AP® Physics 1: Algebra-Based

Course Planning and Pacing Guide

Dolores Gende
Parish Episcopal School
Dallas, Texas

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The College Board strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial and socioeconomic groups that have been traditionally underserved. Schools should make every effort to ensure their AP classes reflect the diversity of their student population. The College Board also believes that all students should have access to academically challenging course work before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

Welcome to the AP® Physics Course Planning and Pacing Guides

This guide is one of four course planning and pacing guides designed for AP® Physics 1 teachers. Each provides an example of how to design instruction for the AP course based on the author's teaching context (e.g., demographics, schedule, school type, setting).

These course planning and pacing guides highlight how the components of the *AP Physics Curriculum Framework* — the learning objectives, conceptual understandings, and science practices — are addressed in the course. Each guide also provides valuable suggestions for teaching the course, including the selection of resources, instructional activities such as laboratory investigations, and formative and summative assessments. The authors have offered insight into the *why* and *how* behind their instructional choices — displayed in boxes along the right side of the individual unit plans — to aid in course planning for AP Physics teachers.

The primary purpose of these comprehensive guides is to model approaches for planning and pacing curriculum throughout the school year. However, they can also help with syllabus development when used in conjunction with the resources created to support the AP Course Audit: the Syllabus Development Guide and the four Annotated Sample Syllabi. These resources include samples of evidence and illustrate a variety of strategies for meeting curricular requirements.

Contents

Instructional Setting

Parish Episcopal School
Dallas, Texas

School	Parish Episcopal School is an independent, coeducational school for students in pre-K through 12th grade.
Student population	Total enrollment is about 1,100 students. Student demographics are as follows: • 85 percent Caucasian • 7 percent Hispanic • 5 percent Asian • 3 percent African American Typically, all seniors are accepted into and choose to attend a four-year college or university.
Instructional time	The school year begins the last week of August and has 180 instructional days. Classes meet for 85 minutes on a modified block schedule (every other day).
Student preparation	All students take Physics in the ninth grade, and two levels are offered: College Prep and Honors Physics. AP Physics 1 is offered through open enrollment to juniors and seniors. The students enrolled in the course have completed algebra courses and are expected to be proficient in solving linear equations, working with ratios and proportions, and using basic trigonometry.
Primary planning resources	Etkina, Eugenia, Michael Gentile, and Alan Van Heuvelen. *College Physics.* San Francisco: Pearson, 2014. *See also the AP edition.* Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach*. 2nd ed., AP® ed. Boston: Pearson, 2012. Christian, Wolfgang, and Mario Belloni. *Physlet® Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics.* Upper Saddle River, NJ: Prentice Hall, 2004. Hieggelke, Curtis, David Maloney, and Stephen Kanim. *Newtonian Tasks Inspired by Physics Education Research: nTIPERs.* Upper Saddle River, NJ: Pearson, 2012. Hieggelke, Curtis, David Maloney, Thomas O'Kuma, and Stephen Kanim. *E&M TIPERs: Electricity & Magnetism Tasks*. Upper Saddle River, NJ: Pearson, 2006.

Overview of the Course

In my AP Physics 1 course, I use inquiry-based instructional strategies that focus on experimentation to develop students' conceptual understanding of physics principles. The students begin studying a topic by making observations and discovering patterns of natural phenomena. The next steps involve developing, testing, and applying models. Throughout the course, the students construct and use multiple representations of physical processes, solve multistep problems, design investigations, and reflect on knowledge construction using self-assessment rubrics.

In the course, I emphasize the three components of scientific argumentation. The first element is the *claim*, which is the response to a prediction. A claim provides an explanation for why or how something happens in a laboratory investigation. The second component is the *evidence*, which supports the claim and consists of the analysis of the data collected during the investigation. The third component consists of *questioning*, in which students examine and defend one another's claims. I provide explicit instruction in posing meaningful questions that clarify and probe assumptions, implications, and consequences. As a result of this emphasis on the scientific argumentation process, students are able to revise their claims and make revisions as appropriate.

Laboratory Investigations

All laboratory investigations in my AP Physics 1 course are designed by the students. Some labs focus on investigating a physical phenomenon without having expectations of the outcomes. In other experiments, the students have expectations of the outcomes based on concepts constructed from prior experiences. In application experiments, the students use acquired physics principles to address practical problems. Lab investigations account for a minimum of 25 percent of the instructional time in the course.

Students report all investigations in a laboratory journal, recording their observations, data, and data analyses. Data analyses include identification of the sources and effects of experimental uncertainty, calculations, results and conclusions, and suggestions for further refinement of the experiment as appropriate.

Problem-Solving Strategy

I guide students to learn and practice an explicit problem-solving strategy that involves three major steps:

1. Prepare
   - Identify each physics principle that pertains to the situation and write it down using an acronym (such as *N2L* for Newton's second law).
   - Include a physical representation in the form of a sketch and/or a free-body diagram or graph.
   - Identify the given quantities and the unknowns.
2. Solve
   - Write the mathematical representations and/or equations needed, and use these to solve the problem.
3. Evaluate
   - Assess whether the answer is reasonable (through estimation of the answer or order of magnitude, unit analysis, etc.).

Graphing

Many of the instructional activities and assessments in my AP Physics 1 course require students to apply both basic and advanced graphing skills. Basic graphing skills involve correct labeling of a graph, including the scale and axes. Advanced graphing skills include the derivation of relationships from a graph and the physical interpretation of graphs through the analysis of slopes, areas under the curve, and intercepts, as well as through the linearization of functions.

(continued)

Homework Assignments

I design homework assignments to provide a careful balance between qualitative and quantitative elements. I also develop assignments based on feedback about student understanding, provided by formative assessments.

Homework assignments often include problems from *College Physics* (Etkina, Gentile, and Van Heuvelen), Physlet-based exercises, nTIPERS, and interactive simulation resources. This guide includes the specific Physlet exercises and nTipers assigned to the students.

Formative and Summative Assessments

I incorporate formative assessment into every class with the use of tools and methods including a classroom response system (such as Socrative), whiteboards, and class discussion. This allows for immediate feedback for both the student and me. Throughout this guide, I describe a variety of specific formative assessment strategies and activities. The students also complete a self-assessment at the end of each unit of instruction, which provides me with valuable feedback.

Summative assessments in my AP Physics 1 course include unit tests, consisting of conceptual questions and application problems, and lab practicums. Specific details about summative assessments can be found within each unit of this guide.

Technology

I encourage students to use probeware technology in data acquisition for lab investigations. In the classroom, students use graphing calculators and laptops for interactive simulations and Physlet-based exercises.

NOTE: Look for Dolores Gende's course planning and pacing guide for Physics 2, available from the College Board website beginning in early 2014. The two course planning and pacing guides by this author present a unified approach to teaching the Physics 1 and 2 courses over two years.

Kinematics in One and Two Dimensions

Laboratory Investigations:

- Meeting Point Investigation
- Match the Graph Investigation
- Free-Fall Investigation
- Vector Addition Investigation
- Shoot the Target Investigation
- Chase Scenario (Lab Practicum)

Estimated Time:

4 Weeks

Guiding Questions: ▼ How can the motion of an object moving at constant velocity be described and represented? ▼ How can the motion of an object that is accelerating be described and represented? ▼ What information can be gathered from motion graphs? ▼ What are the characteristics of the motion of a projectile launched at an angle?

Learning Objectives	Materials	Instructional Activities and Assessments
Express the motion of an object using narrative, mathematical, and graphical representations. [LO 3.A.1.1, SP 1.5, SP 2.1, SP 2.2] Design an experimental investigation of the motion of an object. [LO 3.A.1.2, SP 4.2] Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. [LO 3.A.1.3, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 1: “Kinematics: Motion in One Dimension” Knight, Jones, and Field, Chapter 2: “Motion in One Dimension” Christian and Belloni, Illustration 2.1, Problem 2.1 **Web** Gende, “Graphical Analysis of Motion: Kinematics” **Supplies** Battery-operated cars, stopwatch, metersticks, digital camera (only if students are performing video analysis)	**Instructional Activity: Meeting Point Investigation** In pairs, students develop a way to predict where two battery-powered cars will collide if they are released from opposite ends of the lab table at different times. Students collect data and then make and test their predictions. In their lab journals, students include multiple representations of their investigation that validate their prediction. These include verbal descriptions, motion diagrams, graphical analyses, and equations.

An approach that helps students develop conceptual understanding in kinematics is the use of multiple representations that include both qualitative and quantitative representations. It is best to start with qualitative descriptions of motion and then move on to quantitative representations.

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Express the motion of an object using narrative, mathematical, and graphical representations. [LO 3.A.1.1, SP 1.5, SP 2.1, SP 2.2] Design an experimental investigation of the motion of an object. [LO 3.A.1.2, SP 4.2] Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. [LO 3.A.1.3, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 1: "Kinematics: Motion in One Dimension" Knight, Jones, and Field, Chapter 2: "Motion in One Dimension" **Supplies** Two table-tennis balls, motion detector or stopwatch, meterstick	**Instructional Activity: Free-Fall Investigation** Students working in teams of three or four design and implement an experiment to determine and compare the acceleration of two objects that are dropped simultaneously.

This activity helps students develop a better understanding of the following topics, which many students find confusing:

- *Instantaneous quantities (e.g. velocity and acceleration)*
- *Meaning of positive and negative signs for velocity and acceleration*
- *Average velocity*

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Learning Objectives	Materials	Instructional Activities and Assessments
Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1]	Etkina, Gentile, and Van Heuvelen, Chapter 1: "Kinematics: Motion in One Dimension" Knight, Jones, and Field, Chapter 2: "Motion in One Dimension" **Supplies** Commercial force table set (force table, pulleys, string, set of slotted masses)	**Instructional Activity: Vector Addition Investigation** Students work in teams of three to design and implement an investigation in which they use a force table set to determine the value of a resultant of several vectors, and then compare that value to the values obtained through graphical and analytical methods.
Express the motion of an object using narrative, mathematical, and graphical representations. [LO 3.A.1.1, SP 1.5, SP 2.1, SP 2.2] Design an experimental investigation of the motion of an object. [LO 3.A.1.2, SP 4.2] Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. [LO 3.A.1.3, SP 5.1, SP 2.1, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 1: "Kinematics: Motion in One Dimension" and Chapter 2: "Newtonian Mechanics" Knight, Jones, and Field, Chapter 3: "Vectors and Motion in Two Dimensions" Hieggelke, Maloney, and Kanim, NTipers nT4B-WWT4, nT4E-CCT15, nT4E-QRT16, nT4E-QRT20, and nT4E-QRT21 **Supplies** Projectile launcher with attachment, two steel balls	**Instructional Activity: Dropped Ball Versus Shot Ball** This teacher-led demonstration illustrates the independence of horizontal and vertical components of motion. I use an attachment to the projectile launcher that simultaneously drops one ball while giving the other a horizontal velocity. I ask the students which ball will hit the floor first. This demo works better when the balls hit a hard surface so that there is a simultaneous sound as the balls hit the floor.

If a commercial force table is not available, students can use a setup with spring scales over a printed 360° protractor.

While conducting demos, I always ask my students to predict what will happen and to explain their reasoning. Predictions vary among the groups, so I take a poll and ask for a final vote before doing the actual demonstration.

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Express the motion of an object using narrative, mathematical, and graphical representations. [LO 3.A.1.1, SP 1.5, SP 2.1, SP 2.2] Design an experimental investigation of the motion of an object. [LO 3.A.1.2, SP 4.2] Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. [LO 3.A.1.3, SP 5.1]	**Supplies** Projectile launcher, projectile, meterstick	**Instructional Activity: Shoot the Target Investigation** Given a projectile launcher, a projectile, and a meterstick, students design an experiment to determine the initial velocity of a projectile and the angle at which the maximum range can be attained. As a challenge, the students are asked to predict where the projectile will land.
Express the motion of an object using narrative, mathematical, and graphical representations. [LO 3.A.1.1, SP 1.5, SP 2.1, SP 2.2] Design an experimental investigation of the motion of an object. [LO 3.A.1.2, SP 4.2] Analyze experimental data describing the motion of an object and express the results of the analysis using narrative, mathematical, and graphical representations. [LO 3.A.1.3, SP 5.1]	**Supplies** Battery-powered cart, fan cart, digital camera, Logger *Pro* (video analysis software)	**Summative Assessment: Chase Scenario (Lab Practicum)** Students use a battery-powered cart and a fan cart to recreate a chase scenario (police–thief) to predict the position where the "thief" will be caught. Students use a digital camera to record the simulation. Their data analysis includes qualitative and quantitative interpretation of motion graphs, calculations of slopes (tangent of an x-versus-t graph and a v-versus-t graph), and calculations of areas under the curve (v-versus-t graph and a-versus-t graph). The lab also includes calculations of the acceleration and final velocity of the "police." The students work collaboratively to conduct their investigation but produce an individual formal report. An additional benefit of this practicum is having students engaged in the application of physics in a real-world scenario.

During the activity, I provide feedback to students based on their initial results and how they interact and contribute to their team's learning. For those groups that demonstrate a lack of understanding, I guide them with appropriate questions. I want my students to be able to uncover any misunderstanding they might have through further scientific questioning rather than just asking for the "right" answers.

Students often confuse horizontal and vertical components when solving problems. A useful way to organize the information is to create separate tables for each component. Students should be aware that the "time" variable is the same for both components.

This lab practicum is the unit test. It incorporates elements of conceptual knowledge of constant velocity and accelerated motion as well as the procedural knowledge needed to analyze a physical situation and design a plan to collect data to make a prediction. The assessment addresses these guiding questions:

- *How can the motion of an object that is accelerating be described and represented?*
- *What information can be gathered from motion graphs?*

Dynamics

Laboratory Investigations:

- Inertial and Gravitational Mass Investigation
- Forces Investigation
- Static Equilibrium Investigation
- Newton's Second Law Investigation
- Coefficient of Friction Investigation
- Atwood's Machine Investigation

Estimated Time:

5 Weeks

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
Design an experiment for collecting data to determine the relationship between the net force exerted on an object, its inertial mass, and its acceleration. [LO 1.C.1.1, SP 4.2] Design a plan for collecting data to measure gravitational mass and to measure inertial mass, and to distinguish between the two experiments. [LO 1.C.1.3, SP 4.2]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" **Web** "Inertial vs Gravitational Mass" **Supplies** Torsional balance, triple-beam balance, set of masses, stopwatch	**Instructional Activity: Inertial and Gravitational Mass Investigation** Students working in pairs design and implement an investigation to determine the difference (if any) between inertial mass and gravitational mass.
Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1] Challenge a claim that an object can exert a force on itself. [LO 3.A.3.2, SP 6.1] 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. [LO 2.B.1.1, SP 2.2, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" **Supplies** Assorted materials (balls, books, carts, string), triple-beam balance, spring scales	**Instructional Activity: Forces Investigation** The first part of this activity consists of an observational lab. The students work in pairs to create situations using a variety of materials (balls, books, carts, string) and learn to construct free-body diagrams for those situations. The students use whiteboards to draw their free-body diagrams. The pairs take turns presenting their board to the rest of the class. Each pair displays their diagrams and briefly explains their thinking. I encourage the students to challenge each other's claims and support their answers with evidence (scientific argumentation). The second part of the lab includes a quantitative component, as the students calculate the value of the gravitational force on various objects. The students then determine the values of other forces, such as the normal force.

Students learn the difference between a static measurement and a dynamic measurement. The outcome of their investigation should be that inertial mass and gravitational mass are equal to each other, and the equivalence of these two masses is why all objects fall at the same rate on Earth.

Some students have a tendency to draw extraneous forces on a free-body diagram. It is important to be able to determine the agent of the force involved in the interaction. If the agent cannot be identified, then the force does not exist.

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.A.3.1, SP 6.4, SP 7.2] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1] 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. [LO 3.B.1.2, SP 4.2, SP 5.1] Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [LO 3.B.2.1, SP 1.1, SP 1.4, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" and Chapter 5: "Applying Newton's Laws" Christian and Belloni, Illustrations 4.1 and 4.2, Problem 4.1 Hieggelke, Maloney, and Kanim, NTipers nT5G-CCT76, nT5G-CT80, nT5G-CT81, and nT5G-CT82 **Web** "Bowling Ball Grand Prix" **Supplies** Bowling ball, broom, masking tape to mark the track	**Instructional Activity: Inertia Broom Ball** Students participate in a relay race by hitting a bowling ball with a broom through a clearly marked path. This activity allows students to focus on the kinesthetic experience of inertia.
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. [LO 3.A.3.1, SP 6.4, SP 7.2] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" and Chapter 5: "Applying Newton's Laws"	**Instructional Activity: Inertia Demonstrations** Students work with a partner to conduct inertia demonstrations for the class. Each demonstration should include a clear explanation of how Newton's first law applies. Examples are the tablecloth trick, the penny-on-a-hoop drop, the egg drop into a glass, pulling a dollar bill from between two bottles, sticking a straw through a potato, etc.

Students often believe that motion requires a force. The relay race activity asks the students to describe the motion of the ball at specific points along the path, helping to clarify the relationship between force and motion. Students will be able to clearly articulate Newton's first law.

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The goal of this lab is for the students to determine an operational definition of Newton's second law as

$$\vec{a} = \frac{\Sigma\vec{F}}{m}.$$

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.A.3.1, SP 6.4, SP 7.2] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 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. [LO 3.B.1.1, SP 6.4, SP 7.2] Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [LO 3.B.2.1, SP 1.1, SP 1.4, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 5: "Applying Newton's Laws" **Web** "Forces in 1 Dimension" "Ramp: Forces and Motion"	**Formative Assessment: Simulation Exercises** Working in pairs, students make predictions and/or perform calculations based on scenarios presented in the simulations. They then run the simulations to check their answers. For "Forces in 1 Dimension," students choose the settings for a scenario in which a force is applied to an object. They draw a free-body diagram of the forces acting on the object and predict the corresponding position, velocity, and acceleration graphs. They then check their predictions using the simulation. For "Ramp: Forces and Motion," students choose the settings for a scenario involving an object on an incline. They calculate the net force on the object and use the simulation to check their calculation.
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.A.3.1, SP 6.4, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 5: "Applying Newton's Laws" Hieggelke, Maloney, and Kanim, NTipers nT5C-WWT33, nT5C-TT37, nT5G-CT66, and nT5G-LMCT88	**Formative Assessment: "What, If Anything, Is Wrong?"** Students analyze a statement or a diagram of a physical situation to determine if it is correct. For example, students might be given a scenario and shown a corresponding free-body diagram that is either correctly or incorrectly drawn. Students must either explain why the statement or diagram is correct, or they must identify the error and explain how to fix it.

Students often make simple errors in determining the components of the gravitational force in inclined plane problems. They tend to assume that the y-component always corresponds with the sine of the angle (and x with the cosine). Using the ramp simulation helps students visualize the forces with respect to the angle of the incline. During the activity, I circulate among the pairs and provide guidance as needed. After the activity, I clarify any misunderstandings and/or answer questions.

I project the task on the whiteboard so that students can write directly on the task, and I solicit volunteers to attempt a solution. I then engage the class in a discussion about the proposed solutions and use guiding questions to help the class reach consensus about the answers. I assist students who struggle to reach the correct solution.

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Make claims about various contact forces between objects based on the microscopic cause of those forces. [LO 3.C.4.1, SP 6.1] Explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. [LO 3.C.4.2, SP 6.2] 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. [LO 3.B.1.2, SP 4.2, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 5: "Applying Newton's Laws" Christian and Belloni, Problems 5.1, 5.2, 5.3, and 5.7 Hieggelke, Maloney, and Kanim, NTipers nT5H-RT93 and nT5H-LMCT96 **Supplies** Wooden track, linoleum tiles, triple-beam balance, spring scales, protractor, meterstick	**Instructional Activity: Coefficient of Friction Investigation** Working in small groups, students design and implement two separate experiments to determine the maximum coefficient of static friction between a shoe and provided samples of linoleum and wood. In one experiment, the linoleum and wood samples are placed on a horizontal surface; in the other experiment, they are placed on an inclined plane. After completing the experiments, students find the percent difference between the two values of the coefficient of friction obtained for each surface. The post-lab discussion involves brief whiteboard presentations. Groups work in pairs, with one group presenting its results while the other group asks questions. Then the groups switch roles. My role is to act as a facilitator and to ensure that the question-and-answer rounds run smoothly.

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.B.1.2, SP 4.2, SP 5.1] Reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. [LO 3.B.1.3, SP 1.5, SP 2.2] Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [LO 3.B.2.1, SP 1.1, SP 1.4, SP 2.2] Evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. [LO 4.A.2.2, SP 5.3] 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. [LO 4.A.3.1, SP 2.2] 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. [LO 4.A.3.2, SP 1.4] 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. [LO 4.A.2.1, SP 6.4] 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. [LO 4.A.2.3, SP 1.4, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 5: "Applying Newton's Laws" Christian and Belloni, Problems 4.10 and 4.11 Hieggelke, Maloney, and Kanim, NTiper nT5G-RT58 **Supplies** Atwood's machine: low-friction pulley, assorted masses, mass hangers, string Modified Atwood's machine: dynamics track, dynamics cart, low-friction pulley, string, assorted masses, mass hanger Photogate, motion detector, or stopwatch and meterstick	**Instructional Activity: Atwood's Machine Investigation** Students work in small groups to construct an Atwood's machine or a modified Atwood's machine. They then design and implement an experiment to determine the acceleration of a hanging mass in the machine and the tension in the string.

Students should recognize that they need to analyze the system (both masses) rather than the single mass as the system accelerates at the same rate.

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. [LO 3.A.4.1, SP 1.4, SP 6.2] Use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. [LO 3.A.4.2, SP 6.4, SP 7.2] Analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. [LO 3.A.4.3, SP 1.4]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" Christian and Belloni, Illustration 4.6 and Problems 4.12 and 4.13 Hieggelke, Maloney, and Kanim, NTipers nT5D-WWT47 and nT5D-LMCT48	**Formative Assessment: Physlet-Based Exercises** Students work on the Physlet-based exercises (Christian and Belloni) to analyze a variety of situations, identify the action-reaction pairs, and determine the magnitude and direction of the forces interacting. The solutions to the exercises are published on the class website and the students are required to bring their corrected work to the next class. When students bring in their corrected work, I solicit questions about the assignment and then provide feedback to students as appropriate.

Students often make the assumption that the gravitational force always "cancels" out the normal force or that the gravitational force and the normal force are an action-reaction pair. It is important to pay attention to other force components that may act in the vertical direction.

Guiding Questions: How can the forces acting on an object be represented? ▼ How can a free-body diagram be used to create a mathematical representation of the forces acting on an object? ▼ How do Newton's laws apply to interactions between objects at rest and in motion? ▼ How do Newton's laws apply to systems of two or more objects?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 3.A.3.1, SP 6.4, SP 7.2] Reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. [LO 3.B.1.3, SP 1.5, SP 2.2] Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [LO 3.B.2.1, SP 1.1, SP 1.4, SP 2.2] Evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. [LO 4.A.2.2, SP 5.3] 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. [LO 4.A.3.1, SP 2.2] 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. [LO 4.A.3.2, SP 1.4]	Etkina, Gentile, and Van Heuvelen, Chapter 2: "Newtonian Mechanics" and Chapter 3: "Applying Newton's Laws" Knight, Jones, and Field, Chapter 4: "Forces and Newton's Laws of Motion" and Chapter 5: "Applying Newton's Laws"	**Summative Assessment: Unit Test** The unit assessment includes 10 multiple-choice questions, as well as two context-rich problems that discourage the use of mathematic routines in isolation. Each of the context-rich problems is constructed as a short story in which the main character is the student. These problems do not include pictures or diagrams, so students must visualize the situation and apply physics concepts in the context of real-world situations. It is best for students to analyze the problem qualitatively before applying the mathematical manipulation of equations.

This summative assessment addresses all of the guiding questions for the unit.

Circular Motion and Gravitation

Laboratory Investigations:

- Flying Toy Investigation

Estimated Time:
2 Weeks

Guiding Questions: ▼ What does it mean for a force to be fundamental? ▼ What force or combination of forces keeps an object in circular motion? ▼ How is the motion of the moon around the Earth like the motion of a falling apple? ▼ How does the effect of Earth's gravitational field on an object change as the object's distance from Earth changes?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] 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. [LO 3.A.3.1, SP 6.4, SP 7.2] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1] 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. [LO 3.B.1.2, SP 4.2, SP 5.1] Reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. [LO 3.B.1.3, SP 1.5, SP 2.2] Create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [LO 3.B.2.1, SP 1.1, SP 1.4, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 4: "Circular Motion" Knight, Jones, and Field, Chapter 6: "Circular Motion, Orbits, and Gravity" **Supplies** Battery-operated flying toy, string, meterstick, stopwatch	**Instructional Activity: Flying Toy Investigation** Students work in groups of three or four to design and implement an experiment involving a battery-operated flying toy that is attached to a string and swung in a horizontal circle. Students must find the tension in the string and the centripetal acceleration of the toy.

Students may experience difficulty with the term "centripetal force" as they often consider it to be a special kind of force. Some may even label it as a separate force in a free-body diagram. To clarify students' understanding, ask them to identify the force that causes the object to move in a circle: tension, friction, normal, etc. This force can be identified as the "centripetal force requirement," and it is the force that goes on the free-body diagram.

Guiding Questions: ▼ What does it mean for a force to be fundamental? ▼ What force or combination of forces keeps an object in circular motion? ▼ How is the motion of the moon around the Earth like the motion of a falling apple? ▼ How does the effect of Earth's gravitational field on an object change as the object's distance from Earth changes?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.A.3.1, SP 6.4, SP 7.2]	Hieggelke, Maloney, and Kanim, NTiper nT5J-RT106	**Formative Assessment: Linked Multiple-Choice Tasks** Students are given multiple-choice tasks that present different variations of a physical situation with answers that include possible outcomes. For example, the situation could be a roller coaster car in a vertical loop. Questions can ask for the minimum speed at the top of the loop when the car is inverted, and the maximum speed when the car has returned to the bottom of the loop. Variations can include a car at the top of a hill, and then at the bottom of the hill. Students pass their responses to a classmate and we score the assessment as a group. Students then return the scored sheets to their peers. For each incorrect item, students write a brief statement explaining why they missed the item.
Articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. [LO 3.G.1.1, SP 7.1] 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*. [LO 2.B.2.1, SP 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 the Earth or other reference objects. [LO 2.B.2.2, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 4: "Circular Motion" Knight, Jones, and Field, Chapter 6: "Circular Motion, Orbits, and Gravity" Hieggelke, Maloney, and Kanim, NTiper nT5I-WWT102 **Online video** "The Apple and the Moon"	**Instructional Activity: The Apple and the Moon** The video "The Apple and the Moon" serves as a good introduction to Isaac Newton's life and the work that led to his universal law of gravitation. The video helps students understand how Newton reconciled Galileo's ideas about kinematics with Kepler's work in astronomy. After watching the video, we have a discussion about the accomplishments of Isaac Newton and how the physics principles that will be uncovered in this unit paved the way for astronauts to reach the moon.

Students hand in their work, and I review the items that students missed and their statements about those items. I address any lingering misunderstandings the following day in class.

Circular Motion and Gravitation

(continued)

Guiding Questions: ▼ What does it mean for a force to be fundamental? ▼ What force or combination of forces keeps an object in circular motion? ▼ How is the motion of the moon around the Earth like the motion of a falling apple? ▼ How does the effect of Earth's gravitational field on an object change as the object's distance from Earth changes?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 2.B.1.1, SP 2.2, SP 7.2] Use Newton's law of gravitation to calculate the gravitational force the two objects exert on each other and use that force in contexts other than orbital motion. [LO 3.C.1.1, SP 2.2] Use Newton's law of gravitation to calculate the gravitational force between two objects and use that force in contexts involving circular orbital motion. [LO 3.C.1.2, SP 2.2]	**Web** "My Solar System"	**Instructional Activity: Solar System Simulation** In this virtual lab, students use the "My Solar System" simulation to investigate the effects of mass and distance on the velocity of objects in orbit. Students report the collected data, their data analysis, and a conclusion in their lab journals.
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*. [LO 2.B.2.1, SP 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 the Earth or other reference objects. [LO 2.B.2.2, SP 2.2]	**Web** "Episode 402-3: Data from the *Apollo 11* mission"	**Instructional Activity: Data Analysis** Students analyze data from the *Apollo 11* lunar mission to find the gravitational field at different distances.
Articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. [LO 3.G.1.1, SP 7.1]	Etkina, Gentile, and Van Heuvelen, Chapter 4: "Circular Motion" Knight, Jones, and Field, Chapter 6: "Circular Motion, Orbits, and Gravity"	**Summative Assessment: Research Paper** Students write a research paper in response to two prompts: 1. Explain what is meant by the Newtonian synthesis and its relevance in changing the way people thought about nature. 2. Discuss how the exploration of space is possible because of Isaac Newton's work. Through this assignment, students demonstrate their ability to work and think independently and to apply the concepts they have learned in class.

Students should practice applying proportional reasoning (scaling) to a variety of situations involving gravitational forces and gravitational fields, like doubling the mass of one object, tripling the distance from the centers of two objects, etc.

This summative assessment addresses all of the guiding questions for the unit.

Energy and Conservation of Energy

Laboratory Investigations:

- Roller Coaster Investigation
- Stretching a Spring Investigation
- Energy and Nonconservative Forces (Lab Practicum)

Estimated Time:

5 Weeks

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. [LO 5.B.3.1, SP 2.2, SP 6.4, SP 7.2] Describe and make predictions about the internal energy of everyday systems. [LO 5.B.4.1, SP 6.4, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 6: "Work and Energy" Knight, Jones, and Field, Chapter 10: "Energy and Work"	**Instructional Activity: Where's the Money?** Students are given a scenario in which they begin with a certain amount of money, and they study how that initial amount changes over time due to various deposits and purchases. They must balance the amount of money at different stages. The activity takes about 20 minutes, and after they complete it we have a whole-class discussion to answer the question: "Where did the money go?" The goal is for the students to realize that even though they might not have cash, they have goods and savings at the bank. The activity allows for the introduction of important vocabulary for this unit: transference and transformation.

I find the "money analogy" powerful for its simplicity when introducing the concept of energy, as both money and energy can be transferred and transformed.

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. [LO 5.B.3.1, SP 2.2, SP 6.4, SP 7.2] Make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. [LO 5.B.3.2, SP 1.4, SP 2.2] 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. [LO 5.B.3.3, SP 1.4, SP 2.2] 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. [LO 4.C.1.1, SP 1.4, SP 2.1, SP 2.2] Predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. [LO 4.C.1.2, SP 6.4] Set up 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. [LO 5.B.1.1, SP 1.4, SP 2.2] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 6: "Work and Energy" Knight, Jones, and Field, Chapter 10: "Energy and Work" **Supplies** Toy roller coaster track with a vertical loop and toy cars (polyethylene tube pipe insulation and marbles may be substituted)	**Instructional Activity: Roller Coaster Investigation** Working in groups of three, students design a simple roller coaster using provided materials (a track with a vertical loop and toy cars) to test whether the total energy of a car–Earth system is conserved if there are no external forces exerted on it by other objects. Students include multiple representations of energy to provide evidence for their claims. They should use a bar chart, the mathematical expression of conservation of energy, and the corresponding calculations to evaluate whether the outcome of the experiment supports the idea of energy conservation.

Writing a conservation of energy statement for a system is often challenging for students. The use of a bar chart provides a visual representation of the initial and final energies. Students then use the graph to create the corresponding mathematical representation. They clearly see that there should be an equal number of items in the equation as they have on each side of the graph. If friction is present, the difference in the initial and final energies is the dissipated energy.

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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. [LO 5.B.1.2, SP 1.5] Describe and make predictions about the internal energy of everyday systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. [LO 5.B.4.2, SP 1.4, SP 2.1, SP 2.2]		
Calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. [LO 5.B.4.2, SP 1.4, SP 2.1, SP 2.2]	Hieggelke, Maloney, and Kanim, NTipers nT6F-BCT46, nT6F-BCT52, and nT6F-BCT62	**Formative Assessment: Ranking Task** Students participate in a ranking task in which they rank objects dropped from different heights according to the objects' final kinetic energies. Students must provide an explanation for their rankings. After the exercise we review the solution as a class.

If students have a question about the task, I encourage another student to provide an explanation. This is a good strategy for providing feedback in a student-centered learning environment.

Energy and Conservation of Energy

(continued)

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 3.E.1.1, SP 6.4, SP 7.2] Use net force and velocity vectors to determine qualitatively whether kinetic energy of an object would increase, decrease, or remain unchanged. [LO 3.E.1.2, SP 1.4] Use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether kinetic energy of that object would increase, decrease, or remain unchanged. [LO 3.E.1.3, SP 1.4, SP 2.2] 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. [LO 3.E.1.4, SP 2.2] Design an experiment and analyze data to examine how a force exerted on an object or system does work on the object or system as it moves through a distance. [LO 5.B.5.1, SP 4.2, SP 5.1] 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. [LO 5.B.5.2, SP 4.2, SP 5.1] 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. [LO 5.B.5.3, SP 1.4, SP 2.2, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 6: "Work and Energy" Knight, Jones, and Field, Chapter 10: "Energy and Work" Christian and Belloni, Illustration 6.3, Problems 6.11, 7.5, 7.6, 16.5, and 16.6 **Supplies** Assorted springs of known spring constant, assorted masses, meterstick	**Instructional Activity: Stretching a Spring Investigation** Students work with a partner to design and implement an experiment involving a spring and an increasing applied force. The data collected are represented in a graph that can be either hand-drawn or created with graphing software (Excel or Logger *Pro*). From the force-versus-distance graph, students should be able to calculate the work done on the spring.

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. [LO 5.B.4.2, SP 1.4, SP 2.1, SP 2.2]	Hieggelke, Maloney, and Kanim, NTipers nT6A-BCT8, nT6B-RT11, and nT6C-WWT21	**Formative Assessment: Changing Representations** Students work in pairs to create exercises that involve translation from one representation to another. Some possible translations are: • from a bar chart to a mathematical representation; • from a physical situation diagram to a bar chart; and • from a given equation to a bar chart. Each pair exchanges its exercises with another pair. After the students work through the exercises they received, the pairs meet and offer constructive criticism on each other's solutions.
Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. [LO 5.A.2.1, SP 6.4, SP 7.2] 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). [LO 5.B.5.4, SP 6.4, SP 7.2] 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. [LO 5.B.5.5, SP 2.2, SP 6.4] 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. [LO 4.C.2.1, SP 6.4] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 6: "Work and Energy" Knight, Jones, and Field, Chapter 10: "Energy and Work" **Supplies** Wooden block, string, low-friction pulley, mass, mass hanger, meterstick	**Summative Assessment: Energy and Nonconservative Forces (Lab Practicum)** This summative assessment is given as a lab practicum. The lab is challenging to most students, as it requires good observation skills and thoughtful analysis of the energies due to conservative and nonconservative forces. Students working in teams of three design and implement an experiment to determine the energy dissipated by friction of a system consisting of a modified Atwood's machine. The students are given the coefficient of friction of the block that is pulled across a surface, as well as the masses of the block and the hanging mass. Students are not permitted to use any additional equipment other than a meterstick. In their lab report, students must include the system(s) selected, bar charts, mathematical representations, data analysis, and an explanation of uncertainties in their measurements.

Translation exercises can provide a link between conceptual understanding and traditional problem-solving skills, as they help students compare equivalent representations of physical situations. As students are working, I provide feedback to correct any misconceptions or incorrect translations between representations.

This summative assessment addresses all of the guiding questions for the unit.

Energy and Conservation of Energy

(continued)

Guiding Questions: ▼ How are the different modes of energy storage transformed within a system and transferred between a system and the environment? ▼ How can energy be represented with graphs and equations? ▼ What does it mean for energy to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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. [LO 4.C.2.2, SP 1.4, SP 2.2, SP 7.2] 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, 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. [LO 5.B.2.1, SP 1.4, SP 2.1]		

Unit 5: Impulse, Momentum, and Conservation of Momentum

Laboratory Investigations:

- Bumper Design Investigation
- Impulse and Change in Momentum Investigation
- Elastic and Inelastic Collisions Investigation
- Tire Manufacturing Investigation (Lab Practicum)

Estimated Time:

4 Weeks

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 3.D.2.2, SP 6.4] 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. [LO 3.D.2.3, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 5: "Impulse and Linear Momentum" Knight, Jones, and Field, Chapter 9: "Momentum" **Web** Socrative.com **Supplies** Raw eggs, sheet, large trash bags, tape	**Instructional Activity: Egg Toss** This teacher-led demonstration uses raw eggs. Students are asked to predict the outcome of each of the following activities: 1. A student volunteer throws an egg against one of the whiteboards. 2. The student throws an egg at a loosely held sheet. For each activity, students use mobile devices and a classroom feedback tool (Socrative) to submit predictions. The class then votes for one of the predictions, and we conduct the activity. (I use large trash bags to protect the floor and the whiteboard.) If the result of the activity differs from the class's prediction, I guide the discussion to elicit an explanation of the phenomena observed.
Design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. [LO 3.D.2.4, SP 4.2] 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.). [LO 4.B.1.1, SP 1.4, SP 2.2] Perform analysis on data presented as a force-time graph and predict the change in momentum of a system. [LO 4.B.2.2, SP 5.1]	**Supplies** Dynamics track, wooden block, paper, adhesive tape	**Instructional Activity: Bumper Design Investigation** Students design a paper bumper that will soften the impact of the collision between a cart and a fixed block of wood. Their designs are evaluated by the shape of an acceleration-versus-time graph of the collision.

This demonstration illustrates the relationship between force of impact and length of time of an interaction and will get students ready for the bumper design activity.

Impulse, Momentum, and Conservation of Momentum

(continued)

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 3.D.1.1, SP 4.1] 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. [LO 3.D.2.1, SP 2.1] 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. [LO 3.D.2.3, SP 5.1] Design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. [LO 3.D.2.4, SP 4.2] 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. [LO 4.B.2.1, SP 2.2] Perform analysis on data presented as a force-time graph and predict the change in momentum of a system. [LO 4.B.2.2, SP 5.1]	**Supplies** Dynamics track, dynamics cart, force sensor, motion detector, string	**Instructional Activity: Impulse and Change in Momentum Investigation** Students working in groups of three or four use a motion detector and a force sensor to measure the change in momentum of a dynamics cart and compare it to the impulse received. Students can give a small push to the cart or use the spring plunger to release the cart. The formal lab report includes the students' experimental design, collected data, graphical analysis, and conclusions. Students should account for uncertainties in their measurements and how the uncertainties affect the reliability of their results.

Impulse, Momentum, and Conservation of Momentum

(continued)

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 4.B.1.2, SP 5.1] 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. [LO 4.B.2.1, SP 2.2] Perform analysis on data presented as a force-time graph and predict the change in momentum of a system. [LO 4.B.2.2, SP 5.1]	Hieggelke, Maloney, and Kanim, NTipers nT7A-WWT9 and nT7B-WWT11	**Instructional Activity: Solving Practice Problems** Students work through NTipers that involve impulse and change of momentum as well as graphs of force versus time.

I have students work these problems in class so that I can provide guidance as needed. Common difficulties with problem solving in this topic include the following:

- *Students often forget that velocity is a vector and that they should take into account the direction of the velocity.*
- *The equation relating impulse and momentum can be misread as "impulse equals momentum" rather than as "impulse equals a change in momentum." This is a very common mistake by students.*

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
Define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. [LO 5.A.2.1, SP 6.4, SP 7.2] Make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. [LO 5.D.1.1, SP 6.4, SP 7.2] 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. Solve qualitatively and/or quantitatively for one-dimensional situations and only qualitatively in two-dimensional situations. [LO 5.D.1.2, SP 2.2, SP 3.2, SP 5.1, SP 5.3] 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. [LO 5.D.1.3, SP 2.1, SP 2.2] 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. [LO 5.D.3.1, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 5: "Impulse and Linear Momentum" Knight, Jones, and Field, Chapter 9: "Momentum" Christian and Belloni, Problems 8.6 and 8.9 Hieggelke, Maloney, and Kanim, NTipers nT7C-WWT14 and nT7D-CCT24	**Formative Assessment: Qualitative Reasoning Task** Students work with a partner in a task that requires a qualitative analysis of momentum. The task involves a scenario such as an object moving in one dimension. The task presents an initial and final situation, and students must describe some quantity or aspect that has changed between the initial and final situation. For the initial condition students are given the signs of the position and the net force. They also know whether the kinetic energy is increasing or decreasing. They have to determine the direction and whether the magnitude of the resultant momentum is increasing or decreasing.

We use the online feedback tool Socrative to gather student responses to the task. If there are discrepancies among the answers, I provide feedback through a guided discussion.

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 5.D.1.4, SP 4.2, SP 5.1, SP 5.3, SP 6.4] 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. [LO 5.D.1.5, SP 2.1, SP 2.2] 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. [LO 5.D.2.1, SP 6.4, SP 7.2] 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. [LO 5.D.2.2, SP 4.1, SP 4.2, SP 5.1] Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. [LO 5.D.2.3, SP 6.4, SP 7.2] Analyze data that verify conservation of momentum in collisions with and without an external friction force. [LO 5.D.2.4, SP 4.1, SP 4.2, SP 4.4, SP 5.1, SP 5.3] 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. [LO 5.D.2.5, SP 2.1, SP 2.2]	**Supplies** Set 1: Air track, assorted carts, photogate Set 2: Commercial ballistic pendulum, meterstick	**Instructional Activity: Elastic and Inelastic Collisions Investigation** Students work in groups of three or four to design an experiment to investigate conservation of momentum and conservation of energy using an air track set or a ballistic pendulum. One of the goals of this lab is for students to determine the type of collision (either elastic or inelastic) based on data analysis.

Impulse, Momentum, and Conservation of Momentum

(continued)

Guiding Questions: ▼ How does a force exerted on an object change the object's momentum? ▼ How are Newton's second and third laws related to momentum? ▼ What does it mean for momentum to be conserved? ▼ How can the outcome of a collision be used to characterize a collision as elastic or inelastic?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 5.D.1.4, SP 4.2, SP 5.1, SP 5.3, SP 6.4] Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. [LO 5.D.2.3, SP 6.4, SP 7.2] Analyze data that verify conservation of momentum in collisions with and without an external friction force. [LO 5.D.2.4, SP 4.1, SP 4.2, SP 4.4, SP 5.1, SP 5.3] 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.). [LO 4.B.1.1, SP 1.4, SP 2.2] 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. [LO 4.B.1.2, SP 5.1]	**Supplies** Lab stand, tissue box, pendulum bob (small balloon filled with flour), spring scale, meterstick	**Summative Assessment: Tire Manufacturing Investigation (Lab Practicum)** This summative assessment is conducted over two class periods. Students receive the following scenario: "A tire manufacturer has contracted you to determine the coefficient of kinetic friction between its tires and an asphalt road surface. The manufacturer has provided a car with the manufacturer's tires (represented by the tissue box) and an asphalt road surface (the table top)." Students use a pendulum bob (a small balloon filled with flour) that swings down from a horizontal position and hits the tissue box. The box slides across the table and eventually stops, just as a car skids to a stop. Students work in teams of three or four to design and conduct their experiment, but the final report is completed individually in class.

This practicum requires the application of conservation of energy, conservation of momentum, the work–energy theorem, and a linear model of friction to find the coefficient of kinetic friction. The assessment addresses all of the guiding questions in this unit.

Simple Harmonic Motion

Laboratory Investigations:

- Spring Constant Investigation
- Graphs of an Oscillating System Investigation
- Simple Pendulum Investigation

Estimated Time:

2 Weeks

Guiding Questions: How is simple harmonic motion connected to uniform circular motion? ▼ How can oscillatory motion be represented graphically and mathematically? ▼ How is conservation of energy applied in simple harmonic oscillators?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1]	Etkina, Gentile, and Van Heuvelen, Chapter 19: "Vibrational Motion" Knight, Jones, and Field, Chapter 14: "Oscillations" **Supplies** Set of springs of equal length, set of masses, mass hanger, meterstick, stopwatch	**Instructional Activity: Spring Constant Investigation** Students in small groups design two independent experiments to determine the spring constants of various springs of equal length. (I use sets of five color-coded equal-length springs.) The two approaches used by the students are applying Hooke's law and determining the period of oscillation.
Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. [LO 3.B.3.1, SP 6.4, SP 7.2] 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. [LO 3.B.3.2, SP 4.2] Analyze data to identify qualitative or 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 to use that data to determine the value of an unknown. [LO 3.B.3.3, SP 2.2, SP 5.1] Construct a qualitative and/or a quantitative explanation of oscillatory behavior given evidence of a restoring force. [LO 3.B.3.4, SP 2.2, SP 6.2]	Etkina, Gentile, and Van Heuvelen, Chapter 19: "Vibrational Motion" Knight, Jones, and Field, Chapter 14: "Oscillations" Hieggelke, Maloney, and Kanim, NTipers nT9A-CRT11, nT9A-CRT12, nT9A-CRT13, and nT9A-CT5 **Supplies** Dynamics track and cart, spring, motion detector	**Instructional Activity: Graphs of an Oscillating System Investigation** Students work in groups of three or four to analyze graphs of position, velocity, and acceleration versus time for an oscillating system consisting of a dynamics cart attached to a spring. Important goals for this activity are for students to compare how velocity and acceleration vary at the equilibrium position and at the endpoints. Students should also be able to articulate the role of the restoring force.

Students predict that the stretch will be equal as the springs have the same length. They are surprised to find that each spring has a different spring constant. This lab opens up an interesting discussion about real-life applications, such as shock absorbers in cars and bungee cords.

Guiding Questions: How is simple harmonic motion connected to uniform circular motion? ▼ How can oscillatory motion be represented graphically and mathematically? ▼ How is conservation of energy applied in simple harmonic oscillators?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. [LO 3.B.3.1, SP 6.4, SP 7.2] Analyze data to identify qualitative or 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 to use that data to determine the value of an unknown. [LO 3.B.3.3, SP 2.2, SP 5.1]	Christian and Belloni, Problems 16.2, 16.3, and 16.4	**Formative Assessment: Physlet-Based Exercises** Students work on three Physlet-based exercises (Christian and Belloni) involving a ball on an air track attached to a compressed spring. These exercises help students match the motion of the ball at different parts of its oscillation to graphs of position, velocity, and mechanical energy. I use the think-pair-share strategy in this exercise. Students first work individually and write down their answers. Then they share their answers with one partner and see if they agree or disagree with each other. In the final part of this activity, I ask a few teams to share their answers with the class, and we follow the process of scientific argumentation to discuss their suggested answers.
Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. [LO 3.B.3.1, SP 6.4, SP 7.2] 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. [LO 3.B.3.2, SP 4.2]	Etkina, Gentile, and Van Heuvelen, Chapter 19: "Vibrational Motion" Knight, Jones, and Field, Chapter 14: "Oscillations" Hieggelke, Maloney, and Kanim, NTiper nT9A-RT4 **Supplies** Assorted hooked cylindrical masses, string, ring stand, protractor, meterstick, stopwatch	**Instructional Activity: Simple Pendulum Investigation** This lab investigation is divided into two parts. First the students work with a partner to investigate the factors that affect the period of a simple pendulum. In the second part of the lab, they test whether the period is proportional to the pendulum's length, the square of its length, or the square root of its length. (This test applies only when the amplitude of oscillation is small.) For this experiment the students use hooked cylindrical masses. It is important for the students to recognize that the length of the pendulum should be measured from the pendulum clamp to the center of mass of the cylindrical mass.

I facilitate the class discussion of the suggested answers and provide corrective feedback as needed. This activity provides valuable information about the depth of student knowledge.

Guiding Questions: How is simple harmonic motion connected to uniform circular motion? ▼ How can oscillatory motion be represented graphically and mathematically? ▼ How is conservation of energy applied in simple harmonic oscillators?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. [LO 3.B.3.1, SP 6.4, SP 7.2] 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. [LO 3.B.3.2, SP 4.2] Analyze data to identify qualitative or 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 to use that data to determine the value of an unknown. [LO 3.B.3.3, SP 2.2, SP 5.1] Construct a qualitative and/or a quantitative explanation of oscillatory behavior given evidence of a restoring force. [LO 3.B.3.4, SP 2.2, SP 6.2]		**Summative Assessment: Unit Test** The students complete a unit test with three free-response questions and a set of multiple-choice questions. At least one of the free-response questions includes graphical analysis of harmonic motion.

The summative assessment addresses all of the guiding questions in this unit.

Unit 7: Rotational Motion and Conservation of Angular Momentum

Laboratory Investigations:

- Torque and the Human Arm Investigation
- Rotational Inertia Investigation
- Conservation of Angular Momentum Investigation

Estimated Time:

4 Weeks

Guiding Questions: ▼ How can the particle model be extended to a rigid-body model of an object? ▼ How are the rotational quantities (angular position, velocity, and acceleration) related to linear quantities? ▼ What does it mean for angular momentum to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
Use representations of the relationship between force and torque. [LO 3.F.1.1, SP 1.4] Compare the torques on an object caused by various forces. [LO 3.F.1.2, SP 1.4] Estimate the torque on an object caused by various forces in comparison to other situations. [LO 3.F.1.3, SP 2.3] Design an experiment and analyze data testing a question about torques in a balanced rigid system. [LO 3.F.1.4, SP 4.1, SP 4.2, SP 5.1] Calculate torques on a two-dimensional system in static equilibrium, by examining a representation or model (such as a diagram or physical construction). [LO 3.F.1.5, SP 1.4, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 7: “Extended Bodies at Rest” and Chapter 8: “Rotational Motion” Knight, Jones, and Field, Chapter 7: “Rotational Motion” and Chapter 8: “Equilibrium and Elasticity” Christian and Belloni, Problem 13.8 Hieggelke, Maloney, and Kanim, NTipers nT8H-LMCT62, nT8H-LMCT63, and nT8C-RT18 **Supplies** Meterstick, ring stand, weight hangers, an assortment of blocks, spring scale, additional materials as needed	**Instructional Activity: Torque and the Human Arm Investigation** Students work in groups of three or four to design and build an apparatus that replicates the forearm and biceps muscle system. The objective is to determine the biceps tension when holding an object in a lifted position. Students may use the Internet to research the structure of the biceps muscle. They can use readily available materials in the classroom, such as a meterstick, a ring stand, weight hangers, an assortment of blocks, and a spring scale. In their lab journal, students are required to document the different stages of their design. Required elements include design sketches, force diagrams, mathematical representations of translational and rotational equilibrium, and numerical calculations.
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. [LO 1.A.5.1, SP 1.1, SP 7.1] Use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semiquantitatively. [LO 4.A.1.1, SP 1.2, SP 1.4, SP 2.3, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 7: “Extended Bodies at Rest” and Chapter 8: “Rotational Motion” Knight, Jones, and Field, Chapter 7: “Rotational Motion” and Chapter 8: “Equilibrium and Elasticity” Hieggelke, Maloney, and Kanim, NTiper nT7E-TT27	**Instructional Activity: Juggling Demonstration** After watching a demonstration of someone juggling, I ask for volunteers to explain in their own words the concept of center of mass in the parabolic motion of objects being juggled.

This activity provides an opportunity for students to make an interdisciplinary connection to biological systems by investigating the structure and function of a major muscle (biceps) in the human body.

Using a juggling example to explain the concept of center of mass provides a very powerful (and fun) visualization. I often have students who can juggle, but a suitable video from YouTube can also be used effectively.

Rotational Motion and Conservation of Angular Momentum

(continued)

Guiding Questions: ▼ How can the particle model be extended to a rigid-body model of an object? ▼ How are the rotational quantities (angular position, velocity, and acceleration) related to linear quantities? ▼ What does it mean for angular momentum to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.F.2.1, SP 6.4] 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. [LO 4.D.1.1, SP 1.2, SP 1.4]	Etkina, Gentile, and Van Heuvelen, Chapter 7: "Extended Bodies at Rest" and Chapter 8: "Rotational Motion" Knight, Jones, and Field, Chapter 7: "Rotational Motion" Hieggelke, Maloney, and Kanim, NTipers nT8A-CT6, nT8C-QRT11, and nT8C-CT21 **Supplies** Suspended bicycle wheel, 100 g mass, string, digital camera	**Instructional Activity: Spinning Wheel** This teacher-led demonstration involves a suspended (vertically mounted) bicycle wheel, with a string wrapped around the wheel's rim. One end of the string is attached to the wheel, and the other is attached to a small mass. The mass is released, causing the wheel to rotate. The students create a video that they analyze to determine the rotational inertia of the wheel.
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. [LO 3.F.2.2, SP 4.1, SP 4.2, SP 5.1]	**Supplies** Commercial rotary motion apparatus: rotary motion sensor, mass hanger, assorted cylindrical mass set, string, short support rod, table clamp, meterstick, stopwatch	**Instructional Activity: Rotational Inertia Investigation** Students work with a partner to design and implement a data collection plan to determine the rotational inertia of a cylinder from the slope of a graph of an applied torque versus angular acceleration. The students are able to verify their claims by comparing their evidence with the rotational inertia found directly by measuring the mass and radius of the cylinder.

Students should be aware that even though the bicycle wheel and the small mass constitute a system, they need to analyze the motion of the falling small mass and the motion of the spinning wheel separately. After the students derive equations for both objects, they can substitute one equation into the other to be able to determine the unknown.

Guiding Questions: ▼ How can the particle model be extended to a rigid-body model of an object? ▼ How are the rotational quantities (angular position, velocity, and acceleration) related to linear quantities? ▼ What does it mean for angular momentum to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 1.A.5.1, SP 1.1, SP 7.1] 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. [LO 3.F.3.1, SP 6.4, SP 7.2] 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. [LO 3.F.3.2, SP 2.1] Plan data collection and analysis strategies designed to test the relationship between torques exerted on an object and the change in momentum of that object. [LO 3.F.3.3, SP 4.1, SP 4.2, SP 5.1, SP 5.3] 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. [LO 4.D.1.1, SP 1.2, SP 1.4] 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. [LO 4.D.1.2, SP 3.2, SP 4.1, SP 4.2, SP 5.1, SP 5.3] 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. [LO 4.D.2.1, SP 1.2, SP 1.4] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 8: "Rotational Motion" Knight, Jones, and Field, Chapter 7: "Rotational Motion" Christian and Belloni, Problems 11.5 and 11.6 **Supplies** Commercial rotary motion apparatus: rotary motion sensor, rotating aluminum disks, mass hanger, assorted mass set, string, short support rod, table clamp, meterstick	**Instructional Activity: Conservation of Angular Momentum Investigation** In pairs or small groups, students investigate how the angular momentum of a rotating system responds to changes in the rotational inertia. The experiment involves the collection of data of angle versus time and angular velocity versus time. Students use a rotary motion sensor with an aluminum plate that is spun to a certain angular speed, and then a second plate is dropped onto the first one, resulting in a change of the moment of inertia and the angular speed. The students analyze the graphs before and after the changes in the rotational inertia and determine the effect of changes in the rotational inertia on the angular momentum of the system.

Students should recognize that this situation is analogous to a totally inelastic collision in linear motion.

Guiding Questions: ▼ How can the particle model be extended to a rigid-body model of an object? ▼ How are the rotational quantities (angular position, velocity, and acceleration) related to linear quantities? ▼ What does it mean for angular momentum to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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. [LO 4.D.2.2, SP 4.2] 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. [LO 4.D.3.1, SP 2.2] 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. [LO 4.D.3.2, SP 4.1, SP 4.2] Do qualitative reasoning with compound objects. Do calculations with a fixed set of extended objects and point masses. [LO 5.E.2.1, SP 2.2]		
Make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. [LO 5.E.1.1, SP 6.4, SP 7.2] Make calculations of quantities related to the angular momentum of a system when the net external torque on the system is zero. [LO 5.E.1.2, SP 2.1, SP 2.2]	**Web** "Kepler's Laws"	**Instructional Activity: Data Analysis** Students use provided data to plot a planetary orbit and then analyze the orbit by applying Kepler's laws.

Guiding Questions: ▼ How can the particle model be extended to a rigid-body model of an object? ▼ How are the rotational quantities (angular position, velocity, and acceleration) related to linear quantities? ▼ What does it mean for angular momentum to be conserved?

Learning Objectives	Materials	Instructional Activities and Assessments
Make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. [LO 5.E.1.1, SP 6.4, SP 7.2] 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. [LO 4.D.2.1, SP 1.2, SP 1.4]	Hieggelke, Maloney, and Kanim, NTipers nT8D-RT29, nT8E-CCT36, and nT8F-RT42	**Formative Assessment: Conflicting Contentions** Students are given a couple of problems involving two objects of different masses hanging from a massive pulley. They are then given conflicting statements about the tension of the rope at specific points and then about each object's angular acceleration as the objects are released from rest. The students have to decide which contention they agree with and explain why. Students work their solution on a whiteboard with a partner. This task is useful for contrasting statements of students' alternate conceptions with physically accepted statements. The task can be phrased as "Which statement do you agree with and why?" rather than asking which statement is correct or true.
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. [LO 4.D.3.1, SP 2.2] 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. Do qualitative reasoning with compound objects. Do calculations with a fixed set of extended objects and point masses. [LO 5.E.2.1, SP 2.2]		**Summative Assessment: Unit Test** Students complete a unit test that consists of 10 multiple-choice questions and three free-response questions. One of the free-response questions is a lab-based question in which the students design a procedure to determine the rotational inertia of a pulley.

I walk around the room answering any questions the students might have. If there are any groups with incorrect solutions, I bring the discussion to the class as a whole and guide them to the correct solution.

The summative assessment addresses all of the guiding questions in this unit.

Unit 8: Mechanical Waves and Sound

Laboratory Investigations:

- Mechanical Waves Investigation
- Speed of Sound Investigation
- Wave Boundary Behavior Investigation
- Standing Waves Investigation

Estimated Time:

2 Weeks

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How do the relative velocities of the source of a wave and of the observer affect the frequency of the observed wave? ▼ How do waves from more than one source interfere to make waves of smaller or larger amplitude, depending on the location where the waves meet? ▼ How can wave boundary behavior be used to derive and apply relationships for calculating the characteristic frequencies for standing waves in strings, open pipes, and closed pipes?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 6.A.1.1, SP 6.2] Describe representations of transverse and longitudinal waves. [LO 6.A.1.2, SP 1.2] Use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. [LO 6.A.3.1, SP 1.4]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" Knight, Jones, and Field, Chapter 15: "Traveling Waves and Sound" **Supplies** Spring toy, meterstick, stopwatch	**Instructional Activity: Mechanical Waves Investigation** Students working in teams of three or four model the two types of mechanical waves (longitudinal and transverse) with a spring toy. The students then design and implement an experiment to test whether the following characteristics affect the speed of a pulse: frequency, wavelength, and amplitude.
Describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. [LO 6.A.2.1, SP 6.4, SP 7.2] 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. [LO 6.A.4.1, SP 6.4] Design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. [LO 6.B.4.1, SP 4.2, SP 5.1, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" Knight, Jones, and Field, Chapter 15: "Traveling Waves and Sound" **Supplies** Set 1: Graduated cylinder, water, tuning forks of known frequency, rubber mallet, ruler Set 2: Microphone and audio software Set 3: Clapping device (two pieces of wood strapped together at one end), stopwatch, meterstick Additional supplies as needed	**Instructional Activity: Speed of Sound Investigation** Working in small groups, students design two different procedures to determine the speed of sound in air. They brainstorm their approaches and write them on the whiteboard. Each of the teams presents its ideas to the class. Students receive feedback from their peers and then conduct their experiments. They record the revised procedures in their lab journals. For the post-lab discussion, I match the teams that used similar procedures and have them discuss their results. Then as a class we reach consensus about the estimated value for the speed of sound.

I provide a variety of equipment to encourage the students to be creative in the design of their experiments. Some examples of their experiments include studying resonance in a closed-end tube using a graduated cylinder with water and a tuning fork, using a microphone and free software (Audacity), measuring distance traveled by an echo and time, etc.

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How do the relative velocities of the source of a wave and of the observer affect the frequency of the observed wave? ▼ How do waves from more than one source interfere to make waves of smaller or larger amplitude, depending on the location where the waves meet? ▼ How can wave boundary behavior be used to derive and apply relationships for calculating the characteristic frequencies for standing waves in strings, open pipes, and closed pipes?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 6.B.1.1, SP 1.4, SP 2.2] Use a visual representation of a periodic mechanical wave to determine wavelength of the wave. [LO 6.B.2.1, SP 1.4] Create or use a wave front diagram to demonstrate or interpret qualitatively the observed frequency of a wave, dependent upon relative motions of source and observer. [LO 6.B.5.1, SP 1.4]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" Knight, Jones, and Field, Chapter 15: "Traveling Waves and Sound" Christian and Belloni, Illustration 17.2, Exploration 18.5	**Formative Assessment: Concept Maps** Students work with a partner to create a concept map of the types of waves and characteristics of waves. A concept map is a diagram of nodes, each containing concept labels; the nodes are linked together with directional lines, also labeled. The concept nodes are arranged in hierarchical levels that move from general to specific concepts. Concept maps are a useful instructional strategy as they assess how well students see the "big picture" on a particular topic. The concept maps are to be illustrated with diagrams and include mathematical representations as appropriate. The students share their work by posting their concept maps online using a digital tool such as Exploratree.
Use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. [LO 6.D.1.1, SP 1.1, SP 1.4] Design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for wave pulses or standing waves). [LO 6.D.1.2, SP 4.2, SP 5.1] 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. [LO 6.D.1.3, SP 4.2] 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.[LO 6.D.2.1, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" Knight, Jones, and Field, Chapter 16: "Superposition and Standing Waves" Christian and Belloni, Problems 17.4 and 17.10 **Supplies** Spring toy, string, lab stands	**Instructional Activity: Wave Boundary Behavior Investigation** Working in teams of three or four, students design and implement an experiment to compare what happens to the phase of a transverse wave on a spring toy when a pulse is reflected from a fixed-end boundary and a free-end boundary, and when it is reflected and transmitted from various boundaries (spring to string).

The concept maps are projected on the board and presented by each team. Students are invited to ask questions and/or offer suggestions to the presenters. I provide feedback and clarification as needed.

Mechanical Waves and Sound

(continued)

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How do the relative velocities of the source of a wave and of the observer affect the frequency of the observed wave? ▼ How do waves from more than one source interfere to make waves of smaller or larger amplitude, depending on the location where the waves meet? ▼ How can wave boundary behavior be used to derive and apply relationships for calculating the characteristic frequencies for standing waves in strings, open pipes, and closed pipes?

Learning Objectives	Materials	Instructional Activities and Assessments
Use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. [LO 6.D.1.1, SP 1.1, SP 1.4] 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. [LO 6.D.2.1, SP 5.1]	**Web** "Wave Behavior"	**Instructional Activity: Wave Behavior Simulations** The "Wave Behavior" PhysicsQuest provides a follow-up activity to the previous hands-on investigation. Students complete Activities I and II, in which they use simulations to investigate the following: 1. Boundary Behavior: The behavior of a pulse at the end of a medium, including free-end and fixed-end reflection, and the transmission of a pulse from one medium to another medium with a different density. 2. Interference and Superposition: Wave interference (constructive and destructive interference) and how to apply the principle of superposition.
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. [LO 6.D.3.1, SP 2.1, SP 3.2, SP 4.2] Plan data collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared to 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. [LO 6.D.3.3, SP 3.2, SP 4.1, SP 5.1, SP 5.2, SP 5.3] 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. [LO 6.D.4.2, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" Knight, Jones, and Field, Chapter 16: "Superposition and Standing Waves" Christian and Belloni, Problems 18.12 and 18.14 **Supplies** Commercial standing waves apparatus, string, assorted masses, mass hanger	**Instructional Activity: Standing Waves Investigation** Students working in teams of three or four use a string attached to a mechanical oscillator that vibrates with a known frequency. The other end of the string loops over a pulley system and is attached to a hanger for which the mass can be varied. For a particular tension, students predict the length of the string necessary to generate the first two harmonics of a standing wave on the string. Then they perform the experiment and compare the outcome with their prediction.

The activities on wave boundary behavior provide the foundation of knowledge for understanding thin-film interference. This topic is part of the AP Physics 2 course but might be taught as an extension enrichment topic in AP Physics 1.

Some other important relationships for students to investigate in this lab are as follows:

1. *The effect on the number of segments when tension is increased and frequency is kept constant, or when frequency is increased and tension is kept constant.*
2. *The effect on the speed of the wave when tension is increased and frequency is kept constant, or when frequency is increased and tension is kept constant.*

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How do the relative velocities of the source of a wave and of the observer affect the frequency of the observed wave? ▼ How do waves from more than one source interfere to make waves of smaller or larger amplitude, depending on the location where the waves meet? ▼ How can wave boundary behavior be used to derive and apply relationships for calculating the characteristic frequencies for standing waves in strings, open pipes, and closed pipes?

Learning Objectives	Materials	Instructional Activities and Assessments
Use a visual representation to explain how waves of slightly different frequency give rise to the phenomenon of beats. [LO 6.D.5.1, SP 1.2]	**Web** "Beats"	**Formative Assessment: Beats** Students use the simulation of a model of standing waves to investigate how beats are formed. The follow-up to their investigation is for students to evaluate the extent to which this model accurately represents the movement of the molecules in the air during a longitudinal wave oscillation. Some items to include in the refinement of their scientific questions should include the effect of air pressure, temperature, etc. Students write a report in their lab journals.
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. [LO 6.D.3.2, SP 6.4] Describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. [LO 6.D.3.4, SP 1.2] 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. [LO 6.D.4.1, SP 1.5, SP 6.1]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" **Web** "Standing Longitudinal Waves"	**Formative Assessment: Standing Longitudinal Waves** Working in pairs, students collect data from the simulation and use them to derive the equations for calculating the frequencies of standing longitudinal waves in tubes with either one or both sides closed.
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. [LO 6.D.4.2, SP 2.2]	**Supplies** Microphone, audio software, assorted hardware materials, additional materials (such as copper pipes, guitar strings, and wooden board) as needed	**Summative Assessment: Build a Musical Instrument** Students design and build a musical instrument that can play a full octave scale. Students must use frequency measurements to ensure that the instrument is in tune, and they also must play a simple song for the class.

I collect and review the students' journals, and in the following class I address any misunderstandings found in their reports.

Once students have produced their equations, I review their work. If I determine that the students' derivation does not match the expected equation, the students revise their work and I make suggestions to help guide their corrections accordingly. After completing the activity the students can look up the equations online or in their textbooks to verify their work.

The summative assessment addresses all of the guiding questions for this unit.

Unit 9: Electrostatics

Laboratory Investigations:

- Static Electricity Investigation
- Coulomb's Law (Lab Practicum)

Estimated Time:

1 Week

Guiding Questions: ▼ How can the charge model be used to explain electric phenomena? ▼ How can the forces between two charges be characterized using Newton's third law? ▼ How can preexisting knowledge of forces and energy be applied to processes involving electrically charged objects?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims about natural phenomena based on conservation of electric charge. [LO 1.B.1.1, SP 6.4] 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. [LO 1.B.1.2, SP 6.4, SP 7.2] Construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. [LO 1.B.2.1, SP 6.2] Challenge the claim that an electric charge smaller than the elementary charge has been isolated. [LO 1.B.3.1, SP 1.5, SP 6.1, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces" Hieggelke, Maloney, O'Kuma, and Kanim, E&M Tiper ET3-RT4 **Web** "Electric Charges: Charges and Sticky Tape" and "Electric Forces: Straws and Pens" **Supplies** Sticky tape, straws, pens, assorted cloth (wool, silk, fur), commercial electrostatics kit (optional)	**Instructional Activity: Static Electricity Investigation** Students follow the directions of the two online activities to gain experience with electrostatic phenomena while building understanding of electric charges and their interactions in conductors and insulators. Students use sticky tape and a variety of objects to make qualitative observations of the interactions when objects are charged, discharged, and recharged.
Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. [LO 3.C.2.1, SP 2.2, SP 6.4] Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. [LO 3.C.2.2, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces"	**Formative Assessment: Collaborative Problem Solving** In groups of three, students practice solving problems involving Coulomb's law. I provide them with problem-solving suggestions: • If more than two charged objects interact, draw a diagram showing the position of each object. • If the objects are in contact with each other, then charge transfer occurs and the law of conservation of charge must be applied to determine the charge on each object. • If more than two charged objects interact, use the vector component method to solve the problem applying Coulomb's law.

I circulate among the groups and assign specific teams to write their solutions on the board. The teams then review each other's work, asking questions and providing feedback. I also provide feedback directly to student groups as they work through the practice problems.

Guiding Questions: ▼ How can the charge model be used to explain electric phenomena? ▼ How can the forces between two charges be characterized using Newton's third law? ▼ How can preexisting knowledge of forces and energy be applied to processes involving electrically charged objects?

Learning Objectives	Materials	Instructional Activities and Assessments
Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. [LO 3.C.2.1, SP 2.2, SP 6.4] Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. [LO 3.C.2.2, SP 7.2]	**Supplies** Pith balls, string, analytical balance, meterstick	**Summative Assessment: Coulomb's Law (Lab Practicum)** Students work with a partner to design and conduct an experiment to estimate the charge on two identical, equally charged spherical pith balls of known mass. For this investigation, I require a detailed free-body diagram of the forces acting on each of the pith balls. Students show the sum of the forces and the derivation of the equation that allows them to estimate the charge on the pith balls. Students compare the magnitudes of the electric and gravitational forces exerted on the pith balls.

The summative assessment addresses all of the guiding questions in this unit.

Unit 10: DC Circuits

Laboratory Investigations:

- Brightness Investigation
- Voltage and Current Investigation
- Resistance and Resistivity Investigation
- Series and Parallel Circuits Investigation

Estimated Time:

3 Weeks

Guiding Questions: ▼ How do charges move through a conductor? ▼ How was the conventional direction of electric current determined? ▼ How can phenomena occurring in electric circuits be described by physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims about natural phenomena based on conservation of electric charge. [LO 1.B.1.1, SP 6.4] 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. [LO 1.B.1.2, SP 6.4, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" **Supplies** Small light bulbs, light bulb sockets, wires, batteries	**Instructional Activity: Brightness Investigation** Students working with a partner use wires, light bulbs, and batteries in guided-inquiry tasks that introduce the concepts of electric circuits, series connections, and parallel connections. The tasks require students to make predictions about the brightness of light bulbs in a circuit when some of the bulbs are removed.
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. [LO 5.B.9.2, SP 4.2, SP 6.4, SP 7.2] 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. [LO 5.C.3.2, SP 4.1, SP 4.2, SP 5.1]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" **Supplies** Small light bulbs, light bulb sockets, wires, batteries, digital multimeter or analog voltmeter and ammeter	**Instructional Activity: Voltage and Current Investigation** In the first part of this investigation, students work in small groups to design and implement an experiment to determine the relationship between the current through a resistor and the voltage across the resistor. In the second part of the lab, students test whether the relationship between current and voltage found in the previous experiment is applicable to a light bulb.
Choose and justify the selection of data needed to determine resistivity for a given material. [LO 1.E.2.1, SP 4.1]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" **Supplies** Play-Doh, variable power supply, ammeter, wire with alligator clips, meterstick	**Instructional Activity: Resistance and Resistivity Investigation** Students work with a partner to investigate the effects of cross-sectional area and length on the current through a roll of Play-Doh. To perform the investigation, students construct a simple circuit and take measurements of the current through rolls of Play-Doh of various dimensions.

Play-Doh is an ionic conductor so it offers an inexpensive way to investigate the effect of the geometry of a resistor.

Guiding Questions: ▼ How do charges move through a conductor? ▼ How was the conventional direction of electric current determined? ▼ How can phenomena occurring in electric circuits be described by physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits?

Learning Objectives	Materials	Instructional Activities and Assessments
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). [LO 5.B.9.1, SP 1.1, SP 1.4] 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. [LO 5.B.9.2, SP 4.2, SP 6.4, SP 7.2] 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. [LO 5.B.9.3, SP 2.2, SP 6.4, SP 7.2] 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. [LO 5.C.3.1, SP 6.4, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" Christian and Belloni, Problems 30.1 a–e and 30.3 **Web** "Circuit Construction Kit (DC only)"	**Instructional Activity: Circuits Simulation** Students use the Web simulation to construct a variety of series and parallel circuits. They then write descriptions of how the current and voltage work in each combination. Measurements of resistance, current, and potential differences must be included to validate their descriptions.

Using PhET's "Circuit Construction Kit" simulation is recommended prior to the "Series and Parallel Circuits" lab, as it allows the students to manipulate the equipment in a virtual setting and determine the correct placement of the ammeter and voltmeter.

Guiding Questions: ▼ How do charges move through a conductor? ▼ How was the conventional direction of electric current determined? ▼ How can phenomena occurring in electric circuits be described by physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits?

Learning Objectives	Materials	Instructional Activities and Assessments
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. [LO 5.B.9.2, SP 6.4, SP 7.2] 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. [LO 5.C.3.2, SP 4.1, SP 4.2, SP 5.1] Use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or branches of the circuit. [LO 5.C.3.3, SP 1.4, SP 2.2]	**Supplies** Assorted resistors, wires, battery, digital multimeter or analog voltmeter and ammeter	**Instructional Activity: Series and Parallel Circuits Investigation** Working in teams of three or four, students design and implement an experiment to investigate the behavior of resistors in series, parallel, and series–parallel circuits. The lab should include measurements of voltage and current. In this open-ended investigation, students build a minimum of three circuits, each with not more than four resistors and one battery. In their lab report, students must include their data, circuit schematics, and calculations of effective resistance.
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. [LO 5.B.9.3, SP 2.2, SP 6.4, SP 7.2] 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. [LO 5.C.3.1, SP 6.4, SP 7.2]		**Summative Assessment: Unit Test** Students are given a unit test with a set of multiple-choice questions and three free-response questions. On each of the free-response questions, students are required to clearly articulate how they applied Kirchhoff's rules in solving for unknowns in the circuits given.

The summative assessment addresses these guiding questions:

- *How do charges move through a conductor?*
- *How can phenomena occurring in electric circuits be described by physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power?*
- *How do conservation laws apply to electric circuits?*

Resources

General Resources

Christian, Wolfgang, and Mario Belloni. *Physlet® Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics.* Upper Saddle River, NJ: Prentice Hall, 2004.

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Supplementary Resources

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Unit 1 (Kinematics in One and Two Dimensions) Resources

Gende, Dolores. "Graphical Analysis of Motion: Kinematics." In *Special Focus: Graphical Analysis*, 9–24. AP Physics, Professional Development Workshop Materials, 2006–2007. New York: The College Board, 2006. Accessed January 14, 2013. http://apcentral.collegeboard.com/apc/public/repository/AP_Physics_Graphical_Analysis.pdf.

"The Moving Man." PhET. University of Colorado at Boulder. Accessed August 24, 2012. http://phet.colorado.edu/en/simulation/moving-man.

"Projectile Motion." PhET. University of Colorado at Boulder. Accessed August 24, 2012. http://phet.colorado.edu/en/simulation/projectile-motion.

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Unit 2 (Dynamics) Resources

"Bowling Ball Grand Prix." St. Louis Area Physics Teachers. Accessed September 3, 2012. http://slapt.org/resources/labs/bowlingprix.html.

"Forces in 1 Dimension." PhET. University of Colorado at Boulder. Accessed September 3, 2012. http://phet.colorado.edu/en/simulation/forces-1d.

"Inertial vs Gravitational Mass." Catharine H. Colwell. PhysicsLAB. Accessed September 3, 2012. http://dev.physicslab.org/Document.aspx?doctype=3&filename=Dynamics_InertialGravitationalMass.xml.

"Ramp: Forces and Motion." PhET. University of Colorado at Boulder. Accessed August 24, 2012. http://phet.colorado.edu/en/simulation/ramp-forces-and-motion.

Unit 3 (Circular Motion and Gravitation) Resources

"The Apple and the Moon." From *The Mechanical Universe… and Beyond*. California Institute of Technology and Intelecom, 1985. Video, 5:18. Accessed October 27, 2012. http://www.learner.org/resources/series42.html.

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All links to online resources were verified before publication. In cases where links are no longer working, we suggest that you try to find the resource by doing a keyword Web search.

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Unit 4 (Energy and Conservation of Energy) Resources

No unit-specific resources.

Unit 5 (Impulse, Momentum, and Conservation of Momentum) Resources

No unit-specific resources.

Unit 6 (Rotational Motion) Resources

No unit-specific resources.

Supplementary Resources

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Unit 7 (Rotational Motion and Conservation of Angular Momentum) Resources

"Kepler's Laws." Nuffield Foundation. Accessed March 23, 2013. http://www.nuffieldfoundation.org/node/1785.

Unit 8 (Mechanical Waves and Sound) Resources

"Beats." Walter Fendt. Java Applets on Physics. Accessed October 27, 2012. http://www.walter-fendt.de/ph14e/beats.htm.

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Exploratree. Concept-mapping tool. Accessed March 18, 2013. http://www.exploratree.org.uk.

Unit 9 (Electrostatics) Resources

"Electric Charges: Charges and Sticky Tape." Physics education server at Buffalo State College. Accessed October 27, 2012. http://physicsed.buffalostate.edu/SeatExpts/EandM/charges/index.htm.

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Unit 10 (DC Circuits) Resources

"Circuit Construction Kit (DC Only)." PhET. University of Colorado at Boulder. Accessed October 27, 2012. http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc.