving techniques and strategies • Hands-on exploration of unit topics • Comparison of theoretical simplifications to real-world complexities • Real-world applications and connections to individual student interests • Measurement techniques and error analysis • Calculus applications • Preparation for AP exam **Sample Assessments:** • Daily assignments and homework quizzes • Collaborative projects • Multiple choice: items from textbook test banks and released AP exams • Free response problems from released AP exams • Unit Exam • Lab: Resistors in series and parallel • Lab: Voltage Divider • Lab: Capacitor in series and parallel lab • Lab: Ohm's Law with high power resistor; Non Ohm's Law with light bulb • Lab: Internal resistance of a battery • Lab: RC Circuit **Instructional Strategies:** **Interdisciplinary Connections** • Fluids: extended analogy of current flowing through wires and water flowing through pipes • Social studies: historical context of pioneers of electrical circuits, such as Kirchoff, Ohm, etc. • Health: safety with electrical circuits and currents • Math: methods of solving systems of linear equations **Technology Integration**

For charged conducting spheres or spherical shells, describe the electric potential with respect to position. Calculate the electric potential on the surfaces of two charged conducting spheres when connected by a conducting wire. Apply the general definition of capacitance to a capacitor attached to a charging source. b. Calculate unknown quantities such as charge, potential difference, or capacitance for a physical system with a charged capacitor. 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. Explain how a charged capacitor, which has stored energy, may transfer that energy into other forms of energy. 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. Apply the relationship between the electric field between the capacitor plates and the surface-charge density on the plates. Derive expressions for the energy stored in a parallel plate capacitor or the energy per volume of the capacitor.	● Computer/probeware data collection and analysis for simple and complex circuit labs, including RC circuits ● Computer web-based simulations of simple circuits ● Realization that complex electrical circuits are merely combinations of simple elements studies in class ● Computer simulations of different geometries of capacitors **Media Literacy Integration** ● Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. ● Scientifically literate students should be able to identify the critical difference between the two types of media. **Global Perspectives** ● The internet, made possible through principles of electrical circuits, as a unifying international system ● Importance of electronics for the modern global economy ● The importance of solar cell technology for tackling climate change ● Cultural and historical context of 18th century discoveries related to capacitors

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. Derive expressions for a cylindrical capacitor or a spherical capacitor in terms of the geometry of the capacitor and fundamental constants. 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. Describe and/or explain the physical properties of an insulating material when the insulator is placed in an external electric field. 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. Use the definition of the capacitor to describe changes in the capacitance value when a dielectric is inserted between the plates. Calculate changes in energy, charge, or potential difference when a dielectric is inserted into an isolated charge capacitor. Calculate unknown quantities relating to the definition of current. Describe the relationship between current voltage and resistance in Ohm's Law. Apply Ohm's Law in an operating circuit Explain how the properties of a conductor affect resistance. Compare resistances of different	

geometries or materials Calculate the resistance of a conductor of known resistivity and geometry Describe the relationship between the electric field strength through a conductor and the current density within the conductor. Using the microscopic definition of current in a conductor, describe the properties of the conductor and the idea of “drift velocity.” Derive the expression for resistance of a conductor of uniform cross-sectional area in terms of its dimensions and resistivity. Derive expressions that relate current, voltage, and resistance to the rate at which heat is produced in a resistor. Calculate the amount of heat produced in a resistor given a known time interval and the circuit characteristics. Identify parallel or series arrangement in a circuit containing multiple resistors. Describe series and parallel arrangements of circuits Calculate equivalent resistances for a network of resistors that can be considered a combination of series and parallel arrangements. Calculate quantities for any single source circuit, b. Calculate relationships between the potential difference, current, resistance, and power dissipation for any part of a circuit, given some of the characteristics of the circuit (i.e., battery voltage or current in the battery, or a resistor or branch of resistors). Describe a circuit diagram that will properly produce a given current and a given potential difference across a specified component in the circuit.	

Calculate the terminal voltage and the internal resistance of a battery of specified EMF and known current through the battery Calculate a single unknown current, potential difference, or resistance in a multi-loop circuit using Kirchhoff's Rules. 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. Calculate the equivalent capacitance for series and parallel arrangements 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. Calculate the potential difference across a capacitor in a circuit arrangement containing capacitors, resistors, and an energy source under steady-state conditions. In transient circuit conditions (i.e., RC circuits), calculate the time constant of a circuit containing resistors and capacitors arranged in series. Derive expressions using calculus to describe the time dependence of the stored charge or potential difference across the capacitor, or the current or potential difference across the resistor in an RC circuit when charging or discharging a capacitor. 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. Calculate expressions that determine electrical potential energy stored in a capacitor as a function of time in a transient RC circuit.	

Describe the energy transfer in charging or discharging a capacitor in an RC circuit.	

Unit 8
Magnetic Fields and Electromagnetism

NJSLS Standards:

HS-PS2-5 Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current.

HS-PS3-5 Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

Big Ideas:

BIG IDEA 1: CHANGE
Interactions produce changes in motion.
BIG IDEA 2: FORCE INTERACTIONS
Forces characterize interactions between objects or systems.
BIG IDEA 3: FIELDS
Fields predict and describe interactions.
BIG IDEA 4: CONSERVATION
Conservation laws constrain interactions.

Essential Questions *What provocative questions will foster inquiry, understanding, and transfer of learning?*	**Enduring Understandings** *What will students understand about the big ideas?*
How can magnetic fields create a high-energy beam of neutrons for use in cancer patients? What causes the aurora borealis? Why do the auroras take place primarily or exclusively near Earth's poles? Where does Earth's magnetic field come from, and why is it essential to life? Why are only some metals magnetic? How does a tube television work? How do MRIs work? How do brain scientists measure brain activity?	Charged particles moving through a magnetic field may change the direction of their motion. A magnetic field can interact with a straight conducting wire with current. Current-carrying conductors create magnetic fields that allow them to interact at a distance with other magnetic fields. There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing moving charge. There are laws that use symmetry and calculus to derive mathematical relationships that are applied to physical systems containing a magnetic field. A changing magnetic field over time can induce current in conductors.

Why must a magnetic credit card be moved through a reader rather than sitting still? How could an MRI burn a patient? How do motors, generators, and transformers work? Why do we largely depend on alternating current power? Why are large-scale, charged-particle accelerators in the shape of a circle? How does a guitar pick up work? Why does a current deflect the needle of a compass? Why does the deflection of a pair of parallel conducting wires depend on the directions of current in the wires? How does an electric motor work? How does pushing the button at the door produce a sound inside the house? How does an antenna work? How does the digital recording in your MP3 player generate sound waves in your headphones? How does Wi-Fi work?	Induced forces (arising from magnetic interactions) that are exerted on objects can change the kinetic energy of an object. In a closed circuit containing inductors and resistors, energy and charge are conserved. Electric and magnetic fields that change over time can mutually induce other electric and magnetic fields. --- *From the AP Essential Knowledge:* The magnetic force of interaction between a moving charged particle and a uniform magnetic field is defined by Lorentz's law. 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. 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). 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 magnetic force is defined as a 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. 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.

The definition of the magnetic force acting on a straight-line segment of a current-carrying conductor in a uniform magnetic field is: a. The direction of the force can be determined by the cross-product or by the appropriate right-hand rule.

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.

The definition of torque can be applied to the loop to determine a relationship between the torque, field, current, and area of the loop.

It can be shown or experimentally verified that the magnetic field of a long, straight, current carrying conductor is an inverse law with distance.

The principle of superposition can be used to determine the net magnetic field at a point due to multiple long, straight, current-carrying wires.

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. a. The direction of the force can be determined from the cross-product definition or from the appropriate right-hand rule.

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 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. 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. Ampère’s Law can be used to determine magnetic-field relationships at different locations in cylindrical current-carrying conductors. The principle of superposition can be used to determine the net magnetic field at a point in space due to various combinations of current carrying conductors, loops, segments, or cylindrical conductors. Ampère’s Law can be used to determine individual field magnitudes. The principle of superposition can be used to add those individual fields. Magnetic flux is the scalar product of the magnetic-field vector and the area vector over the entire area contained by the loop. Induced currents arise in a conductive loop (or long wire) when there is a change in magnetic flux occurring through the loop. 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. 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. Newton's second law can be applied to a moving conductor as it experiences a flux change. 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. The very nature of the inductor is to oppose the change in the current. 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. 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. 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. 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
Areas of Focus: Proficiencies (Cumulative Progress Indicators)	**Examples, Outcomes, Assessments**
From the NGSS DCI's: **PS2.B: Types of Interactions** • Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects. (HS-PS2-4)	**Instructional Focus:** ● Mathematical derivation of key formulas and concepts ● Problem solving techniques and strategies ● Hands-on exploration of unit topics ● Comparison of theoretical simplifications to real-world complexities ● Real-world applications and connections to individual student interests ● Measurement techniques and error analysis

• Forces at a distance are explained by fields (gravitational, electric, and magnetic) permeating space that can transfer energy through space. Magnets or electric currents cause magnetic fields; electric charges or changing magnetic fields cause electric fields. (HS-PS2-4),(HS-PS2-5) ——————————————— *From AP Physics C Learning Objectives* Students can… Calculate the magnitude of the Lorentz force 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 to experience no interaction Describe the path of different moving charged particles (i.e., of different type of charge or mass) in a uniform magnetic field. Derive an expression for the radius of a circular path for a charged particle of specified characteristics moving in a specified magnetic field. Explain why the magnetic force acting on a moving charge particle does not work on the moving charged particle. Describe the conditions under which a moving charged particle can move through a region of crossed electric and magnetic fields with a constant velocity. Calculate the magnitude of the magnetic force acting on a straight-line segment of a conductor with current in a uniform magnetic field. Describe or indicate the direction of magnetic forces acting on a complete conductive loop with current in a region of uniform magnetic field.	• Calculus applications • Preparation for AP exam **Sample Assessments:** • Daily assignments and homework quizzes • Collaborative projects • Multiple choice: items from textbook test banks and released AP exams • Free response problems from released AP exams • Unit exam • Lab: Tangent Galvanometer • Lab: Electromagnets (nails, wire, iron filings) • Lab: Building DC motors • Lab: Measuring transformers • Lab: Magnetic field of a slinky • Lab: RL circuits **Instructional Strategies:** **Interdisciplinary Connections** • Math: Calculus integration techniques to describe magnetic field geometries • Social studies: worldwide discoveries associated with magnetism • Math: mathematical comparison of derivative and integral forms of Maxwell's equations • Social studies: historical context of electromagnetic inventions associated with Edison, Westinghouse, and Tesla • Social studies: historical context of theoretical contributions of Faraday and Maxwell • Social studies: geopolitical ramifications of energy production associated with electromagnetic devices **Technology Integration** • Computer/probeware data collection and analysis of magnetic field experiments • Computer simulations of Earth's magnetic field and magnetic fields around electrical currents • Computer simulations of motors, generators, and transformers

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. 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 the magnetic field of a straight wire to deduce the direction of a magnetic field near a long, straight, current carrying wire. 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 a long straight wire. Calculate an unknown current value or position value, given a specified magnetic field at a point due to multiple long, straight, current-carrying wires. Calculate the force of attraction/repulsion between two parallel wires Describe the consequence when the two wires have known current directions. Describe and calculate the Biot-Savart Law Derive the expression for the magnitude of the magnetic field on the axis of a circular loop of current or a segment of a circular loop. t b. Explain how the Biot–Savart Law can be used to determine the field of a long, straight, current-carrying wire at perpendicular distances close to the wire. Explain and apply Ampere's Law. 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. Calculate magnetic flux through a loop and due to a long straight wire.	● Computer and probeware based data collection in electromagnetic experiments **Media Literacy Integration** ● Articles published in magazines are significantly different from articles published in peer reviewed scholarly journals. ● Scientifically literate students should be able to identify the critical difference between the two types of media. **Global Perspectives** ● Importance of the magnetic field of Earth for all life on Earth ● Multicultural context of magnetic field discoveries: China, Greece, etc. ● Energy production via electromagnetic devices and related cultural context

Calculate the magnetic flux due to a non-uniform magnetic field. 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. 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 a 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. Determine if a net force or net torque exists on a conductive loop. 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 the expression for the magnetic field of a long solenoid.	

Calculate the EMF in an inductor with a changing current. Calculate the rate of change of current in a transient inductor. Calculate the stored electrical energy in an inductor that has a steady state current. Calculate currents in an RL circuit Calculate the max current in a circuit that contains only a capacitor and inductor. Derive a diff eq for an LR circuit; Derive the solution to the LR diff eq. 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. 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.	

Post AP Exam Ideas

After AP exams are over, students generally have about four remaining weeks of school before graduation. This time provides an opportunity to explore topics neglected during the school year because of the pressures of a large curriculum. Here are a few ideas for class time beyond the exams:

1. Unit on a special topic, such as:
    a. Special theory of relativity
    b. Quantum mechanics
    c. Thermodynamics
    d. Fluid Mechanics

2. STEM Book reports: students read a STEM themed book and present an oral report (15 minutes) to the class. Classmates are encouraged to ask the presenter questions.

3. Climate Change study: students could use concepts learned throughout high school science courses to make recommendations for how the school could reduce its carbon footprint. Students can educate the school community on these concepts.

4. Hands-on Arduino Design Projects: students use Arduino to construct a Design Project in partners or teams. Motors, sensors, lights, and other input/outputs can be integrated into the system to apply physics to the real world.

Texts and Resources

Adopted Course textbook:

Young and Freedman. University Physics, 14th Edition. Pearson Education, 2015.

Supplemental resources:

Serway and Beichner. PHYSICS For Scientists and Engineers, Fifth Edition. Thomson Learning, 2000.

Tipler and Mosca. Physics for Scientists and Engineers, Fifth Edition. W.H. Freeman and Co, 2004.

Halliday, Resnick, and Walker. Fundamentals of Physics, 7th Edition. John Wiley & Sons, 2005.

Serway and Faughn. College Physics, 7th Edition. Brooks Cole, 2005.

Halliday, Resnick and Krane. Physics, Fifth Edition. John Wiley & Sons, 2002.

Chabay and Sherwood. Matter & Interactions 1 and 2, Second Edition. John Wiley & Sons, 2007.

AP Physics C E&M Course Description and Outline.

AP Physics C Mechanics Course Description and Outline.

New Jersey 9-12 Science standards 2020. https://www.nj.gov/education/standards/science/Docs/NJSLS-Science_9-12.pdf

Next Generation Science Standards. https://www.nextgenscience.org

"Video Encyclopedia of Physics Demonstrations". The Education Group. http://www.physicsdemos.com

MIT Open CourseWare Physics.

"The Mechanical Universe and Beyond". Annenberg Foundation. http://www.learner.org/resources/series42.html

AP Physics Lab Manual (College Board)