Course at a Glance

Plan

The Course at a Glance provides a useful visual organization of the AP Physics 1 course components, including:

- Sequence of units, along with approximate weighting and suggested pacing. Please note, pacing is based on 45-minute class periods, meeting five days each week for a full academic year.
- Progression of topics within each unit.
- Spiraling of the big ideas and science practices across units.

Teach

PRACTICES

Science practices spiral throughout the course.

1 Modeling
2 Mathematical Routines
3 Scientific Questioning
4 Experimental Methods
5 Data Analysis
6 Argumentation
7 Making Connections

+ Indicates 3 or more science pratices for a given topic. The individual topic page will show all the science practices.

BIG IDEAS

Big ideas spiral across topics and units.

SYS 1-Systems
FLD 2-Fields
INT 3-Force Interactions
CHA 4-Change
CON 5-Conservation
WAV 6-Waves

Assess

Assign the Personal Progress Checks—either as homework or in class—for each unit. Each Personal Progress Check contains formative multiple-choice and free-response questions. The feedback from these checks shows students the areas where they need to focus.

UNIT 1 Kinematics

~16–19 Class Periods | **10–16%** AP Exam Weighting

INT	+	**1.1** Position, Velocity, and Acceleration
CHA	+	**1.2** Representations of Motion

Personal Progress Check 1

Multiple-choice: ~15 questions
Free-response: 2 questions

- Experimental Design
- Paragraph Argument Short Answer

UNIT 2 Dynamics

~19–22 Class Periods | **12–18%** AP Exam Weighting

SYS	1 7	**2.1** Systems
FLD	2 7	**2.2** The Gravitational Field
INT	6	**2.3** Contact Forces
SYS	4	**2.4** Newton's First Law
INT	+	**2.5** Newton's Third Law and Free-Body Diagrams
INT	+	**2.6** Newton's Second Law
CHA	+	**2.7** Applications of Newton's Second Law

Personal Progress Check 2

Multiple-choice: ~40 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Short Answer

UNIT 3 Circular Motion and Gravitation

~7–9 Class Periods | **4–6%** AP Exam Weighting

FLD		3.1 Vector Fields
INT	7	3.2 Fundamental Forces
INT	2 7	3.3 Gravitational and Electric Forces
FLD	2 7	3.4 Gravitational Field/ Acceleration Due to Gravity on Different Planets
SYS	4	3.5 Inertial vs. Gravitational Mass
CHA	5	3.6 Centripetal Acceleration and Centripetal Force
INT	+	3.7 Free-Body Diagrams for Objects in Uniform Circular Motion
INT	+	3.8 Applications of Circular Motion and Gravitation

Personal Progress Check 3

Multiple-choice: ~40 questions
Free-response: 2 questions
- Experimental Design
- Paragraph Argument Short Answer

UNIT 4 Energy

~19–22 Class Periods | **16–24%** AP Exam Weighting

CON	6 7	4.1 Open and Closed Systems: Energy
INT CHA	+	4.2 Work and Mechanical Energy
CON	+	4.3 Conservation of Energy, the Work-Energy Principle, and Power

Personal Progress Check 4

Multiple-choice: ~30 questions
Free-response: 2 questions
- Quantitative/Qualitative Translation
- Short Answer

UNIT 5 Momentum

~12–15 Class Periods | **10–16%** AP Exam Weighting

INT	+	5.1 Momentum and Impulse
CHA	+	5.2 Representations of Changes in Momentum
CON	6 7	5.3 Open and Closed Systems: Momentum
CON	+	5.4 Conservation of Linear Momentum

Personal Progress Check 5

Multiple-choice: ~35 questions
Free-response: 2 questions
- Experimental Design
- Paragraph Argument Short Answer

UNIT 6 Simple Harmonic Motion

~2–5 Class Periods | **2–4%** AP Exam Weighting

INT
+
6.1 Period of Simple Harmonic Oscillators

CON
+
6.2 Energy of a Simple Harmonic Oscillator

Personal Progress Check 6

Multiple-choice: ~20 questions
Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT 7 Torque and Rotational Motion

~12–17 Class Periods | **10–16%** AP Exam Weighting

INT
1
2
7.1 Rotational Kinematics

INT
+
7.2 Torque and Angular Acceleration

CHA
+
7.3 Angular Momentum and Torque

CHA
+
7.4 Conservation of Angular Momentum

Personal Progress Check 7

Multiple-choice: ~40 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT 8 Electric Charge and Electric Force

~3–5 Class Periods | **4–6%** AP Exam Weighting

CON
6
7
8.1 Conservation of Charge

SYS
+
8.2 Electric Charge

INT
+
8.3 Electric Force

Personal Progress Check 8

Multiple-choice: ~15 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT 9

DC Circuits

~9–12 Class Periods | **6–8%** AP Exam Weighting

SYS 6 7 — **9.1** Definition of a Circuit

SYS 4 — **9.2** Resistivity

CON + — **9.3** Ohm's Law, Kirchhoff's Loop Rule (Resistors in Series and Parallel)

CON + — **9.4** Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)

Personal Progress Check 9

Multiple-choice: ~30 questions
Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT 10

Mechanical Waves and Sound

~11–14 Class Periods | **12–16%** AP Exam Weighting

WAV + — **10.1** Properties of Waves

WAV + — **10.2** Periodic Waves

WAV + — **10.3** Interference and Superposition (Waves in Tubes and on Strings)

Personal Progress Check 10

Multiple-choice: ~30 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

AP PHYSICS 1

UNIT 1

Kinematics

10–16%
AP EXAM WEIGHTING

~16–19
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 1

Multiple-choice: ~15 questions
Free-response: 2 questions

- Experimental Design
- Paragraph Argument Short Answer

UNIT
1

10–16% AP EXAM WEIGHTING

~16–19 CLASS PERIODS

Kinematics

BIG IDEA 3

Force Interactions **INT**

- How can the motion of objects be predicted and/or explained?
- Can equations be used to answer questions regardless of the questions' specificity?
- How can the idea of frames of reference allow two people to tell the truth yet have conflicting reports?

BIG IDEA 4

Change **CHA**

- How can we use models to help us understand motion?
- Why is the general rule for stopping your car "when you double your speed, you must give yourself four times as much distance to stop?"

Unit Overview

The world is in a constant state of motion. To understand the world, students must first understand movement. Unit 1 introduces students to the study of motion and serves as a foundation for all of AP Physics 1 by beginning to explore the complex idea of acceleration and showing them how representations can be used to model and analyze scientific information as it relates to the motion of objects. By studying kinematics, students will learn to represent motion—both uniform and accelerating—in narrative, graphical, and/or mathematical forms and from different frames of reference. These representations will help students analyze the specific motion of objects and systems while also dispelling some common misconceptions they may have about motion, such as exclusively using negative acceleration to describe an object slowing down. Additionally, students will have the opportunity to go beyond their traditional understanding of mathematics. Instead of solving equations, students will use them to support their reasoning and tighten their grasp on the laws of physics. Lastly, students will begin making predictions about motion and justifying claims with evidence by exploring the relationships between the physical quantities of acceleration, velocity, position, and time. This is an important starting point for students, as these fundamental science practices will spiral throughout the course and appear in multiple units.

Preparing for the AP Exam

On the AP Physics 1 Exam, there is an experimental design question in the free-response section that is worth 12 points. Students must be able to justify their selection of the kind of data needed to answer the question and then design a plan to collect that data.

When presented with an experimental design question, students often do not know where to start. Students should be given scaffolded opportunities to determine the appropriate data needed to answer a scientific question. To create laboratory experiments for students who struggle with identifying the data needed to answer a particular question, please refer to the learning objectives linked to this unit.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~16–19 CLASS PERIODS
3.A	**1.1 Position, Velocity, and Acceleration**	**1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships.	
4.A	**1.2 Representations of Motion**	**1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.* **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **2.3** The student can estimate quantities that describe natural phenomena.* **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 1. Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

AVAILABLE RESOURCES FOR UNIT 1

- Classroom Resources > *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*
- Classroom Resources > **Multiple Representations of Knowledge: Mechanics and Energy**
- Classroom Resources > **Graphical Analysis**
- Classroom Resources > **AP Physics Featured Question: Projectile Concepts**
- Classroom Resources > **Critical Thinking Questions in Physics**
- Classroom Resources > **Physics Instruction Using Video Analysis Technology**
- Classroom Resources > **Teaching Strategies for Limited Class Time**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	1.1	**Desktop Experiment Task** Have students find the acceleration of a yo-yo as it falls and unwinds using only a meterstick and stopwatch. Students then draw (with correct shapes and scales) distance, speed, and acceleration versus time graphs.
2	1.1	**Identify Subtasks** Each group is given a spring-loaded ball launcher and a meterstick. Students launch the ball horizontally from a known height and then predict where it will land on the floor when fired at a given angle from the floor. Have students articulate subtasks and then perform each one.
3	1.2	**Changing Representations** Show a curvy x versus t graph, a v versus t graph made of connected straight-line segments, or an a versus t graph made of horizontal steps. Have students sketch the other two graphs and either walk them out along a line or move a cart on a track to demonstrate the motion (the track can be tilted slightly to provide constant acceleration in either direction).
4	1.2	**Changing Representations** Students throw/project a ball from the second or third story to the ground and measure the ball's initial height, horizontal distance, and time in the air. From this, students calculate initial velocity components and draw (with scales) horizontal/vertical position/velocity/acceleration versus time graphs.
5	1.2	**Desktop Experiment Task** Give each group a pull-back toy car. Students lay out strips of paper 0.5 m apart and take a phone video of the car as it is released, speeds up, and slows down. Using a frame-by-frame review app to get the time each strip is passed to get x versus t data, have students make v versus t data tables out of this, and graph both.

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 1.1

Position, Velocity, and Acceleration

SCIENCE PRACTICES

Modeling

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Required Course Content

ENDURING UNDERSTANDING

3.A

All forces share certain common characteristics when considered by observers in inertial reference frames.

LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

3.A.1.2

Design an experimental investigation of the motion of an object. **[SP 4.2]**

3.A.1.3

Analyze experimental data describing the motion of an object and be able to express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

3.A.1

An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.

a. Displacement, velocity, and acceleration are all vector quantities.

b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values.

Relevant Equations:

$$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$$

c. A choice of reference frame determines the direction and the magnitude of each of these quantities.

d. There are three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects.

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LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

3.A.1.2

Design an experimental investigation of the motion of an object. **[SP 4.2]**

3.A.1.3

Analyze experimental data describing the motion of an object and be able to express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force.

f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. Circular motion is further covered in Unit 3. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$$

$$v_x^2 = v_{x0}^2 + 2a_x (x - x_0)$$

g. For rotational motion, there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$\omega^2 = \omega_0^2 + 2\alpha_x (\theta - \theta_0)$$

h. This also includes situations where there is both a radial and tangential acceleration for an object moving in a circular path.

Relevant Equation:

$$a_c = \frac{v^2}{r}$$

For uniform circular motion of radius *r*, *v* is proportional to omega, *ω* (for a given *r*), and proportional to *r* (for a given omega, *ω*). Given a radius *r* and a period of rotation *T*, students derive and apply *v* = (2*πr*)/*T*.

BOUNDARY STATEMENT:

AP Physics 2 has learning objectives under Enduring Understanding 3.A that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.

SCIENCE PRACTICES

Modeling

1.2

The student can describe representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

2.3

The student can estimate quantities that describe natural phenomena.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

TOPIC 1.2

Representations of Motion

Required Course Content

ENDURING UNDERSTANDING

4.A

The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$.

LEARNING OBJECTIVE

4.A.1.1

Use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semi-quantitatively. **[SP 1.2, 1.4, 2.3, 6.4]**

ESSENTIAL KNOWLEDGE

4.A.1

The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.

a. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities.

Relevant Equations:

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$$

$$v_x{}^2 = v_{x0}^2 + 2a_x (x - x_0)$$

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LEARNING OBJECTIVE

4.A.2.1

Make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. **[SP 6.4]**

4.A.2.3

Create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

4.A.2

The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.

a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.

b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.

c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of position of the center of mass with time.

d. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities.

Relevant Equations:

$$\vec{a} = \frac{\sum \vec{F}}{m_{system}}$$

$$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$$

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AP PHYSICS 1

UNIT 2

Dynamics

12–18%
AP EXAM WEIGHTING

~19–22
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 2

Multiple-choice: ~40 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Short Answer

UNIT
2

12–18% AP EXAM WEIGHTING

~19–22 CLASS PERIODS

Dynamics

BIG IDEA 1
***Systems* SYS**

- How can the properties of internal and gravitational mass be experimentally verified to be the same?
- How do you decide what to believe about scientific claims?
- How does something we cannot see determine how an object behaves?

BIG IDEA 2
***Fields* FLD**

- How do objects with mass respond when placed in a gravitational field?
- Why is the acceleration due to gravity constant on Earth's surface?

BIG IDEA 3
***Force Interactions* INT**

- Are different kinds of forces *really* different?
- How can Newton's laws of motion be used to predict the behavior of objects?

BIG IDEA 4
***Change* CHA**

- Why does the same push change the motion of a shopping cart more than the motion of a car?

Unit Overview

In Unit 2, students are introduced to the term force, which is the interaction of an object with another object. Part of the larger study of dynamics, forces are used as the lens through which students analyze and come to understand a variety of physical phenomena. This is accomplished by revisiting and building upon the representations presented in Unit 1, specifically the introduction to the free-body diagram. Translation, however, is key in this unit: Students must be able to portray the same object–force interactions through different graphs, diagrams, and mathematical relationships. Students will continue to make meaning from models and representations that will help them further analyze systems, the interactions between systems, and how these interactions result in change.

Alongside mastering the use of specific force equations, Unit 2 also encourages students to derive new expressions from fundamental principles to help them make predictions in unfamiliar, applied contexts. The skill of making predictions will be nurtured throughout the course to help students craft sound scientific arguments.

Preparing for the AP Exam

The AP Physics 1 Exam requires students to be able to re-express key elements of natural phenomena across multiple representations in the domain. This skill appears in the Qualitative/Quantitative Translation (QQT), a long free-response question that requires students to go between words and mathematics in describing and analyzing a situation. A QQT question might ask students to work with multiple representations or to evaluate another student's words or representations. Representations include mathematical equations, narrative descriptions, graphs, diagrams, and data tables.

Students who have primarily been exposed to numerical problem solving often struggle with a QQT question because it requires students to have a more conceptual understanding of both content and representations. Opportunities to translate between different representations, including equations, diagrams, graphs, and written descriptions, will help students prepare for the QQT question.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods
			~19–22 CLASS PERIODS
1.A	**2.1 Systems**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain.* **7.1** The student can connect phenomena and models across spatial and temporal scales.*	
2.B	**2.2 The Gravitational Field**	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.C	**2.3 Contact Forces**	**6.1** The student can justify claims with evidence. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.*	
1.C	**2.4 Newton's First Law**	**4.2** The student can design a plan for collecting data to answer a particular scientific question.	
3.A	**2.5 Newton's Third Law and Free-Body Diagrams**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **6.1** The student can justify claims with evidence. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~19–22 CLASS PERIODS
3.B	**2.6 Newton's Second Law**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question.* **5.1** The student can analyze data to identify patterns or relationships. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods
			~19–22 CLASS PERIODS
4.A	**2.7** Applications of Newton's Second Law	**1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.* **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **2.3** The student can estimate quantities that describe natural phenomena.* **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 2. Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

AVAILABLE RESOURCES FOR UNIT 2:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Multiple Representations of Knowledge: Mechanics and Energy**
- Classroom Resources > **Physics Instruction Using Video Analysis Technology**
- Classroom Resources > **Teaching Strategies for Limited Class Time**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	2.1	**Changing Representations** Have students consider an accelerating two-object system from everyday life (e.g., person pushes a shopping cart, car pulls a trailer). Have them draw the forces on one object, then on the other, and then the external forces acting on the two-object system.
2	2.4	**Desktop Experiment Task** Have students measure the coefficient of static friction of their shoe on a wood plank or metal track. Level 1: Use a spring scale. Level 2: Use a pulley, a spring, a toy bucket, and an electronic balance. Level 3: Use a protractor.
3	2.5	**Desktop Experiment Task** Give students a yo-yo, a low mass, low friction pulley, 50 paper clips, and a scale. Have them find the acceleration of the falling, unrolling yo-yo and then determine the mass of the paper clips to attach to the free end of the string so that the paper clips stay at rest even as the yo-yo falls and the string passes over the pulley.
4	2.6	**Working Backward** Student A writes a Newton's second law equation either with symbols or plugged-in numbers including units. Student B must then describe a situation that the equation applies to, including the object's velocity direction and how velocity is changing, a diagram, and a free-body diagram.
5	2.7	**Troubleshooting** Students take some force-related problem from the homework or textbook (one that requires setting up Newton's second law and maybe more). Students write out a detailed solution that has exactly *one* mistake in it (not a calculation error). Post everyone's problems/ solutions, and then ask students to identify everyone else's errors. The last student to have his or her error found wins.

Unit Planning Notes

Use the space below to plan your approach to the unit.

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

Making Connections

7.1

The student can connect phenomena and models across spatial and temporal scales.

TOPIC 2.1

Systems

Required Course Content

ENDURING UNDERSTANDING

1.A

The internal structure of a system determines many properties of the system.

LEARNING OBJECTIVE

[While there is no specific learning objective for it, EK 1.A.1 serves as a foundation for other learning objectives in the course.]

1.A.5.1

Model verbally or visually the properties of a system based on its substructure and relate this to changes in the system properties over time as external variables are changed. **[SP 1.1, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.1

A system is an object or a collection of objects. Objects are treated as having no internal structure.

a. A collection of particles in which internal interactions change little or not at all, or in which changes in these interactions are irrelevant to the question addressed, can be treated as an object.

b. Some elementary particles are fundamental particles, (e.g., electrons). Protons and neutrons are composed of fundamental particles (i.e., quarks) and might be treated as either systems or objects, depending on the question being addressed.

c. The electric charges on neutrons and protons result from their quark compositions.

1.A.5

Systems have properties that are determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an object.

TOPIC 2.2

The Gravitational Field

SCIENCE PRACTICES

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Required Course Content

ENDURING UNDERSTANDING

2.B

A gravitational field is caused by an object with mass.

LEARNING OBJECTIVE

2.B.1.1

Apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass *m* in a gravitational field of strength *g* in the context of the effects of a net force on objects and systems. **[SP 2.2, 7.2]**

ESSENTIAL KNOWLEDGE

2.B.1

A gravitational field $\vec{g}$ at the location of an object with mass *m* causes a gravitational force of magnitude *mg* to be exerted on the object in the direction of the field.

a. On Earth, this gravitational force is called weight.

b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.

c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location.

Relevant Equation:

$$\vec{g} = \frac{\vec{F}_g}{m}$$

TOPIC 2.3

Contact Forces

SCIENCE PRACTICES

Argumentation

6.1

The student can justify claims with evidence.

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

Required Course Content

ENDURING UNDERSTANDING

3.C

At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

LEARNING OBJECTIVE

3.C.4.1

Make claims about various contact forces between objects based on the microscopic cause of these forces. **[SP 6.1]**

3.C.4.2

Explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. **[SP 6.2]**

ESSENTIAL KNOWLEDGE

3.C.4

Contact forces result from the interaction of one object touching another object, and they arise from interatomic electric forces. These forces include tension, friction, normal, spring (Physics 1), and buoyant (Physics 2).

Relevant Equations:

$$\left|\vec{F}_f\right| \leq \mu\left|\vec{F}_n\right|$$

$$\left|\vec{F}_s\right| = k\left|\vec{x}\right|$$

TOPIC 2.4

Newton’s First Law

SCIENCE PRACTICE

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Required Course Content

ENDURING UNDERSTANDING

1.C

Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.C.1.1 Design an experiment for collecting data to determine the relationship between the net force exerted on an object, its inertial mass, and its acceleration. **[SP 4.2]**	**1.C.1** Inertial mass is the property of an object or system that determines how its motion changes when it interacts with other objects or systems. a. $\vec{a} = \frac{\sum \vec{F}}{m}$
1.C.3.1 Design a plan for collecting data to measure gravitational mass and inertial mass and to distinguish between the two experiments. **[SP 4.2]**	**1.C.3** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Argumentation

6.1

The student can justify claims with evidence.

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 2.5

Newton's Third Law and Free-Body Diagrams

Required Course Content

ENDURING UNDERSTANDING

3.A

All forces share certain common characteristics when considered by observers in inertial reference frames.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.A.2.1 Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**	**3.A.2** Forces are described by vectors. a. Forces are detected by their influence on the motion of an object. b. Forces have magnitude and direction.
3.A.3.1 Analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]** **3.A.3.2** Challenge a claim that an object can exert a force on itself. **[SP 6.1]** **3.A.3.3** Describe a force as an interaction between two objects, and identify both objects for any force. **[SP 1.4]**	**3.A.3** A force exerted on an object is always due to the interaction of that object with another object. a. An object cannot exert a force on itself. b. Even though an object is at rest, there may be forces exerted on that object by other objects. c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

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LEARNING OBJECTIVE

3.A.4.1

Construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]**

3.A.4.2

Use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**

3.A.4.3

Analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

3.A.4

If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

TOPIC 2.6

Newton’s Second Law

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Required Course Content

ENDURING UNDERSTANDING

3.B

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.

LEARNING OBJECTIVE

3.B.1.1

Predict the motion of an object subject to forces exerted by several objects using an application of Newton’s second law in a variety of physical situations, with acceleration in one dimension. **[SP 6.4, 7.2]**

3.B.1.2

Design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurement, and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**

3.B.1.3

Re-express a free-body diagram into a mathematical representation, and solve the mathematical representation for the acceleration of the object. **[SP 1.5, 2.2]**

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. Projectile motion and circular motion are both included in AP Physics 1.

Relevant Equation:

$$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$$

BOUNDARY STATEMENT:

AP Physics 2 contains learning objectives for Enduring Understanding 3.B that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.

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LEARNING OBJECTIVE

3.B.2.1

Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. **[SP 1.1, 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

3.B.2

Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.

a. An object can be drawn as if it were extracted from its environment and the interactions with the environment were identified.

b. A force exerted on an object can be represented as an arrow whose length represents the magnitude of the force and whose direction shows the direction of the force.

c. A coordinate system with one axis parallel to the direction of the acceleration simplifies the translation from the free-body diagram to the algebraic representation.

d. Free-body or force diagrams may be depicted in one of two ways—one in which the forces exerted on an object are represented as arrows pointing outward from a dot, and the other in which the forces are specifically drawn at the point on the object at which each force is exerted.

SCIENCE PRACTICES *(CONT'D)*

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 2.7

Applications of Newton's Second Law

SCIENCE PRACTICES

Modeling

1.2

The student can describe representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

2.3

The student can estimate quantities that describe natural phenomena.

Data Analysis

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Required Course Content

ENDURING UNDERSTANDING

4.A

The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
4.A.1.1 Use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semi-quantitatively. **[SP 1.2, 1.4, 2.3, 6.4]**	**4.A.1** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities. *Relevant Equations:* $v_x = v_{x0} + a_x t$ $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ $v_x^{\,2} = v_{x0}^2 + 2a_x(x - x_0)$
4.A.2.2 Evaluate, using given data, whether all the forces on a system or all the parts of a system have been identified. **[SP 5.3]**	**4.A.2** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time. a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system. b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.

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LEARNING OBJECTIVE

4.A.2.2

Evaluate, using given data, whether all the forces on a system or all the parts of a system have been identified. **[SP 5.3]**

ESSENTIAL KNOWLEDGE

c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of position of the center of mass with time.

d. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities.

Relevant Equations:

$$\vec{a} = \frac{\sum \vec{F}}{m_{system}}$$

$$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$$

4.A.3.1

Apply Newton's second law to systems to calculate the change in the center-of-mass velocity when an external force is exerted on the system. **[SP 2.2]**

4.A.3.2

Use visual or mathematical representations of the forces between objects in a system to predict whether or not there will be a change in the center-of-mass velocity of that system. **[SP 1.4]**

4.A.3

Forces that the systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system.

Relevant Equation:

$$\vec{a} = \frac{\Sigma \vec{F}}{m_{system}} = \frac{\vec{F}_{net}}{m}$$

AP PHYSICS 1

UNIT 3

Circular Motion and Gravitation

4–6%
AP EXAM WEIGHTING

~7–9
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 3

Multiple-choice: ~40 questions
Free-response: 2 questions

- Experimental Design
- Paragraph Argument Short Answer

UNIT
3

4–6% AP EXAM WEIGHTING

~7–9 CLASS PERIODS

Circular Motion and Gravitation

BIG IDEA 1
Systems **SYS**
- How does changing the mass of an object affect the gravitational force?
- Why is a refrigerator hard to push in space?

BIG IDEA 2
Fields **FLD**
- Why do we feel pulled toward Earth but not toward a pencil?
- How can the acceleration due to gravity be modified?

BIG IDEA 3
Force Interactions **INT**
- How can Newton's laws of motion be used to predict the behavior of objects?
- How can we use forces to predict the behavior of objects and keep us safe?

BIG IDEA 4
Change **CHA**
- How is the acceleration of the center of mass of a system related to the net force exerted on the system?
- Why is it more difficult to stop a fully loaded dump truck than a small passenger car?

Unit Overview

In Unit 3, students will continue to enhance their understanding of the physical world using models and representations to create a more complete and complex model of motion, particularly as it relates to gravitational mass and inertial mass. Again, translation and connections are essential—students must be able to use content and science practices from the previous two units and apply them in different ways.

While it's essential that students are able to calculate numerical answers to questions, it is more important that they can combine mathematical representations to make new representations that more accurately describe natural phenomena. For example, students should be comfortable combining equations for uniform circular motion with gravitational equations to describe the circular path of a satellite circling a planet.

It is also vital that students are given opportunities to think about and discuss the impact that changes or modifications have on physical scenarios. For example, students should be able to use mathematical and graphical representations to determine how doubling the distance of a satellite from a planet will change the period of orbit and then justify their answer with evidence and reasoning. Specific preconceptions will be addressed in this unit, such as the idea of a centrifugal force. Students will also have opportunities to wrestle with the idea of field models, which will be expanded upon in Unit 8.

Preparing for the AP Exam

Students will be asked to give a paragraph-length response to demonstrate their ability to communicate their understanding of a physical situation in a reasoned, expository analysis. For full credit, the response should be a coherent, organized, and sequential description of the analysis of a situation that draws from evidence, cites physical principles, and clearly presents the student's thinking. Full credit may not be earned if the response contains any of the following: principles not presented in a logical order, lengthy digressions within an argument, or a lack of linking prose between equations or diagrams.

Students will also be asked to explain phenomena based on evidence produced through scientific practices while using mathematical routines as evidence for claims. Students who are weak mathematically will need significant scaffolding to help them develop the conceptual mathematical understanding necessary to succeed on the AP Physics 1 Exam.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~7–9 CLASS PERIODS
2.A	**3.1 Vector Fields**	N/A	
3.G	**3.2 Fundamental Forces**	**7.1** The student can connect phenomena and models across spatial and temporal scales.	
3.C	**3.3 Gravitational and Electric Forces**	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
2.B	**3.4 Gravitational Field/Acceleration Due to Gravity on Different Planets**	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
1.C	**3.5 Inertial vs. Gravitational Mass**	**4.2** The student can design a plan for collecting data to answer a particular scientific question.	
4.A	**3.6 Centripetal Acceleration and Centripetal Force**	**5.3** The students can evaluate the evidence provided by data sets in relation to a particular scientific question.	
3.B	**3.7 Free-Body Diagrams for Objects in Uniform Circular Motion**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships.*	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods **~7–9** CLASS PERIODS
3.A	**3.8** Applications of Circular Motion and Gravitation	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 3.
Review the results in class to identify and address any student misunderstandings.

AVAILABLE RESOURCES FOR UNIT 3:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Multiple Representations of Knowledge: Mechanics and Energy**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	3.3	**Desktop Experiment Task** Have students use the "My Solar System" PhET applet to create circular orbits of varying radii around the central star and record radius, period, and planet mass for various trials. Next, have them calculate the speed using $v = 2\pi r/T$ and force using $F = mv^2/r$. Using the data, students show that gravitational force is directly proportional to mass and inversely proportional to radius.
2	3.6	**Construct an Argument** Ask students to consider two identical objects moving in circles (or parts of circles) of different radii. Ask them to think of a situation where the object with the smaller radius has a greater net force and another situation where the object with the larger radius has a greater net force.
3	3.7	**Changing Representations** Describe something a driver could be doing in a car (e.g., "turning the steering wheel to the right while pressing the brake"). Have students walk out the motion while holding out one arm representing the velocity vector and the other arm representing the acceleration vector.
4	3.8	**Create a Plan** Find a data table on stopping distance. Have students determine the coefficient of static friction of the car's tires from this data and then create a new table of different car speeds and minimum turning radii to not skid.
5	3.8	**Predict and Explain** Attach a pendulum of known weight (say, 2 N) to a force sensor and cause the bob to swing in a 180-degree arc. Ask students, "At the bottom, the bob is neither speeding up nor slowing down, so what force is registered at the bottom?" Expect students to (incorrectly) answer, "2 N."

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 3.1

Vector Fields

Required Course Content

ENDURING UNDERSTANDING

2.A

A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces), as well as a variety of other physical phenomena.

LEARNING OBJECTIVE

[While there is no specific learning objective for it, EK 2.A.1 serves as a foundation for other learning objectives in the course.]

ESSENTIAL KNOWLEDGE

2.A.1

A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.

a. Vector fields are represented by field vectors indicating direction and magnitude.

b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition.

c. Conversely, a known vector field can be used to make inferences about the number, relative size, and locations of sources.

BOUNDARY STATEMENT:

Physics 1 treats gravitational fields; Physics 2 treats electric and magnetic fields.

SCIENCE PRACTICE

Making Connections

7.1

The student can connect phenomena and models across spatial and temporal scales.

TOPIC 3.2

Fundamental Forces

Required Course Content

ENDURING UNDERSTANDING

3.G

Certain types of forces are considered fundamental.

LEARNING OBJECTIVE

3.G.1.1

Articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

3.G.1

Gravitational forces are exerted at all scales and dominate at the largest distances and mass scales.

TOPIC 3.3

Gravitational and Electric Forces

Required Course Content

ENDURING UNDERSTANDING

3.C

At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

LEARNING OBJECTIVE

3.C.1.1

Use Newton's law of gravitation to calculate the gravitational force that two objects exert on each other and use that force in contexts other than orbital motion. **[SP 2.2]**

3.C.1.2

Use Newton's law of gravitation to calculate the gravitational force between two objects and use that force in contexts involving orbital motion (for circular orbital motion only in Physics 1). **[SP 2.2]**

3.C.2.2

Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**

ESSENTIAL KNOWLEDGE

3.C.1

Gravitational force describes the interaction of one object with mass with another object with mass.

a. The gravitational force is always attractive.
b. The magnitude of force between two spherically symmetric objects of mass m_1 and m_2 is $G\frac{m_1 m_2}{r^2}$, where r is the center-to-center distance between the objects.
c. In a narrow range of heights above Earth's surface, the local gravitational field, g, is approximately constant.

Relevant Equations:

$$\left|F_g\right| = G\frac{m_1 m_2}{r^2}$$

$$\vec{g} = \frac{\vec{F}_g}{m}$$

SCIENCE PRACTICES

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

SCIENCE PRACTICES

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 3.4

Gravitational Field/Acceleration Due to Gravity on Different Planets

Required Course Content

ENDURING UNDERSTANDING

2.B

A gravitational field is caused by an object with mass.

LEARNING OBJECTIVE

2.B.1.1

Apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass *m* in a gravitational field of strength *g* in the context of the effects of a net force on objects and systems. **[SP 2.2, 7.2]**

ESSENTIAL KNOWLEDGE

2.B.1

A gravitational field $\vec{g}$ at the location of an object with mass *m* causes a gravitational force of magnitude *mg* to be exerted on the object in the direction of the field.

a. On Earth, this gravitational force is called weight.

b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.

c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location.

Relevant Equation:

$$\vec{g} = \frac{\vec{F}_g}{m}$$

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LEARNING OBJECTIVE

2.B.2.1

Apply $g = G\frac{m}{r^2}$ to calculate the gravitational field due to an object with mass *m*, where the field is a vector directed toward the center of the object of mass *m*. **[SP 2.2]**

2.B.2.2

Approximate a numerical value of the gravitational field (*g*) near the surface of an object from its radius and mass relative to those of Earth or other reference objects. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

2.B.2

The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object.

a. The gravitational field cause by a spherically symmetric object is a vector whose magnitude outside the object is equal to $G\frac{m}{r^2}$.

b. Only spherically symmetric objects will be considered as sources of the gravitational field.

Relevant Equation:

$$\vec{a} = \frac{\Sigma\vec{F}}{m_{system}} = \frac{\vec{F}_{net}}{m}$$

SCIENCE PRACTICE

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

TOPIC 3.5

Inertial vs. Gravitational Mass

Required Course Content

ENDURING UNDERSTANDING

1.C

Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
[While there is no specific learning objective for it, EK 1.C.2 serves as a foundation for other learning objectives in the course.]	**1.C.2** Gravitational mass is the property of an object or a system that determines the strength of the gravitational interaction with other objects, systems, or gravitational fields. a. The gravitational mass of an object determines the amount of force exerted on the object by a gravitational field. b. Near Earth's surface, all objects fall (in a vacuum) with the same acceleration, regardless of their inertial mass.
1.C.3.1 Design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]**	**1.C.3** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

TOPIC 3.6

Centripetal Acceleration and Centripetal Force

SCIENCE PRACTICE

Data Analysis

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Required Course Content

ENDURING UNDERSTANDING

4.A

The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$.

LEARNING OBJECTIVE

4.A.2.2

Evaluate, using given data, whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]**

ESSENTIAL KNOWLEDGE

4.A.2

The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.

a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.

b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.

c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of position of the center of mass with time.

d. The variables *x*, *v*, and *a* all refer to the center-of-mass quantities.

Relevant Equations:

$$\vec{a} = \frac{\sum \vec{F}}{m_{system}}$$

$$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$$

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

TOPIC 3.7

Free-Body Diagrams for Objects in Uniform Circular Motion

Required Course Content

ENDURING UNDERSTANDING

3.B

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma\vec{F}}{m}$.

LEARNING OBJECTIVE

3.B.1.2

Design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements, and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**

3.B.1.3

Re-express a free-body diagram representation into a mathematical representation, and solve the mathematical representation for the acceleration of the object. **[SP1.5, 2.2]**

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. Projectile motion and circular motion are both included in AP Physics 1.

Relevant Equation:

$$\vec{a} = \frac{\Sigma\vec{F}}{m} = \frac{\vec{F}_{net}}{m}$$

BOUNDARY STATEMENT:

AP Physics 2 contains learning objectives for Enduring Understanding 3.B that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.

continued on next page

LEARNING OBJECTIVE

3.B.2.1

Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. **[SP 1.1, 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

3.B.2

Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.

a. An object can be drawn as if it were extracted from its environment and the interactions with the environment were identified.

b. A force exerted on an object can be represented as an arrow whose length represents the magnitude of the force and whose direction shows the direction of the force.

c. A coordinate system with one axis parallel to the direction of the acceleration simplifies the translation from the free-body diagram to the algebraic representation.

d. Free-body or force diagrams may be depicted in one of two ways—one in which the forces exerted on an object are represented as arrows pointing outward from a dot, and the other in which the forces are specifically drawn at the point on the object at which each force is exerted.

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

TOPIC 3.8

Applications of Circular Motion and Gravitation

Required Course Content

ENDURING UNDERSTANDING

3.A

All forces share certain common characteristics when considered by observers in inertial reference frames.

LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

3.A.1.2

Design an experimental investigation of the motion of an object. **[SP 4.2]**

3.A.1.3

Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

3.A.1

An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.

a. Displacement, velocity, and acceleration are all vector quantities.

b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values.

Relevant Equations:

$$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$$

c. A choice of reference frame determines the direction and the magnitude of each of these quantities.

d. There are three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects.

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LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

3.A.1.2

Design an experimental investigation of the motion of an object. **[SP 4.2]**

3.A.1.3

Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force.

f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. Circular motion is further covered in Unit 3. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$$

$$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$$

g. For rotational motion, there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$\omega^2 = \omega_0^2 + 2\alpha_x(\theta - \theta_0)$$

h. This also includes situations where there is both a radial and tangential acceleration for an object moving in a circular path.

Relevant Equation:

$$a_c = \frac{v^2}{r}$$

For uniform circular motion of radius *r*, *v* is proportional to omega, *ω* (for a given *r*), and proportional to *r* (for a given omega, *ω*). Given a radius *r* and a period of rotation *T*, students derive and apply *v* = (2*πr*)/*T*.

BOUNDARY STATEMENT:

AP Physics 2 has learning objectives under Enduring Understanding 3.A that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.

SCIENCE PRACTICES ***(CONT'D)***

Argumentation

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.A.2.1 Represent forces in diagrams or mathematically, using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**	**3.A.2** Forces are described by vectors. a. Forces are detected by their influence on the motion of an object. b. Forces have magnitude and direction.
3.A.3.1 Analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]** **3.A.3.3** Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**	**3.A.3** A force exerted on an object is always due to the interaction of that object with another object. a. An object cannot exert a force on itself. b. Even though an object is at rest, there may be forces exerted on that object by other objects. c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.
3.A.4.1 Construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]** **3.A.4.2** Use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]** **3.A.4.3** Analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**	**3.A.4** If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

AP PHYSICS 1

UNIT 4

Energy

16–24%
AP EXAM WEIGHTING

~19–22
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 4

Multiple-choice: ~30 questions

Free-response: 2 questions

- Quantitative/Qualitative Translation
- Short Answer

UNIT
4

16–24% AP EXAM WEIGHTING

~19–22 CLASS PERIODS

Energy

BIG IDEA 3

Force Interactions **INT**

- How does pushing something give it energy?

BIG IDEA 4

Change **CHA**

- How is energy exchanged and transformed within or between systems?
- How does the choice of system influence how energy is stored or how work is done?
- How does energy conservation allow the riders in the back car of a rollercoaster to have a thrilling ride?

BIG IDEA 5

Conservation **CON**

- How can the idea of potential energy be used to describe the work done to move celestial bodies?
- How is energy transferred between objects or systems?
- How does the law of conservation of energy govern the interactions between objects and systems?

Unit Overview

In Unit 4, students will be introduced to the idea of conservation as a foundational model of physics, along with the concept of work as the agent of change for energy. As in earlier units, students will once again utilize both familiar and new models and representations to analyze physical situations, now with force or energy as major components. Students will be encouraged to call upon their knowledge of Units 1–4 to determine the most appropriate technique and will be challenged to understand the limiting factors of each. Describing, creating, and using these representations will also help students grapple with common misconceptions that they may have about energy, such as whether or not a single object can "have" potential energy. A thorough understanding of these energy models will support students' ability to make predications—and ultimately justify claims with evidence—about physical situations. This is crucial, as the mathematical models and representations used in Unit 4 will mature throughout the course and appear in subsequent units.

As students' comprehension of energy (particularly kinetic, potential, and microscopic internal energy) evolves, they will begin to connect and relate knowledge across scales, concepts, and representations, as well as across disciplines, particularly physics, chemistry, and biology.

Preparing for the AP Exam

When students work with mathematical representations, it's crucial that they understand the connections between the mathematical description, physical phenomena, and the concepts represented in those mathematical descriptions. On the exam, students need to be able to justify why using a particular equation to analyze a situation is useful and be aware of the conditions under which equations/mathematical representations can be used. Familiarity with symbolic solutions is also necessary, because students will not often encounter a question that asks them to directly solve for a numerical answer. Finally, students need to be able to evaluate equations in terms of units and limiting case analysis. The exam asks students to translate between functional relationships in equations (proportionalities, inverse proportionalities, etc.) and cause-and-effect relationships in the physical world.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods
			~19–22 CLASS PERIODS
5.A	**4.1 Open and Closed Systems: Energy**	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.E, 4.C	**4.2 Work and Mechanical Energy**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.B	**4.3 Conservation of Energy, the Work-Energy Principle, and Power**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 4.
Review the results in class to identify and address any student misunderstandings.

continued on next page

UNIT AT A GLANCE *(cont'd)*

AVAILABLE RESOURCES FOR UNIT 4:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Conservation Concepts**
- Classroom Resources > **Multiple Representations of Knowledge: Mechanics and Energy**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	4.2	**Concept-Oriented Demonstration** Release a low-friction cart (mass *m*) from the top of a ramp, have students time (*t*) how long it takes to reach the bottom, and measure the release height *h* and track length *L*. Have students calculate velocity using $v = L/t$, and then calculate mgh and $\frac{1}{2}mv^2$. The two energies are different; explain what incorrect assumptions lead to the difference in energies.
2	4.2	**Desktop Experiment Task** Give each group a spring-loaded ball launcher, scale, and meterstick. Ask them to determine the spring constant of the spring in the launcher.
3	4.2	**Four-Square Problem Solving** First square: Describe an everyday situation (e.g., “a car goes downhill, speeding up even as the brakes are pressed”) along with a diagram. Second square: Free-body diagram with an arrow off to the side representing the object’s displacement. Third square: Energy bar charts (initial and final). Fourth square: For each force on the free-body diagram, state whether that force performs positive or negative work and what energy transformation that force is responsible for.
4	4.3	**Construct an Argument** Ask students to consider a cart that rolls from rest down a ramp and then around a vertical loop. For the cart to complete the loop without falling out, the cart must be released at a height higher than the top of the loop. Have students explain why this is the case using energy and circular motion principles.
5	4.3	**Working Backward** Student A writes a conservation of energy equation (either symbolically or with numbers and units plugged in). Student B then describes a situation that the equation could apply to, draws a diagram, and draws energy bar charts.

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 4.1

Open and Closed Systems: Energy

Required Course Content

ENDURING UNDERSTANDING

5.A

Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
[While there is no specific learning objective for it, EK 5.A.1 serves as a foundation for other learning objectives in the course.]	**5.A.1** A system is an object or a collection of objects. The objects are treated as having no internal structure.
5.A.2.1 Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**	**5.A.2** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.
[While there is no specific learning objective for it, EK 5.A.3 serves as a foundation for other learning objectives in the course.]	**5.A.3** An interaction can be either a force exerted by objects outside the system or the transfer of some quantity with objects outside the system.
[While there is no specific learning objective for it, EK 5.A.4 serves as a foundation for other learning objectives in the course.]	**5.A.4** The placement of a boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis.

SCIENCE PRACTICES

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 4.2

Work and Mechanical Energy

SCIENCE PRACTICES

Modeling

1.4
The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.1
The student can justify the selection of a mathematical routine to solve problems.

2.2
The student can apply mathematical routines to quantities that describe natural phenomena.

Argumentation

6.4
The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2
The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Required Course Content

ENDURING UNDERSTANDING

3.E
A force exerted on an object can change the kinetic energy of the object.

LEARNING OBJECTIVE

3.E.1.1
Make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. **[SP 6.4, 7.2]**

3.E.1.2
Use net force and velocity vectors to determine qualitatively whether the kinetic energy of an object would increase, decrease, or remain unchanged. **[SP 1.4]**

3.E.1.3
Use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether the kinetic energy of that object would increase, decrease, or remain unchanged. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

3.E.1
The change in the kinetic energy of an object depends on the force exerted on the object and on the displacement of the object during the interval that the force is exerted.

a. Only the component of the net force exerted on an object parallel or antiparallel to the displacement of the object will increase (parallel) or decrease (antiparallel) the kinetic energy of the object.

b. The magnitude of the change in the kinetic energy is the product of the magnitude of the displacement and of the magnitude of the component of force parallel or antiparallel to the displacement.

Relevant Equation:

$$\Delta E = W = F_{\parallel} d$$

c. The component of the net force exerted on an object perpendicular to the direction of the displacement of the object can change the direction of the motion of the object without changing the kinetic energy of the object. This should include uniform circular motion and projectile motion.

continued on next page

LEARNING OBJECTIVE

3.E.1.4

Apply mathematical routines to determine the change in kinetic energy of an object given the forces on the object and the displacement of the object. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

d. The kinetic energy of a rigid system may be translational, rotational, or a combination of both. The change in the rotational kinetic energy of a rigid system is the product of the angular displacement and the net torque.

Relevant Equations:

$$K = \frac{1}{2}mv^2$$

$$\Delta E = W = F_{\parallel}d = Fd\cos\theta$$

ENDURING UNDERSTANDING

4.C

Interactions with other objects or systems can change the total energy of a system.

LEARNING OBJECTIVE

4.C.1.1

Calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]**

4.C.1.2

Predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

4.C.1

The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples include gravitational potential energy, elastic potential energy, and kinetic energy.

a. A rotating, rigid body may be considered to be a system and may have both translational and rotational kinetic energy.

b. Although thermodynamics is not part of Physics 1, included is the idea that, during an inelastic collision, some of the mechanical energy dissipates as (converts to) thermal energy.

Relevant Equations:

$$K = \frac{1}{2}mv^2$$

$$K = \frac{1}{2}I\omega^2$$

$$\Delta U_g = mg\Delta y$$

$$U_G = -\frac{Gm_1m_2}{r}$$

$$U_s = \frac{1}{2}kx^2$$

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LEARNING OBJECTIVE

4.C.2.1

Make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. **[SP 6.4]**

4.C.2.2

Apply the concepts of conservation of energy and the work-energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. **[SP 1.4, 2.2, 7.2]**

ESSENTIAL KNOWLEDGE

4.C.2

Mechanical energy (the sum of kinetic and potential energy) is transferred into or out of a system when an external force is exerted on a system such that a component of the forces is parallel to its displacement. The process through which the energy is transferred is called work.

a. If the force is constant during a given displacement, then the work done is the product of the displacement and the component of the force parallel or antiparallel to the displacement.

Relevant Equation:

$$W = F_{\parallel}d$$

b. Work (change in energy) can be found from the area under a graph of the magnitude of the force component parallel to the displacement versus displacement.

Relevant Equation:

$$\Delta E = W = F_{\parallel}d = Fd\cos\theta$$

TOPIC 4.3

Conservation of Energy, the Work-Energy Principle, and Power

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.1.1

Create a representation or model showing that a single object can only have kinetic energy and use information about that object to calculate its kinetic energy. **[SP 1.4, 2.2]**

5.B.1.2

Translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. **[SP 1.5]**

ESSENTIAL KNOWLEDGE

5.B.1

Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects.

Relevant Equation:

$$K = \frac{1}{2}mv^2$$

BOUNDARY STATEMENT:

Conservation principles apply in the context of the appropriate Physics 1 and Physics 2 courses. Work, potential energy, and kinetic energy concepts are related to mechanical systems in Physics 1 and electric, magnetic, thermal, and atomic and elementary particle systems in Physics 2.

continued on next page

SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.B.2.1 Calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. **[SP 1.4, 2.1]**	**5.B.2** A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. [Physics 1 includes mass-spring oscillators and simple pendulums. Physics 2 includes charged objects in electric fields and examining changes in internal energy with changes in configuration.]
5.B.3.1 Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]** **5.B.3.2** Make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]** **5.B.3.3** Apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**	**5.B.3** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces. a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system. b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators and objects falling in a gravitational field. c. The change in electric potential in a circuit is the change in potential energy per unit charge. [In Physics 1, only in the context of circuits] *Relevant Equations:* $T_p = 2\pi\sqrt{\frac{l}{g}}$ $T_s = 2\pi\sqrt{\frac{m}{k}}$ $U_s = \frac{1}{2}kx^2$ $\Delta U_g = mg\Delta y$

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.B.4.1 Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **5.B.4.2** Calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**	**5.B.4** The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system. a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy. b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.
5.B.5.1 Design an experiment and analyze data to determine how a force exerted on an object or system does work on the object or system as it moves through a distance. **[SP 4.2, 5.1]** **5.B.5.2** Design an experiment and analyze graphical data in which interpretations of the area under a force-distance curve are needed to determine the work done on or by the object or system. **[SP 4.2, 5.1]** **5.B.5.3** Predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance. **[SP 1.4, 2.2, 6.4]**	**5.B.5** Energy can be transferred by an external force exerted on an object or a system that moves the object or system through a distance; this energy transfer is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system. [A piston filled with gas getting compressed or expanded is treated in Physics 2 as part of thermodynamics.] *Relevant Equations:* $\Delta E = W = F_{\parallel} d = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$

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LEARNING OBJECTIVE

5.B.5.4

Make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). **[SP 6.4, 7.2]**

5.B.5.5

Predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. **[SP 2.2, 6.4]**

ESSENTIAL KNOWLEDGE

5.B.5

Energy can be transferred by an external force exerted on an object or a system that moves the object or system through a distance; this energy transfer is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system. [A piston filled with gas getting compressed or expanded is treated in Physics 2 as part of thermodynamics.]

Relevant Equations:

$$\Delta E = W = F_{\parallel} d = Fd\cos\theta$$

$$P = \frac{\Delta E}{\Delta t}$$

AP PHYSICS 1

UNIT 5

Momentum

10–16%
AP EXAM WEIGHTING

~12–15
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 5

Multiple-choice: ~35 questions
Free-response: 2 questions

- Experimental Design
- Paragraph Argument Short Answer

UNIT
5

10–16% AP EXAM WEIGHTING

~12–15 CLASS PERIODS

Momentum

BIG IDEA 3
Force Interactions **INT**
- How does pushing an object change its momentum?

BIG IDEA 4
Change **CHA**
- How do interactions with other objects or systems change the linear momentum of a system?
- How is the physics definition of momentum different from how momentum is used to describe things in everyday life?

BIG IDEA 5
Conservation **CON**
- How does the law of the conservation of momentum govern interactions between objects or systems?
- How can momentum be used to determine fault in car crashes?

Unit Overview

Unit 5 introduces students to the relationship between force, time, and momentum via calculations, data analysis, designing experiments, and making predictions. Students will learn how to use new models and representations to illustrate the law of the conservation of momentum of objects and systems while simultaneously building on their knowledge of previously studied representations. Using the law of the conservation of momentum to analyze physical situations gives students a more complete picture of forces and leads them to revisit their misconceptions surrounding Newton's third law. Students will also have the opportunity to make connections between the conserved quantities of momentum and energy to determine under what conditions each quantity is conserved. It's essential that students are not only comfortable solving numerical equations (such as the speed of a system after an inelastic collision) but also confident in their ability to discuss when momentum is conserved and how the type of collision affects the outcome. Threading such connections between physical quantities is fundamental to understanding the broader relationship between this unit and the rest of the course.

Students will have more opportunities to apply conservation laws to make predictions and justify claims in Unit 7 when they are introduced to rotational quantities.

Preparing for the AP Exam

Physicists often use models and representations to show the design or workings of a system, an object, or a concept. Representations and models include, but are not limited to, sketching the physical situation, free-body diagrams, graphs, mathematical equations, and narratives. Unit 5 focuses on the creation/use and re-representation of models and representations. Students should be presented with multiple opportunities to create, use, and re-represent models and representations, including non-traditional representations. For example, while it is important that students be able to create a force versus time graph and explain that the area under the curve is equal to the momentum, they also need to feel comfortable with sketching or analyzing a graph of momentum versus time where the slope of the line is the net external force. In every situation, students need to be able to think about possible re-representations and how the new representation would change the model and/or introduce new data for analysis.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods **~12–15** CLASS PERIODS
3.D	**5.1** Momentum and Impulse	**2.1** The student can justify the selection of a mathematical routine to solve problems. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	
4.B	**5.2** Representations of Changes in Momentum	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **5.1** The student can analyze data to identify patterns or relationships.	
5.A	**5.3** Open and Closed Systems: Momentum	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods
			~12–15 CLASS PERIODS
5.D	**5.4** **Conservation of Linear Momentum**	**2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **3.2** The student can refine scientific questions. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **4.4** The student can evaluate sources of data to answer a particular scientific question.* **5.1** The student can analyze data to identify patterns or relationships. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 5.
Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

AVAILABLE RESOURCES FOR UNIT 5:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Conservation Concepts**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	5.1	**Conflicting Contentions** Ask students to imagine a pitcher throwing a baseball and a catcher catching it. Students will debate who exerted more force on the ball (no way to know), who applied greater impulse (same for both), and who did a greater magnitude of net work on the ball (same). Repeat for a pitcher throwing the baseball and a batter hitting it back at the same speed.
2	5.1	**Desktop Experiment Task** Connect a spring-loaded lanyard between a cart and force sensor, with a motion sensor on the other side of the cart. Have students take force and motion versus time data as the lanyard contracts and pulls, accelerating the cart. Show that impulse applied to the cart equals the cart's change in momentum.
3	5.2	**Bar Chart/Construct an Argument** Have students use momentum bar charts to explain why a dart bouncing off a cart makes the cart move faster than if the dart sticks to the cart, passes through the cart, or stops and drops after colliding with the cart.
4	5.2	**Predict and Explain/Concept-Oriented Demonstration** Have a cart crash into a force sensor set to its highest setting in three different ways: cart sticks to sensor, cart bounces off the sensor on its hard side, and cart bounces off the sensor with its spring side. Have students predict in which case more force is registered, and explain why after each experiment is done.
5	5.4	**Desktop Experiment Task** Have two carts with different masses collide in a non-stick collision. Film the carts with a phone camera from above, with a meterstick next to the track. Have students use a frame-by-frame review app to determine the cart's initial/final speeds, whether momentum was conserved, and whether the collision was elastic.

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 5.1

Momentum and Impulse

Required Course Content

ENDURING UNDERSTANDING

3.D

A force exerted on an object can change the momentum of the object.

LEARNING OBJECTIVE

3.D.1.1

Justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. **[SP 4.1]**

3.D.2.1

Justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. **[SP 2.1]**

3.D.2.2

Predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

3.D.1

The change in momentum of an object is a vector in the direction of the net force exerted on the object.

Relevant Equation:

$\vec{p} = m\vec{v}$

3.D.2

The change in momentum of an object occurs over a time interval.

a. The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object).

b. The change in momentum of that object depends on the impulse, which is the product of the average force and the time interval during which the interaction occurred.

Relevant Equation:

$\vec{p} = m\vec{v}$

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SCIENCE PRACTICES

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

LEARNING OBJECTIVE

3.D.2.3

Analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 5.1]**

3.D.2.4

Design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. **[SP 4.2]**

ESSENTIAL KNOWLEDGE

3.D.2

The change in momentum of an object occurs over a time interval.

a. The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object).

b. The change in momentum of that object depends on the impulse, which is the product of the average force and the time interval during which the interaction occurred.

Relevant Equation:

$\vec{p} = m\vec{v}$

TOPIC 5.2

Representations of Changes in Momentum

Required Course Content

ENDURING UNDERSTANDING

4.B

Interactions with other objects or systems can change the total linear momentum of a system.

LEARNING OBJECTIVE

4.B.1.1

Calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). **[SP 1.4, 2.2]**

4.B.1.2

Analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

4.B.1

The change in linear momentum for a constant-mass system is the product of the mass of the system and the change in velocity of the center of mass.

Relevant Equation:

$\vec{p} = m\vec{v}$

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SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

LEARNING OBJECTIVE

4.B.2.1

Apply mathematical routines to calculate the change in momentum of a system by analyzing the average force exerted over a certain time on the system. **[SP 2.2]**

4.B.2.2

Perform an analysis on data presented as a force-time graph and predict the change in momentum of a system. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

4.B.2

The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted.

a. The units for momentum are the same as the units of the area under the curve of a force versus time graph.

b. The change in linear momentum and force are both vectors in the same direction.

Relevant Equations:

$$\vec{p} = m\vec{v}$$

$$\vec{p} = \vec{F}\Delta t$$

TOPIC 5.3

Open and Closed Systems: Momentum

Required Course Content

ENDURING UNDERSTANDING

5.A

Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems.

LEARNING OBJECTIVE

5.A.2.1

Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

5.A.2

For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.

SCIENCE PRACTICES

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 5.4
Conservation of Linear Momentum

Required Course Content

ENDURING UNDERSTANDING

5.D

The linear momentum of a system is conserved.

LEARNING OBJECTIVE

5.D.1.1

Make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]**

5.D.1.2

Apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]**

ESSENTIAL KNOWLEDGE

5.D.1

In a collision between objects, linear momentum is conserved. In an elastic collision, kinetic energy is the same before and after.

a. In a closed system, the linear momentum is constant throughout the collision.

b. In a closed system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision.

Relevant Equations:

$$\vec{p} = m\vec{v}$$

$$K = \frac{1}{2}mv^2$$

SCIENCE PRACTICES

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Scientific Questioning

3.2

The student can refine scientific questions.

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

4.4

The student can evaluate sources of data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

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LEARNING OBJECTIVE

5.D.1.3

Apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]**

5.D.1.4

Design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]**

5.D.1.5

Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

BOUNDARY STATEMENT:

Physics 1 includes a quantitative and qualitative treatment of conservation of momentum in one dimension and a semiquantitative treatment of conservation of momentum in two dimensions. Test items involving solution of simultaneous equations are not included in Physics 1, but items testing whether students can set up the equations properly and can reason about how changing a given mass, speed, or angle would affect other quantities are included.

Physics 1 includes only conceptual understanding of the center of mass motion of a system without the need for calculation of center of mass.

The Physics 1 course includes topics from Enduring Understanding 5.D in the context of mechanical systems.

5.D.2.1

Qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]**

5.D.2

In a collision between objects, linear momentum is conserved. In an inelastic collision, kinetic energy is not the same before and after the collision.

a. In a closed system, the linear momentum is constant throughout the collision.

b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.

Relevant Equations:

$\vec{p} = m\vec{v}$

$K = \frac{1}{2}mv^2$

SCIENCE PRACTICES
(CONT'D)

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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LEARNING OBJECTIVE

5.D.2.2

Plan data-collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. **[SP 4.1, 4.2, 5.1]**

5.D.2.3

Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. **[SP 6.4, 7.2]**

5.D.2.4

Analyze data that verify conservation of momentum in collisions with and without an external frictional force. **[SP 4.1, 4.2, 4.4, 5.1, 5.3]**

5.D.2.5

Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum as the appropriate solution method for an inelastic collision, recognize that there is a common final velocity for the colliding objects in the totally inelastic case, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

5.D.2

In a collision between objects, linear momentum is conserved. In an inelastic collision, kinetic energy is not the same before and after the collision.

a. In a closed system, the linear momentum is constant throughout the collision.

b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.

Relevant Equations:

$\vec{p} = m\vec{v}$

$K = \frac{1}{2}mv^2$

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LEARNING OBJECTIVE

5.D.3.1

Predict the velocity of the center of mass of a system when there is no interaction outside of the system but there is an interaction within the system (i.e., the student simply recognizes that interactions within a system do not affect the center-of-mass motion of the system and is able to determine that there is no external force). **[SP 6.4]**

ESSENTIAL KNOWLEDGE

5.D.3

The velocity of the center of mass of the system cannot be changed by an interaction within the system. [Physics 1 includes no calculations of centers of mass; the equation is not provided until Physics 2. However, without doing calculations, Physics 1 students are expected to be able to locate the center of mass of highly symmetric mass distributions, such as a uniform rod or cube of uniform density, or two spheres of equal mass.]

a. The center of mass of a system depends on the masses and positions of the objects in the system. In an isolated system (a system with no external forces), the velocity of the center of mass does not change.
b. When objects in a system collide, the velocity of the center of mass of the system will not change unless an external force is exerted on the system.
c. Included in Physics 1 is the idea that, where there is both a heavier and lighter mass, the center of mass is closer to the heavier mass. Only a qualitative understanding of this concept is required.

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AP PHYSICS 1

UNIT 6

Simple Harmonic Motion

2–4%
AP EXAM WEIGHTING

~2–5
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 6

Multiple-choice: ~20 questions

Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT 6

2–4% AP EXAM WEIGHTING

~2–5 CLASS PERIODS

Simple Harmonic Motion

BIG IDEA 3

***Force Interactions* INT**

- How does a restoring force differ from a "regular" force?
- How does the presence of restoring forces predict and lead to harmonic motion?
- How does a spring cause an object to oscillate?
- How can oscillations be used to make our lives easier?

BIG IDEA 5

***Conservation* CON**

- How does the law of conservation of energy govern the interactions between objects and systems?
- How can energy stored in a spring be used to create motion?

Unit Overview

In Unit 6, students will continue to use the same tools, techniques, and models that they have been using throughout this course. However, they will now use them to analyze a new type of motion: simple harmonic motion. Although simple harmonic motion is unique, students will learn that even in new situations, the fundamental laws of physics remain the same. Energy bar charts, as well as free-body diagrams, become increasingly important as students work toward determining which model is most appropriate for a given physical situation. Preconceptions—such as the relationship between the amplitude and period of oscillation—will also be addressed to provide students with a more nuanced awareness of simple harmonic motion.

Students are expected to use the content knowledge they gained in the first five units to make and defend claims while also making connections in and across the content topics and big ideas. Because Unit 6 is the first unit in which students possess all the tools of force, energy, and momentum conservation, it's important that teachers scaffold lessons to help them develop a better understanding of each fundamental physics principles as well as its limitations. Throughout this unit, students will be asked to create force, energy, momentum, and position versus time graphs for a single scenario and to make predictions based on their representations. Students will enhance their study of motion when they learn about oscillatory motion in Unit 10.

Preparing for the AP Exam

Some questions on AP Physics 1 Exam require students to identify more than one correct answer. Because these multiple-select questions can easily intimidate students, we highly recommend that they take the time to read the entire prompt. Students who jump right to the answers could be frustrated to find answer choices that are factually correct but do not complete the task. Remember: Students will only get credit if they choose *all* the correct answers.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~2–5 CLASS PERIODS
3.B	**6.1 Period of Simple Harmonic Oscillators**	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.B	**6.2 Energy of a Simple Harmonic Oscillator**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 6.
Review the results in class to identify and address any student misunderstandings.

AVAILABLE RESOURCES FOR UNIT 6:

- Classroom Resources > *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	6.1	**Desktop Experiment Task** Have students determine the spring constant of a spring using (1) known masses and meterstick only and then (2) known masses and stopwatch only.
2	6.1	**Desktop Experiment Task** Have students use a pendulum to measure the acceleration of gravity. Ask them to refine the experiment from single-trial calculation, to taking an average, to making a graph of linearized data.
3	6.1	**Predict and Explain** Make a pendulum bob oscillate with the other end of the string “clamped” between your fingers. While the bob oscillates, pull the string through your fingers so that the string length is shortened. Before doing this, ask students what will happen to the period of the oscillation and the amplitude (measured in degrees), and then explain why the period decreases and the amplitude angle increases.
4	6.2	**Construct an Argument** A cart wiggles on a horizontal spring. A blob of clay is dropped on the cart and sticks (could be when the cart is at the center or at one end). Ask students to explain what happened to the period, total energy, amplitude of motion, and maximum speed?
5	6.2	**Create a Plan** Students choose a song and find its tempo (beats per minute). Students then must build a pendulum so that it swings back and forth on each beat. Students are then given a spring. They must find the spring’s constant and then find the amount of mass necessary to make the spring-mass oscillate on each beat.

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 6.1

Period of Simple Harmonic Oscillators

SCIENCE PRACTICES

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Required Course Content

ENDURING UNDERSTANDING

3.B

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.

LEARNING OBJECTIVE

3.B.3.1

Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. **[SP 6.4, 7.2]**

3.B.3.2

Design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. **[SP 4.2]**

3.B.3.3

Analyze data to identify qualitative and quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion and use those data to determine the value of an unknown. **[SP 2.2, 5.1]**

ESSENTIAL KNOWLEDGE

3.B.3

Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object will undergo a special type of motion called simple harmonic motion. Examples include gravitational force exerted by Earth on a simple pendulum and mass-spring oscillator.

a. For a spring that exerts a linear restoring force, the period of a mass-spring oscillator increases with mass and decreases with spring stiffness.

b. For a simple pendulum, the period increases with the length of the pendulum and decreases with the magnitude of the gravitational field.

c. Minima, maxima, and zeros of position, velocity, and acceleration are features of harmonic motion. Students should be able to calculate force and acceleration for any given displacement for an object oscillating on a spring.

Relevant Equations:

$$T_p = 2\pi\sqrt{\frac{l}{g}}$$

$$T_s = 2\pi\sqrt{\frac{m}{k}}$$

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LEARNING OBJECTIVE

3.B.3.4

Construct a qualitative and/or quantitative explanation of oscillatory behavior given evidence of a restoring force. **[SP 2.2, 6.2]**

ESSENTIAL KNOWLEDGE

3.B.3

Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object will undergo a special type of motion called simple harmonic motion. Examples include gravitational force exerted by Earth on a simple pendulum and mass-spring oscillator.

a. For a spring that exerts a linear restoring force, the period of a mass-spring oscillator increases with mass and decreases with spring stiffness.

b. For a simple pendulum, the period increases with the length of the pendulum and decreases with the magnitude of the gravitational field.

c. Minima, maxima, and zeros of position, velocity, and acceleration are features of harmonic motion. Students should be able to calculate force and acceleration for any given displacement for an object oscillating on a spring.

Relevant Equations:

$$T_p = 2\pi\sqrt{\frac{l}{g}}$$

$$T_s = 2\pi\sqrt{\frac{m}{k}}$$

TOPIC 6.2

Energy of a Simple Harmonic Oscillator

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.2.1

Calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. **[SP 1.4, 2.1]**

ESSENTIAL KNOWLEDGE

5.B.2

A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. [Physics 1 includes mass-spring oscillators and simple pendulums. Physics 2 includes charged objects in electric fields and examining changes in internal energy with changes in configuration.]

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SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.B.3.1 Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]** **5.B.3.2** Make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]** **5.B.3.3** Apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**	**5.B.3** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces. a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system. b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators and objects falling in a gravitational field. c. The change in electric potential in a circuit is the change in potential energy per unit charge. [In Physics 1, only in the context of circuits] *Relevant Equations:* $T_p = 2\pi\sqrt{\frac{l}{g}}$ $T_s = 2\pi\sqrt{\frac{m}{k}}$ $U_s = \frac{1}{2}kx^2$ $\Delta U_g = mg\Delta y$
5.B.4.1 Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **5.B.4.2** Calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**	**5.B.4** The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system. a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy. b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.

AP PHYSICS 1

UNIT 7

Torque and Rotational Motion

10–16%
AP EXAM WEIGHTING

~12–17
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 7

Multiple-choice: ~40 questions

Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT 7

10–16% AP EXAM WEIGHTING

~12–17 CLASS PERIODS

Torque and Rotational Motion

BIG IDEA 3

Force Interactions **INT**

- How does a system at rotational equilibrium compare to a system in translational equilibrium?
- How does the choice of system and rotation point affect the forces that can cause a torque on an object or a system?
- How can balanced forces cause rotation?
- Why does it matter where the door handle is placed?
- Why are long wrenches more effective?

BIG IDEA 4

Change **CHA**

- How can an external net torque change the angular momentum of a system?
- Why is a rotating bicycle wheel more stable than a stationary one?

BIG IDEA 5

Conservation **CON**

- How does the conservation of angular momentum govern interactions between objects and systems?
- Why do planets move faster when they travel closer to the sun?

Unit Overview

Unit 7 completes the study of mechanical physics by introducing students to torque and rotational motion. Although these topics present more complex scenarios, the tools of analysis remain the same: The content and models explored in the first six units of AP Physics 1 set the foundation for Unit 7.

During their study of torque and rotational motion, students will be confronted with different ways of thinking about and modeling forces. As in previous units, it's critical that students are given opportunities to create and use representations and models to make predictions and justify claims. It's equally important that students are comfortable deriving new expressions from fundamental principles to help them make predictions in unfamiliar, applied contexts.

Unit 7 also focuses on the mathematical practice of estimating quantities that can describe natural phenomena. For example, students need to be able to estimate the torque on an object caused by various forces in comparison to other situations. Although this particular science practice doesn't appear often in AP Physics 1, it nonetheless is an important conceptual skill for students to be able to compare estimated values of physical quantities.

Throughout this unit, students will have opportunities to compare and connect their understanding of linear and rotational motion, dynamics, energy, and momentum to make meaning of these concepts as a whole, rather than as distinct and separate units.

Preparing for the AP Exam

Students must be familiar with identifying and analyzing functional relationships, especially with equations that are not found on the equation sheet. It is likely that students will be asked to explain why a new equation—one that they have never seen before—does or does not support a claim. They may also have to briefly address functional dependence in questions. Students will be more prepared for the type of mathematical reasoning required on the AP Physics 1 Exam if they understand and practice making logical mathematical derivations while showing their starting principle and annotating their steps.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~12–17 CLASS PERIODS
3.A	**7.1 Rotational Kinematics**	**1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena.	
3.F	**7.2 Torque and Angular Acceleration**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena.* **2.3** The student can estimate quantities that describe natural phenomena. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods
			~12–17 CLASS PERIODS
4.D	**7.3** Angular Momentum and Torque	**1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.* **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **3.2** The student can refine scientific questions.* **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question.	
5.E	**7.4** Conservation of Angular Momentum	**2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 7.
Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

AVAILABLE RESOURCES FOR UNIT 7:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Conservation Concepts**
- Classroom Resources > **Rotational Motion**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	7.1	**Predict and Explain** Spin a bike wheel (preferably with the tire removed so that it will roll on its metal rims), and release it from rest on a floor or long table. Have students predict what will happen to the wheel's linear velocity (will increase) and its angular velocity (will decrease) as the wheel "peels out." Then explain why this happens using a force diagram.
2	7.2	**Desktop Experiment Task** Have students release a yo-yo from rest, calculate its acceleration from distance and time measurements, and then determine the yo-yo's rotational inertia (requires the yo-yo's mass and the radius at which the string connects to the yo-yo). Next, have them roll the yo-yo down a ramp and use distance and time data to construct a conservation of energy equation that can be solved for the yo-yo's rotational inertia.
3	7.3	**Concept-Oriented Demonstration** Obtain a ring and a disk of equal mass and radius, and load up a low-friction cart with weights to make it the same mass. "Race" the three objects from rest down identical inclines to show students the cart wins, then the disk, and then the ring. Have students explain why, with forces and then with energy.
4	7.3	**Ranking** A wheel rolls down an incline from rest and across a flat surface. Case 1: Tracks are rough enough that there is no slipping. Case 2: Tracks have some friction, but there is slipping. Case 3: Tracks have negligible friction. Have students rank translational kinetic energies at the end, rotational kinetic energies at the end, and total mechanical energies of the wheel at the end as three separate tasks. ($K_{T3} > K_{T2} > K_{T1}$), ($K_{R1} > K_{R2} > K_{R3}$), and ($E_1 = E_3 > E_2$).

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 7.1

Rotational Kinematics

Required Course Content

ENDURING UNDERSTANDING

3.A

All forces share certain common characteristics when considered by observers in inertial reference frames.

LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

3.A.1

An observer in a reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.

a. Displacement, velocity, and acceleration are all vector quantities.

b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values.

Relevant Equations:

$$\vec{v}_{avg} = \frac{\Delta\vec{x}}{\Delta t}$$

$$\vec{a}_{avg} = \frac{\Delta\vec{v}}{\Delta t}$$

c. A choice of reference frame determines the direction and the magnitude of each of these quantities.

d. There are three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects.

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SCIENCE PRACTICES

Modeling

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

LEARNING OBJECTIVE

3.A.1.1

Express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force.

f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. Circular motion is further covered in Unit 3. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$$

$$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$$

g. For rotational motion, there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$\omega^2 = \omega_0^2 + 2\alpha_x(\theta - \theta_0)$$

h. This also includes situations where there is both a radial and tangential acceleration for an object moving in a circular path.

Relevant Equation:

$$a_c = \frac{v^2}{r}$$

For uniform circular motion of radius *r*, *v* is proportional to omega, *ω* (for a given *r*), and proportional to *r* (for a given omega, *ω*). Given a radius *r* and a period of rotation *T*, students derive and apply *v* = (2*πr*)/*T*.

BOUNDARY STATEMENT:

AP Physics 2 has learning objectives under Enduring Understanding 3.A that focus on electric and magnetic forces and other forces arising in the context of interactions introduced in Physics 2, rather than the mechanical systems introduced in Physics 1.

TOPIC 7.2

Torque and Angular Acceleration

Required Course Content

ENDURING UNDERSTANDING

3.F

A force exerted on an object can cause a torque on that object.

LEARNING OBJECTIVE

3.F.1.1

Use representations of the relationship between force and torque. **[SP 1.4]**

3.F.1.2

Compare the torques on an object caused by various forces. **[SP 1.4]**

3.F.1.3

Estimate the torque on an object caused by various forces in comparison with other situations. **[SP 2.3]**

3.F.1.4

Design an experiment and analyze data testing a question about torques in a balanced rigid system. **[SP 4.1, 4.2, 5.1]**

3.F.1.5

Calculate torques on a two-dimensional system in static equilibrium by examining a representation or model (such as a diagram or physical construction). **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

3.F.1

Only the force component perpendicular to the line connecting the axis of rotation and the point of application of the force results in a torque about that axis.

a. The lever arm is the perpendicular distance from the axis of rotation or revolution to the line of application of the force.

b. The magnitude of the torque is the product of the magnitude of the lever arm and the magnitude of the force.

c. The net torque on a balanced system is zero.

Relevant Equations:

$$\tau = r_{\perp} F = rF\sin\theta$$

BOUNDARY STATEMENT:

Quantities such as angular acceleration, velocity, and momentum are defined as vector quantities, but in Physics 1 the determination of "direction" is limited to clockwise and counterclockwise with respect to a given axis of rotation.

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SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

2.3

The student can estimate quantities that describe natural phenomena.

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

SCIENCE PRACTICES *(CONT'D)*

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE

3.F.2.1

Make predictions about the change in the angular velocity about an axis for an object when forces exerted on the object cause a torque about that axis. **[SP 6.4]**

3.F.2.2

Plan data-collection and analysis strategies designed to test the relationship between a torque exerted on an object and the change in angular velocity of that object about an axis. **[SP 4.1, 4.2, 5.1]**

ESSENTIAL KNOWLEDGE

3.F.2

The presence of a net torque along any axis will cause a rigid system to change its rotational motion or an object to change its rotational motion about that axis.

a. Rotational motion can be described in terms of angular displacement, angular velocity, and angular acceleration about a fixed axis.

b. Rotational motion of a point can be related to linear motion of the point using the distance of the point from the axis of rotation.

c. The angular acceleration of an object or a rigid system can be calculated from the net torque and the rotational inertia of the object or rigid system.

Relevant Equations:

$$\tau = r_\perp F = rF\sin\theta$$

$$\alpha = \frac{\sum \tau}{I}$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$$

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LEARNING OBJECTIVE

3.F.3.1

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

3.F.3.2

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

3.F.3.3

Plan data-collection and analysis strategies designed to test the relationship between torques exerted on an object and the change in angular momentum of that object. **[SP 4.1, 4.2, 5.1, 5.3]**

ESSENTIAL KNOWLEDGE

3.F.3

A torque exerted on an object can change the angular momentum of an object.

a. Angular momentum is a vector quantity, with its direction determined by a right-hand rule.

b. The magnitude of angular momentum of a point object about an axis can be calculated by multiplying the perpendicular distance from the axis of rotation to the line of motion by the magnitude of linear momentum.

c. The magnitude of angular momentum of an extended object can also be found by multiplying the rotational inertia by the angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense of what factors affect rotational inertia—for example, why a hoop has more rotational inertia than a puck of the same mass and radius.

d. The change in angular momentum of an object is given by the product of the average torque and the time the torque is exerted.

Relevant Equations:

$L = I\omega$

$\Delta L = \tau \Delta t$

$L = mvr$

TOPIC 7.3

Angular Momentum and Torque

SCIENCE PRACTICES

Modeling

1.2

The student can describe representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Scientific Questioning

3.2

The student can refine scientific questions.

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Required Course Content

ENDURING UNDERSTANDING

4.D

A net torque exerted on a system by other objects or systems will change the angular momentum of the system.

LEARNING OBJECTIVE

4.D.1.1

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

4.D.1.2

Plan data-collection strategies designed to establish that torque, angular velocity, angular acceleration, and angular momentum can be predicted accurately when the variables are treated as being clockwise or counterclockwise with respect to a well-defined axis of rotation, and refine the research question based on the examination of data. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]**

ESSENTIAL KNOWLEDGE

4.D.1

Torque, angular velocity, angular acceleration, and angular momentum are vectors and can be characterized as positive or negative depending on whether they give rise to or correspond to counterclockwise or clockwise rotation with respect to an axis.

Relevant Equations:

$$\tau = r_{\perp}F = rF\sin\theta$$

$$\alpha = \frac{\sum\tau}{I}$$

$$L = I\omega$$

$$\Delta L = \tau\Delta t$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$$

BOUNDARY STATEMENT:

Students do not need to know the right-hand rule. A full dynamic treatment of rolling without slipping—for instance, using forces and torques to find the linear and angular acceleration of a cylinder rolling down a ramp—is not included in Physics 1.

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LEARNING OBJECTIVE

4.D.2.1

Describe a model of a rotational system and use that model to analyze a situation in which angular momentum changes due to interaction with other objects or systems. **[SP 1.2, 1.4]**

4.D.2.2

Plan a data-collection and analysis strategy to determine the change in angular momentum of a system and relate it to interactions with other objects and systems. **[SP 4.2]**

ESSENTIAL KNOWLEDGE

4.D.2

The angular momentum of a system may change due to interactions with other objects or systems.

a. The angular momentum of a system with respect to an axis of rotation is the sum of the angular momenta, with respect to that axis, of the objects that make up the system.

b. The angular momentum of an object about a fixed axis can be found by multiplying the momentum of the particle by the perpendicular distance from the axis to the line of motion of the object.

c. Alternatively, the angular momentum of a system can be found from the product of the system's rotational inertia and its angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation.

Relevant Equations:

$$L = I\omega$$

$$\Delta L = \tau\Delta t$$

$$\tau = r_\perp F = rF\sin\theta$$

Alternatively, the angular momentum of a system can be found from the product of the system's rotational inertia and its angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation.

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LEARNING OBJECTIVE

4.D.3.1

Use appropriate mathematical routines to calculate values for initial or final angular momentum, or change in angular momentum of a system, or average torque or time during which the torque is exerted in analyzing a situation involving torque and angular momentum. **[SP 2.2]**

4.D.3.2

Plan a data-collection strategy designed to test the relationship between the change in angular momentum of a system and the product of the average torque applied to the system and the time interval during which the torque is exerted. **[SP 4.1, 4.2]**

ESSENTIAL KNOWLEDGE

4.D.3

The change in angular momentum is given by the product of the average torque and the time interval during which the torque is exerted.

Relevant Equations:

$L = I\omega$

$\Delta L = \tau \Delta t$

$\tau = r_{\perp} F = rF \sin\theta$

TOPIC 7.4

Conservation of Angular Momentum

Required Course Content

ENDURING UNDERSTANDING

5.E

The angular momentum of a system is conserved.

LEARNING OBJECTIVE

5.E.1.1

Make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. **[SP 6.4, 7.2]**

5.E.1.2

Make calculations of quantities related to the angular momentum of a system when the net external torque on the system is zero. **[SP 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

5.E.1

If the net external torque exerted on the system is zero, the angular momentum of the system does not change.

Relevant Equations:

$L = I\omega$

$\Delta L = \tau \Delta t$

$\tau = r_{\perp} F = rF \sin\theta$

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SCIENCE PRACTICES

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE

5.E.2.1

Describe or calculate the angular momentum and rotational inertia of a system in terms of the locations and velocities of objects that make up the system. Use qualitative reasoning with compound objects and perform calculations with a fixed set of extended objects and point masses. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

5.E.2

The angular momentum of a system is determined by the locations and velocities of the objects that make up the system. The rotational inertia of an object or a system depends on the distribution of mass within the object or system. Changes in the radius of a system or in the distribution of mass within the system result in changes in the system's rotational inertia, and hence in its angular velocity and linear speed for a given angular momentum. Examples include elliptical orbits in an Earth-satellite system. Mathematical expressions for the moments of inertia will be provided where needed. Students will not be expected to know the parallel axis theorem. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation.

Relevant Equation:

$I = mr^2$

AP PHYSICS 1

UNIT 8

Electric Charge and Electric Force

4–6%
AP EXAM WEIGHTING

~3–5
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 8

Multiple-choice: ~15 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT 8

4–6% AP EXAM WEIGHTING

~3–5 CLASS PERIODS

Electric Charge and Electric Force

Unit Overview

Although Unit 8 presents students with physical phenomena that are difficult or impossible to directly observe, the concepts of electric charge and electric force are the cornerstones of the study of electricity and magnetism. As in earlier units, the foundation of this unit includes the study of relationships and change: Students are expected to be able to discuss what happens to force when there is a change in the separation between charges or the magnitude of charges. It's essential for students to be able to use mathematics and mathematical relationships as evidence for claims, to analyze someone else's mathematical derivation, and/or to explain their own mathematical derivation in a narrative.

Throughout this unit, students will also apply and make predictions about conserved quantities, which will be further developed and applied in Unit 9. Helping students practice the skill of constructing scientific explanations of phenomena based on scientific practices should also be a focus of Unit 8, as it helps students readily make comprehensive predictions about new phenomena.

Students will also use familiar representations and models to make predictions and justify claims. These will help students dispel some of the common misconceptions that they may continue to have about forces, such as two charged objects with different net charges applying different magnitude forces on the other object. The content and ideas presented in Unit 8 set a solid foundation for students to be able to investigate and understand both DC circuits, in Unit 9, and the topics of electricity and magnetism, in AP Physics 2.

Preparing for the AP Exam

When using physical laws and fundamental ideas of physics as justification for claims, students must be aware not only of what changed, but also what could happen when a physical scenario is modified. It is therefore recommended that students be provided with opportunities to investigate changes in systems.

Additionally, when writing justifications for claims, it is important to remember that simply referencing an equation, a law, or a physical principle is not enough. For example, stating that one object is going faster than another because of "conservation of energy" is not sufficient to earn credit on the free-response section. Students must clearly and concisely explain the equation, law, or physical principle and how it justifies their claim.

BIG IDEA 1
***Systems* SYS**
- How does electric charge change the way that something interacts with its surroundings?
- How do you decide what to believe about scientific claims?
- How does something we cannot see determine how an object behaves?

BIG IDEA 3
***Force Interactions* INT**
- How do charges exert forces on each other?

BIG IDEA 5
***Conservation* CON**
- How does the conservation of charge help us understand how charged objects behave?
- Why can you stick a balloon on the ceiling, if rubber is an insulator?

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~3–5 CLASS PERIODS
5.A	**8.1** Conservation of Charge	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
1.B	**8.2** Electric Charge	**1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **6.1** The student can justify claims with evidence. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.C	**8.3** Electric Force	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 8.
Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

AVAILABLE RESOURCES FOR UNIT 8:

- Classroom Resources > **The Capacitor as a Bridge from Electrostatics to Circuits**
- Classroom Resources > **Electrostatics**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	8.3	**Concept-Oriented Demonstration** Charge two identical balloons connected to the ceiling by 1 to 2 m long strings. (It may need to be rubbed against a Van de Graaf generator.) As they repel each other and cause their strings to angle, have students make the necessary measurements to be able to calculate the charge on each balloon (assuming they have the same charge).
2	8.3	**Construct an Argument** Object 1 is fixed in place, and object 2 is free to move; both are charged. Have students explain how the velocity and acceleration of object 2 are changing (increasing or decreasing) as object 2 moves toward (or away from) object 1 if both have the same (or different) sign and magnitude of charge.
3	8.3	**Conflicting Contentions** Two charged balloons hang at equal heights from strings attached at the same point on the ceiling. However, balloon 1's string makes a greater angle with the vertical. Student A thinks that balloon 2 has more charge than balloon 1, and Student B thinks that balloon 2 has more mass than balloon 1. Have students discuss the predictions and outline which parts of each argument are correct or incorrect.
4	8.3	**Identify Subtasks** Two identical spheres made of carbon-12 are in space. An equal number of electrons are removed from both spheres so that the spheres remain at rest, with electric and gravitational forces balanced. Have students determine what fraction of the total electrons on each sphere were removed. (Answer: One out of every $5.56 \cdot 10^{17}$ electrons was removed.)
5	8.3	**Predict and Explain** Have students calculate the electric force repelling two protons in a helium nucleus (230.4 N if $r = 10^{-15}$ m), then predict whether it is gravity that holds the nucleus together. Next, have students calculate the gravitational force attracting the protons ($1.86 \cdot 10^{-34}$ N).

Unit Planning Notes

Use the space below to plan your approach to the unit.

SCIENCE PRACTICES

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 8.1

Conservation of Charge

Required Course Content

ENDURING UNDERSTANDING

5.A

Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems.

LEARNING OBJECTIVE

5.A.2.1

Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

5.A.2

For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.

TOPIC 8.2

Electric Charge

Required Course Content

ENDURING UNDERSTANDING

1.B

Electric charge is a property of an object or a system that affects its interactions with other objects or systems containing charge.

LEARNING OBJECTIVE

1.B.1.1

Make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**

1.B.1.2

Make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

1.B.1

Electric charge is conserved. The net charge of a system is equal to the sum of the charges of all the objects in the system.

a. An electrical current is a movement of charge through a conductor.

b. A circuit is a closed loop of electrical current.

Relevant Equation:

$$I \equiv \frac{\Delta q}{\Delta t}$$

BOUNDARY STATEMENT:

Full coverage of electrostatics occurs in Physics 2. A basic introduction to the concepts that there are positive and negative charges, and the electrostatic attraction and repulsion between these charges, is included in Physics 1 as well. Physics 1 treats gravitational fields only; Physics 2 treats electric and magnetic fields.

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SCIENCE PRACTICES

Modeling

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Argumentation

6.1

The student can justify claims with evidence.

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.B.2.1 Construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**	**1.B.2** There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge. a. Like-charged objects and systems repel, and unlike-charged objects and systems attract. *Relevant Equation:* $\left\|F_E\right\| = k\left\|\frac{q_1 q_2}{r^2}\right\|$
1.B.3.1 Challenge the claim that an electric charge smaller than the elementary charge has been isolated. **[SP 1.5, 6.1, 7.2]**	**1.B.3** The smallest observed unit of charge that can be isolated is the electron charge, also known as the elementary charge. a. The magnitude of the elementary charge is equal to 1.6 × 10^{-19} coulombs. b. Electrons have a negative elementary charge; protons have a positive elementary charge of equal magnitude, although the mass of a proton is much larger than the mass of an electron.

TOPIC 8.3

Electric Force

Required Course Content

ENDURING UNDERSTANDING

3.C

At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

LEARNING OBJECTIVE

3.C.2.1

Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges (interactions between collections of electric point charges are not covered in Physics 1 and instead are restricted to Physics 2). **[SP 2.2, 6.4]**

3.C.2.2

Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**

ESSENTIAL KNOWLEDGE

3.C.2

Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.

a. Electric forces dominate the properties of the objects in our everyday experiences. However, the large number of particle interactions that occur make it more convenient to treat everyday forces in terms of nonfundamental forces called contact forces, such as normal force, friction, and tension.

b. Electric forces may be attractive or repulsive, depending on the charges on the objects involved.

Relevant Equations:

$$\left|\vec{F}_E\right| = k\left|\frac{q_1 q_2}{r^2}\right|$$

$$\left|\vec{F}_g\right| = G\frac{m_1 m_2}{r^2}$$

SCIENCE PRACTICES

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

AP PHYSICS 1

UNIT 9

DC Circuits

6–8%
AP EXAM WEIGHTING

~9–12
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 9

Multiple-choice: ~30 questions

Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT
9

6–8% AP EXAM WEIGHTING

~9–12 CLASS PERIODS

DC Circuits

BIG IDEA 1
Systems **SYS**

- How do you decide what to believe about scientific claims?
- How does something we cannot see determine how an object behaves?

BIG IDEA 5
Conservation **CON**

- How do the laws of conservation of charge and energy allow us to light our homes and businesses?
- How does the conservation of charge govern interactions between objects and systems?
- How does the law of conservation of energy govern the interactions between objects and systems?

Unit Overview

In Unit 9, students will draw on their knowledge of electricity and apply it to the conservation of charge in electric circuits. This unit will push students to move beyond mathematically solving for current, resistance, and voltage and will challenge them to make connections between system interactions and the changes that result from these interactions. For example, students must not only be able to calculate the resistance of a light bulb in a circuit; they must also be able to articulate the impact on other bulbs in the circuit if that light bulb is removed.

Throughout the unit, it is essential that students have opportunities to create and use representations and models, especially as evidence to make predictions, justify claims, and overcome any preconceived notions about circuits. It is also important that students develop an understanding of the language used in Unit 8. Correctly using vocabulary terms such as "voltage," "current," and "energy" is essential to accurately describe, analyze, and reason with content presented in this course.

By helping students relate theoretical models of electricity to real circuits, Unit 9 sets the stage for AP Physics C: Electricity and Magnetism, which explores circuits in greater depth.

Preparing for the AP Exam

Throughout their study of physics, students may come to hold common pre- and misconceptions. For example, they may believe that the number of wires, length of wires, and proximity of a light bulb to a battery are relevant to understanding the function of a circuit. Misconceptions can be challenged by coaching students to identify the fundamental physical principle needed to answer the question, which will help them eliminate irrelevant or extraneous information. It is also important, especially in Unit 9, that students use correct vocabulary and terminology when defending claims with evidence. Students can inadvertently miscommunicate their answer by using words incorrectly or not fully understanding their nuances. For example, they should know the difference in the meanings of "voltage," "current," and "energy." Scaffolded instruction in correct vocabulary use and writing clear, concise explanations will help students be more successful on the AP Physics 1 Exam.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods **~9–12** CLASS PERIODS
1.B	**9.1 Definition of a Circuit**	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
1.E	**9.2 Resistivity**	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.	
5.B	**9.3 Ohm's Law, Kirchhoff's Loop Rule (Resistors in Series and Parallel)**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods **~9–12** CLASS PERIODS
5.C	**9.4 Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 9.
Review the results in class to identify and address any student misunderstandings.

UNIT 9 AVAILABLE RESOURCES:

- Classroom Resources > *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	9.2	**Construct an Argument** Ask students to imagine a wire immersed in water with both ends connected to a battery to short the wire and heat the water. Ask, "What heats the water faster: thick or thin wire? Long or short wire?"
2	9.3	**Desktop Experiment** Have students choose an object or a substance that somewhat conducts electricity but is not normally used in a circuit (e.g., cylinder of modeling dough, cup of water). Students determine whether this substance is ohmic using five batteries and a multimeter.
3	9.3	**Diagram and Switch** Student A draws a two- or three-resistor circuit with resistors labeled X, Y, and (maybe) Z. There are also a voltmeter and an ammeter in the circuit, correctly connected (voltmeter is connected in parallel to only one of the resistors). Student A says, "the voltmeter reading needs to increase" (or decrease) and "the ammeter reading needs to decrease" (or increase). It is up to Student B to determine which resistor needs to change (and how: increase or decrease) to make the meters both change in that way.
4	9.3, 9.4	**Ranking** Resistors R_s and r_s are in series with a battery, and R_p and r_p are in parallel with an identical battery, where $R_s = R_p > r_s = r_p$. Have students rank potential difference, current, and power dissipated for all four resistors. (Voltage: $R_p = r_p > R_s > r_s$, Current: $r_p > R_p > R_s = r_s$, Power: $r_p > R_p > R_s > r_s$).

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 9.1

Definition of a Circuit

Required Course Content

ENDURING UNDERSTANDING

1.B

Electric charge is a property of an object or a system that affects its interactions with other objects or systems containing charge.

LEARNING OBJECTIVE

1.B.1.1

Make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**

1.B.1.2

Make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

1.B.1

Electric charge is conserved. The net charge of a system is equal to the sum of the charges of all the objects in the system.

a. An electrical current is a movement of charge through a conductor.

b. A circuit is a closed loop of electrical current.

Relevant Equation:

$$I \equiv \frac{\Delta q}{\Delta t}$$

BOUNDARY STATEMENT:

Full coverage of electrostatics occurs in Physics 2. A basic introduction to the concepts that there are positive and negative charges, and the electrostatic attraction and repulsion between these charges, is included in Physics 1 as well. Physics 1 treats gravitational fields only; Physics 2 treats electric and magnetic fields.

SCIENCE PRACTICES

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 9.2
Resistivity

SCIENCE PRACTICE

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

Required Course Content

ENDURING UNDERSTANDING

1.E

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

LEARNING OBJECTIVE

1.E.2.1

Choose and justify the selection of data needed to determine resistivity for a given material. **[SP 4.1]**

ESSENTIAL KNOWLEDGE

1.E.2

Matter has a property called resistivity.

a. The resistivity of a material depends on its molecular and atomic structure.

b. The resistivity depends on the temperature of the material. Resistivity changes with temperature.

Relevant Equation:

$$R = \frac{\rho l}{A}$$

BOUNDARY STATEMENT:

Knowledge of what causes temperature to affect resistivity is not a part of Physics 1.

TOPIC 9.3

Ohm's Law, Kirchhoff's Loop Rule (Resistors in Series and Parallel)

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.9.1

Construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule). **[SP 1.1, 1.4]**

5.B.9.2

Apply conservation of energy concepts to the design of an experiment that will demonstrate the validity of Kirchhoff's loop rule ($\sum \Delta V = 0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches. **[SP 4.2, 6.4, 7.2]**

5.B.9.3

Apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. **[SP 2.2, 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

5.B.9

Kirchhoff's loop rule describes conservation of energy in electrical circuits. [The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.]

The potential difference across an ideal battery is also referred to as the emf of the battery, represented as ε. [Non-ideal batteries are not covered in Physics 1.]

a. Energy changes in simple electrical circuits are conveniently represented in terms of energy change per charge moving through a battery and a resistor.
b. Since electric potential difference times charge is energy, and energy is conserved, the sum of the potential differences about any closed loop must add to zero.
c. The electric potential difference across a resistor is given by the product of the current and the resistance.
d. The rate at which energy is transferred from a resistor is equal to the product of the electric potential difference across the resistor and the current through the resistor.

Relevant Equations:

$$I = \frac{\Delta V}{R}$$

$$P = I\Delta V$$

SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

TOPIC 9.4

Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)

Required Course Content

ENDURING UNDERSTANDING

5.C

The electric charge of a system is conserved.

LEARNING OBJECTIVE

5.C.3.1

Apply conservation of electric charge (Kirchhoff's junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if configurations of the circuit are changed. **[SP 6.4, 7.2]**

5.C.3.2

Design an investigation of an electrical circuit with one or more resistors in which evidence of conservation of electric charge can be collected and analyzed. **[SP 4.1, 4.2, 5.1]**

5.C.3.3

Use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or branches of the circuit. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

5.C.3

Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Since charge is conserved, current must be conserved at each junction in the circuit. Examples include circuits that combine resistors in series and parallel. [Physics 1 covers circuits with resistors in series, with at most one parallel branch, one battery only. Physics 2 includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]

Relevant Equations:

$$I \equiv \frac{\Delta q}{\Delta t}$$

$$I = \frac{\Delta V}{R}$$

$$P = I\Delta V$$

$$R_s = \sum_i R_i$$

$$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$$

AP PHYSICS 1

UNIT 10

Mechanical Waves and Sound

12–16%
AP EXAM WEIGHTING

~11–14
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Personal Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Personal Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Personal Progress Check 10

Multiple-choice: ~30 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT
10

12–16% AP EXAM WEIGHTING

~11–14 CLASS PERIODS

Mechanical Waves and Sound

BIG IDEA 6
Waves **WAV**

- How can data be used to help us create models of phenomena we see around us?
- Why does a police siren sound different when it is moving toward you than when it is moving away from you?
- What happens when two waves meet?
- How is resonance responsible for the Tacoma Narrows Bridge collapse?
- How is sound produced?

Unit Overview

In Unit 10, students will move away from the main themes of the previous units and learn about mechanical waves. Although concepts like oscillation, energy, and motion carry over into the study of waves, students will be introduced to new tools to communicate scientific phenomena and solve scientific models. Standing wave models, for example, are applied in Unit 10 to support a more in-depth knowledge of musical instruments and sounds.

Because knowledge of mechanical waves is essential for understanding a wide range of physical phenomena (including light and the wave properties of matter), students will have several opportunities in Unit 10 to connect and relate knowledge across various scales, concepts, and representations. Being able to identify and describe the relationships between physical quantities and use these relationships as justification for claims are equally essential.

Although its content remains distinct from earlier units, Unit 10 presents concepts that will help students succeed in later physics courses. Students who take AP Physics 2 will further investigate the ideas presented in Unit 10 through their additional study of mechanical waves.

Preparing for the AP Exam

On the exam, students must be able use representations and models to analyze situations. Students often struggle with questions that present a model that is different from the models they studied in class (e.g., introducing air resistance or a string with mass).
The introduction of a “real-life” scenario often leads students to misinterpret the problem and, as a result, not defend a claim correctly. Ensure that students understand that the models we use to explain and analyze can change depending on the physical scenario. Students need to be prepared to analyze the given model and not revert to a model studied in class.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~11–14 CLASS PERIODS
6.A	**10.1** Properties of Waves	**1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.* **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.* **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
6.B	**10.2** Periodic Waves	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~11–14 CLASS PERIODS
6.D	**10.3** Interference and Superposition (Waves in Tubes and on Strings)	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain.* **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain.* **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **3.2** The student can refine scientific questions.* **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.* **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.2** The student can refine observations and measurements based on data analysis. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.1** The student can justify claims with evidence. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	

Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 10. Review the results in class to identify and address any student misunderstandings.

*Indicates a science practice not assessed with its paired topic on this unit's Personal Progress Check.

UNIT 10 AVAILABLE RESOURCES:

- Essential Course Materials > *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 173 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	10.2	**Desktop Experiment Task** Have students use long springs to create a standing wave. The students make measurements necessary to find the wave speed (wavelength and period data) and the maximum speed attained at an antinode point (amplitude and period data). Students then calculate the wave speed and maximum "particle speed" and see that they are different.
2	10.2	**Write and Switch** Student A chooses one quantity (frequency, wavelength, wave speed) that stays constant, and a second that either increases or decreases. Student B must state what the third quantity does (increase or decrease) and then describe a situation where a wave undergoes the changes that A prescribed.
3	10.3	**Create a Plan** Students are given several glass bottles. The students choose a song, research its sheet music, fill the bottles with amounts of water calculated to cause the bottles to resonate at the different tones of the song, and then play the song with the bottles.
4	10.3	**Desktop Experiment Task** Have students blow perpendicularly across a straw while a tone-detecting app on a smartphone is listening. The app registers the fundamental frequency of the standing wave in the straw; students use this and the straw length to calculate the speed of sound. Cut off lengths of straw and repeat, linearizing frequency and wavelength to get the speed of sound.
5	10.3	**Four-Square Problem Solving** A pipe 2 m long is in a room where the speed of sound in the air is 343 m/s. Square 1: Students draw the first three harmonics if the pipe is open and calculate the harmonic frequencies. Square 2: Students draw the first three harmonics if the pipe is closed and calculate the frequencies. Square 3: Students plot on a number line the first three open frequencies and the first three closed frequencies with different symbols. Square 4: Students describe the pattern on the number line.

Unit Planning Notes

Use the space below to plan your approach to the unit.

TOPIC 10.1

Properties of Waves

Required Course Content

ENDURING UNDERSTANDING

6.A

A wave is a traveling disturbance that transfers energy and momentum.

LEARNING OBJECTIVE

6.A.1.1

Use a visual representation to construct an explanation of the distinction between transverse and longitudinal waves by focusing on the vibration that generates the wave. **[SP 6.2]**

6.A.1.2

Describe representations of transverse and longitudinal waves. **[SP 1.2]**

ESSENTIAL KNOWLEDGE

6.A.1

Waves can propagate via different oscillation modes such as transverse and longitudinal.

a. Mechanical waves can be either transverse or longitudinal. Examples include waves on a stretched string and sound waves.

b. This includes, as part of the mechanism of "propagation," the idea that the speed of a wave depends only on properties of the medium.

c. The propagation of sound waves included in this EK includes the idea that the traveling disturbance consists of pressure variations coupled to displacement variations.

d. This applies to both periodic waves and to wave pulses.

BOUNDARY STATEMENT:

Physics 1 treats mechanical waves only. Mathematical modeling of waves using sines or cosines is included in Physics 2. Superposition of no more than two wave pulses and properties of standing waves is evaluated in Physics 1.

Interference is revisited in Physics 2, where two-source interference and diffraction may be demonstrated with mechanical waves, leading to the development of these concepts in the context of electromagnetic waves, the focus of Physics 2.

SCIENCE PRACTICES

Modeling

1.2

The student can describe representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Argumentation

6.2

The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.A.2.1 Describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. **[SP 6.4, 7.2]**	**6.A.2** For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples include light traveling through a vacuum and sound not traveling through a vacuum. **BOUNDARY STATEMENT:** *Electromagnetic waves are not tested in Physics 1. This applies to both periodic waves and wave pulses.*
6.A.3.1 Use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. **[SP 1.4]**	**6.A.3** The amplitude is the maximum displacement of a wave from its equilibrium value. a. The amplitude is the maximum displacement from equilibrium of the wave. A sound wave may be represented by either the pressure or the displacement of atoms or molecules. This covers both periodic waves and wave pulses. b. The pressure amplitude of a sound wave is the maximum difference between local pressure and atmospheric pressure.
6.A.4.1 Explain and/or predict qualitatively how the energy carried by a sound wave relates to the amplitude of the wave and/or apply this concept to a real-world example. **[SP 6.4]**	**6.A.4** Classically, the energy carried by a wave depends on and increases with amplitude. Examples include sound waves. a. Higher amplitude refers to both greater pressure variations and greater displacement variations. b. Examples include both periodic waves and wave pulses.

TOPIC 10.2

Periodic Waves

Required Course Content

ENDURING UNDERSTANDING

6.B

A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.B.1.1 Use a graphical representation of a periodic mechanical wave (position versus time) to determine the period and frequency of the wave and describe how a change in the frequency would modify features of the representation. **[SP 1.4, 2.2]**	**6.B.1** For a periodic wave, the period is the repeat time of the wave. The frequency is the number of repetitions of the wave per unit time. a. In a periodic sound wave, pressure variations and displacement variations are both present and with the same frequency. *Relevant Equation:* $T = \frac{1}{f}$
6.B.2.1 Use a visual representation of a periodic mechanical wave to determine the wavelength of the wave. **[SP 1.4]**	**6.B.2** For a periodic wave, the wavelength is the repeat distance of the wave.
6.B.4.1 Design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. **[SP 4.2, 5.1, 7.2]**	**6.B.4** For a periodic wave, wavelength is the ratio of speed over frequency. *Relevant Equation:* $\lambda = \frac{v}{f}$

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SCIENCE PRACTICES

Modeling

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Mathematical Routines

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Experimental Method

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Making Connections

7.2

The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

LEARNING OBJECTIVE

6.B.5.1

Create or use a wave front diagram to demonstrate or interpret qualitatively the observed frequency of a wave, dependent on relative motions of source and observer. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

6.B.5

The observed frequency of a wave depends on the relative motion of source and observer. This is a qualitative treatment only.

TOPIC 10.3

Interference and Superposition (Waves in Tubes and on Strings)

Required Course Content

ENDURING UNDERSTANDING

6.D

Interference and superposition lead to standing waves and beats.

LEARNING OBJECTIVE

6.D.1.1

Use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. **[SP 1.1, 1.4]**

6.D.1.2

Design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for wave pulses or standing waves). **[SP 4.2, 5.1]**

6.D.1.3

Design a plan for collecting data to quantify the amplitude variations when two or more traveling waves or wave pulses interact in a given medium. **[SP 4.2]**

ESSENTIAL KNOWLEDGE

6.D.1

Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition.

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SCIENCE PRACTICES

Modeling

1.1

The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.2

The student can describe representations and models of natural or man-made phenomena and systems in the domain.

1.4

The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

1.5

The student can re-express key elements of natural phenomena across multiple representations in the domain.

Mathematical Routines

2.1

The student can justify the selection of a mathematical routine to solve problems.

2.2

The student can apply mathematical routines to quantities that describe natural phenomena.

Scientific Questioning

3.2

The student can refine scientific questions.

SCIENCE PRACTICES *(CONT'D)*

Experimental Method

4.1

The student can justify the selection of the kind of data needed to answer a particular scientific question.

4.2

The student can design a plan for collecting data to answer a particular scientific question.

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.2

The student can refine observations and measurements based on data analysis.

5.3

The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Argumentation

6.1

The student can justify claims with evidence.

6.4

The student can make claims and predictions about natural phenomena based on scientific theories and models.

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.D.2.1 Analyze data or observations or evaluate evidence of the interaction of two or more traveling waves in one or two dimensions (i.e., circular wave fronts) to evaluate the variations in resultant amplitudes. **[SP 5.1]**	**6.D.2** Two or more traveling waves can interact in such a way as to produce amplitude variations in the resultant wave.
6.D.3.1 Refine a scientific question related to standing waves and design a detailed plan for the experiment that can be conducted to examine the phenomenon qualitatively or quantitatively. **[SP 2.1, 3.2, 4.2]** **6.D.3.2** Predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. **[SP 6.4]** **6.D.3.3** Plan data-collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared with the prediction, explain any discrepancy, and, if necessary, revise the relationship among variables responsible for establishing standing waves on a string or in a column of air. **[SP 3.2, 4.1,5.1, 5.2, 5.3]** **6.D.3.4** Describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. **[SP 1.2]**	**6.D.3** Standing waves are the result of the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. Examples include waves on a fixed length of string and sound waves in both closed and open tubes. a. Reflection of waves and wave pulses, even if a standing wave is not created, is covered in Physics 1. b. For standing sound waves, pressure nodes correspond to displacement antinodes, and vice versa. For example, the open end of a tube is a pressure node because the pressure equalizes with the surrounding air pressure and therefore does not oscillate. The closed end of a tube is a displacement node because the air adjacent to the closed end is blocked from oscillating.

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LEARNING OBJECTIVE

6.D.4.1

Challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source, regardless of the size of the region. **[SP 1.5, 6.1]**

6.D.4.2

Calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined and calculate numerical values of wavelengths and frequencies. Examples include musical instruments. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

6.D.4

The possible wavelengths of a standing wave are determined by the size of the region to which it is confined.

a. A standing wave with zero amplitude at both ends can only have certain wavelengths. Examples include fundamental frequencies and harmonics.

b. Other boundary conditions or other region sizes will result in different sets of possible wavelengths.

c. The term first harmonic refers to the standing waves corresponding to the fundamental frequency (i.e., the lowest frequency corresponding to a standing wave). The second harmonic is the standing wave corresponding to the second lowest frequency that generates a standing wave in the given scenario.

d. Resonance is another term for standing sound wave.

Relevant Equations:

$$\lambda = \frac{v}{f}$$

$$T = \frac{1}{f}$$

6.D.5.1

Use a visual representation to explain how waves of slightly different frequency give rise to the phenomenon of beats. **[SP 1.2]**

6.D.5

Beats arise from the addition of waves of slightly different frequency.

a. Because of the different frequencies, the two waves are sometimes in phase and sometimes out of phase. The resulting regularly spaced amplitude changes are called beats. Examples include the tuning of an instrument.

b. The beat frequency is the difference in frequency between the two waves.

c. In Physics 1, only qualitative understanding of EK 6.D.5 is necessary.

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