AP® Physics 2: Algebra-Based

Course Planning and Pacing Guide

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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 2 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

Oak Ridge High School
Oak Ridge, Tennessee

School	Oak Ridge High School is a comprehensive public high school in a small rural city. The community values science and mathematics education in particular, in part due to the nearby presence of Oak Ridge National Laboratory.
Student population	The population of approximately 1,300 students is ethnically diverse; additionally, about 35 percent of the students at the high school and about 45 percent of the students in the district are considered economically disadvantaged. The school offers a wide variety of AP courses in all subject areas and has an 80–90 percent pass rate on AP examinations. Students' racial/ethnic demographics include the following: • African American: 13 percent • Asian/Pacific Islander: 4 percent • Hispanic: 5 percent • Native American/Alaskan: 0.4 percent • White: 77 percent
Instructional time	The school's instructional calendar typically runs from mid-August until very early June. Students attend each class every day on a traditional seven-period schedule. Classes are 53 minutes long every day except Wednesday, when classes meet for 35 minutes to accommodate early dismissal.
Student preparation	Students typically take AP Physics 2 during their junior or senior year after taking either AP Physics 1 or another prior introductory physics course. Most students' math co-enrollment is Algebra II or higher.

Primary planning resources	Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach.* 2nd ed. Boston: Addison-Wesley, 2012. This text is more conceptual than most AP or college textbooks and provides good scaffolding of concepts. It is organized in a way that is consistent with the redesigned algebra-based AP Physics course. Walker, James. *Physics*. 4th ed. Boston: Addison-Wesley, 2009. This text clearly explains difficult concepts, and has very good end-of-chapter problems, particularly those supporting graphical skills. O'Kuma, Thomas L., David P. Maloney, and Curtis J. Hieggelke. *Ranking Task Exercises in Physics*. Student ed. Boston: Addison-Wesley, 2004. This student workbook contains a set of challenging conceptual problems that require little in the way of mathematical prowess to solve. The problems are particularly valuable for formative assessment. Nearly all content areas in AP Physics are covered. Hieggelke, Curtis J., David P. Maloney, Stephen E. Kanim, and Thomas L. O'Kuma. *E&M TIPERs: Electricity and Magnetism Tasks*. Boston: Addison-Wesley, 2005. Conceptual questions in this student workbook are limited to electricity and magnetism. In addition to ranking tasks, other conceptual problem types are included. "The AP Physics B Exam." The College Board. Accessed March 12, 2013. http://apcentral.collegeboard.com/apc/members/exam/exam_information/2007.html. Although the Physics 2 Exam differs from the Physics B Exam, some Physics B free-response questions are appropriate for student practice and can provide formative assessment data for the teacher. "AP Physics 2 Practice Exam." The College Board. http://www.collegeboard.com/html/apcourseaudit/teacher.html. This practice exam will be available beginning in summer 2014 through the AP Course Audit website.

Overview of the Course

During the 14 years I have taught AP Physics at Oak Ridge High School, I have come to the realization that the less I *tell* students about physics, the better. Instead, I offer more hands-on exploratory activities in the curriculum, encourage more collaboration, and ask more questions that demand a high-quality explanation — this is how my students build an enduring understanding of physics principles. This is particularly true with students who are less proficient in mathematics. All students seem to enjoy physics more when it is taught in a relaxed, inquiry-based, collaborative setting, with mathematics used as a valuable tool rather than the driving force.

I believe that active engagement is foundational to a student's ability to understand physics. Through empirical investigation, students engage in hands-on data collection and analysis; other instructional activities encourage students to ask and answer questions and support conclusions based on evidence. The student who does not become a scientist or engineer benefits by gaining an appreciation of scientific practices and an understanding of the nature of scientific inquiry. Embedded mathematics and graphical skills are learned in context. Students develop the ability to communicate the results of their investigations through creating and analyzing multiple representations, including diagrams, graphs, equations, and words. They learn to brainstorm and to talk intelligently about science.

Students devote at least 25 percent of their time in class to laboratory investigations. Some teachers tend to avoid inquiry-based and open-ended lab investigations because of time constraints imposed by written lab reports. We all know that full lab reports take a lot of time to write and grade! I get around this limitation by allowing partial reports for some laboratories. Once or twice per grading term I require complete lab reports consisting of purpose, hypothesis, theory, equipment, procedure, data, calculation, results, and discussion sections. I recommend that all laboratory investigations include some combination of written data, calculation, results, and discussion to support student learning.

My AP Physics students are all individuals in terms of learning styles, mathematical prowess, creativity, and verbal expressiveness; therefore, differentiation of instructional activities is important. In collaborative activities, such as major projects, students are allowed a great deal of choice in how they approach the assignment. Activities such as the Hurricane Katrina Project, which is part of my fluid mechanics unit, are particularly engaging for students, in part because of the choice they are allowed. I also like to give collaborative groups different problems to work on for presentation to the class. This allows me to keep everyone working at his or her level of mathematical expertise. In algebra-based physics, students who are prepared to solve problems using calculus should be provided with an opportunity to do so.

Over time, I have developed an increasing appreciation for formative assessment, and I use some form of it every day in class. I typically begin class with clicker questions (in which students use electronic devices to register their responses), and from the histogram of responses I can tell how well the class understands a concept. I sometimes ask clicker questions before introducing a topic, to gain a sense of students' prior knowledge. I also make extensive use of ranking tasks and other conceptual questions, which allow me (and my students) to know which concepts need to be reinforced. Some published AP Physics B problems are useful for this as well. In this guide, I provide several examples of formative assessment strategies and activities that I use.

The most important thing about an inquiry- and activity-based physics course, however, is that it is just plain fun. I hope that if you base your course on this guide, you and your students will find the course engaging and memorable.

Unit 1: Fluid Mechanics

Laboratory Investigations:

- Water Pressure and Depth
- Using Buoyant Force to Determine Water Density
- Bernoulli Principle and Energy

Estimated Time: *20 days*

Guiding Questions: ▼ What causes pressure to be exerted by a fluid, and why does liquid pressure vary with depth when gas pressure does not? ▼ How is the buoyant force generated, and how can this force be mathematically modeled? ▼ Why does the buoyant force not vary significantly with depth, even though liquid pressure does? ▼ How can conservation of mass and conservation of energy be used to predict the behavior of moving liquids?

Learning Objectives	Materials	Instructional Activities and Assessments
Use Bernoulli's equation and the relationship between force and/or pressure to make calculations related to a moving fluid. [LO 5.B.10.2, SP 2.2]	**Supplies** Bucket, water, meterstick, nail **Web** "Fluids Experiment: Show Relationship Between Water Pressure and Depth" **Online video** "27: Gases and Incompressible Fluids"	**Instructional Activity:** Students explore the relationship between water pressure and depth in a lab by doing the following: 1. Punch a small hole on the side and near the bottom of a small plastic bucket. 2. Place the bucket on a low platform. 3. Fill the bucket with water. 4. For various water depths, measure the horizontal distance traveled by the emerging stream of water. Following the lab activity, students watch a short portion of a lecture about hydrostatic pressure by MIT's Walter Lewin. Students then examine the terms in Bernoulli's equation and write an explanation of how each term applies both to the lab and to Lewin's lecture.
	Print O'Kuma, Maloney, and Hieggelke, SHM and Properties of Matter Ranking Tasks, pp. 107–108	**Formative Assessment:** In these ranking task activities, students examine illustrations and collaboratively rank pressure at various depths of water. I review the rankings to determine how well the students understand the relationship of pressure to depth and ask students who clearly understand the relationship to explain their reasoning to the class. Once students demonstrate that they have mastered this skill, they attempt the exercise again for liquids that also vary in density.

Bernoulli's equation is usually used for calculating the pressure of moving fluids, but it is applicable to stationary fluids as well. Students should be able to show how this equation predicts a linear relationship between fluid pressure and depth for a stationary fluid.

Ranking tasks are particularly good for assessing conceptual understanding. They are fun and challenging and do not require much math. Students must explain reasoning as part of the activity, and their explanations provide me with valuable feedback about their understanding of concepts. I correct any misconceptions the students demonstrate as they provide their rankings.

Guiding Questions: ▼ What causes pressure to be exerted by a fluid, and why does liquid pressure vary with depth when gas pressure does not? ▼ How is the buoyant force generated, and how can this force be mathematically modeled? ▼ Why does the buoyant force not vary significantly with depth, even though liquid pressure does? ▼ How can conservation of mass and conservation of energy be used to predict the behavior of moving liquids?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction. [LO 1.E.1.1, SP 4.2, SP 6.4] Select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects. [LO 1.E.1.2, SP 4.1, SP 6.4] 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]	**Supplies** Small metal cylinders (approximately 100 g each), string, low-friction pulleys and stands, calibrated masses, paper clips of known mass to use for small masses, cups of water, Vernier calipers	**Instructional Activity:** In this guided-inquiry activity, students use the materials provided to determine the density of water. They hang a cylinder on one side of a pulley and hang known weights on the other side to balance it. By doing this with the cylinder hanging in air and again submerged in water, they can observe and record the apparent weight change. The volume of the cylinder is determined using the caliper.
		Formative Assessment: Students explain, in terms of pressure differential, how water and other liquids exert a net upward force that reduces the apparent weight of a submerged object. They compare the buoyant force exerted on submerged cylinders of equal mass but different density. They evaluate their own reasoning in subsequent group and class discussions, and finally by reading about Archimedes' principle in their textbooks.
		Formative Assessment: Students individually describe in writing the molecular origin of buoyancy. I use a document camera to present student work to the class for discussion. During this activity, the class provides peer feedback.

I get information about students' learning based on the class discussion. I can then provide feedback and correct misconceptions as needed.

I provide verbal feedback directly to students when necessary to guide the class to a correct conceptual understanding.

Guiding Questions: ▼ What causes pressure to be exerted by a fluid, and why does liquid pressure vary with depth when gas pressure does not? ▼ How is the buoyant force generated, and how can this force be mathematically modeled? ▼ Why does the buoyant force not vary significantly with depth, even though liquid pressure does? ▼ How can conservation of mass and conservation of energy be used to predict the behavior of moving liquids?

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] 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] Re-express 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] 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. [LO 3.B.1.4, SP 6.4, SP 7.2]	**Web** "Buoyancy"	**Instructional Activity:** Students explore the buoyancy force using this PhET simulation lab, which enables them to visualize the buoyant force vector, its dependence on displaced fluid volume, and its relationship to other forces. Students record their experiments and observations in a lab book and describe how the phenomena they observe can be explained by the relative magnitudes of the buoyant, gravitational, and contact (normal) forces.
	Print O'Kuma, Maloney, and Hieggelke, SHM and Properties of Matter Ranking Tasks, pp. 105–106	**Formative Assessment:** These ranking tasks require students to collaboratively determine the magnitude of the buoyant force on floating objects and on objects at rest at the bottom of a filled container. Groups must explain their rankings to their classmates and to me.
	Web Bertrand, "Hurricane Katrina: A Teachable Moment"	**Instructional Activity:** Based on a photograph taken of a brick house that floated during Hurricane Katrina's storm surge, students estimate the mass of the house plus its contents. In this collaborative activity, students develop the skill of estimation in addition to an understanding of buoyant force.
Make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). [LO 5.F.1.1, SP 2.1, SP 2.2, SP 7.2] Use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. [LO 5.B.10.3, SP 2.2]	**Web** "Bernoulli Principle Animation"	**Instructional Activity:** Students explore the Bernoulli principle using the "Pipe Demo" simulation on this website. This and other online simulations enable students to qualitatively describe how the speed of fluid flow is related to cross-sectional area of a level pipe.

In this simulation, the term contact force is used specifically for the normal force. The simulation does not present the buoyant force as a type of contact force.

I provide direct feedback to students as they present their rankings to their classmates.

Guiding Questions: ▼ What causes pressure to be exerted by a fluid, and why does liquid pressure vary with depth when gas pressure does not? ▼ How is the buoyant force generated, and how can this force be mathematically modeled? ▼ Why does the buoyant force not vary significantly with depth, even though liquid pressure does? ▼ How can conservation of mass and conservation of energy be used to predict the behavior of moving liquids?

Learning Objectives	Materials	Instructional Activities and Assessments
Make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). [LO 5.F.1.1, SP 2.1, SP 2.2, SP 7.2] Use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. [LO 5.B.10.3, SP 2.2]		**Formative Assessment:** Students discuss the following questions: *What is constant when fluid flows in a continuous pipe of varying cross-sectional area? What varies?* Using dimensional analysis and the principle of conservation of mass, students develop expressions for fluid flow continuity: $\frac{V}{t} = Av$ and $A_1v_1 = A_2v_2$. Deriving equations, when they are within the mathematical capabilities of the students, is highly effective in producing conceptual understanding, provided the derivations are done with great attention to the physical meaning of each mathematical symbol.
Use Bernoulli's equation to make calculations related to a moving fluid. [LO 5.B.10.1, SP 2.2] Use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. [LO 5.B.10.2, SP 2.2] Use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. [LO 5.B.10.3, SP 2.2] Construct an explanation of Bernoulli's equation in terms of the conservation of energy. [LO 5.B.10.4, SP 6.2]	**Web** "Fluid Pressure and Flow"	**Instructional Activity:** The "Pressure" and "Flow" experiments in this comprehensive simulation reinforce previous activities in this unit, while the "Water Tower" simulation provides a fuller investigation of the Bernoulli principle. Students collect data and analyze it using the Bernoulli equation.
		Instructional Activity: I show video clips of "Demonstrations in Physics with Julius Sumner Miller – Gases and Liquids Part 1." (This video can easily be found online.) Miller's videos are still one of the best ways to engage students and get them thinking about a particular physics concept. In these clips, Professor Miller performs several demonstrations in rapid-fire sequence in his typical exuberant style. After watching the video clips, students use appropriate physics concepts to explain each of the demonstrations.

I evaluate the quality of the discussion and the clarity and correctness of the derivations, providing assistance where needed. This helps me determine whether any reteaching is necessary before we move on to the next topic.

The visual and auditory quality of these old video clips is poor by today's standards. Nonetheless, students often find them very engaging, perhaps in part because of their vintage appearance.

Guiding Questions: ▼ What causes pressure to be exerted by a fluid, and why does liquid pressure vary with depth when gas pressure does not? ▼ How is the buoyant force generated, and how can this force be mathematically modeled? ▼ Why does the buoyant force not vary significantly with depth, even though liquid pressure does? ▼ How can conservation of mass and conservation of energy be used to predict the behavior of moving liquids?

Learning Objectives	Materials	Instructional Activities and Assessments
Use Bernoulli's equation to make calculations related to a moving fluid. [LO 5.B.10.1, SP 2.2] Use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. [LO 5.B.10.2, SP 2.2] Use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. [LO 5.B.10.3, SP 2.2] Construct an explanation of Bernoulli's equation in terms of the conservation of energy. [LO 5.B.10.4, SP 6.2]	**Supplies** Supplies will vary based on students' experimental designs	**Instructional Activity:** Students design and run a lab to show the validity of the Bernoulli equation. To support the understanding that the Bernoulli principle is based on conservation of energy, students should compare experimentally determined energy content at a minimum of two locations on their designed apparatus. To do so, they must explicitly analyze each part in the Bernoulli equation in terms of how it relates specifically to energy.
	Web Bertrand, "Hurricane Katrina: A Teachable Moment"	**Formative Assessment:** Topics in the "Hurricane Katrina: A Teachable Moment" article include the fluid mechanics of Hurricane Katrina, the Bernoulli principle, building in storm-prone areas, dam and levee construction, the physics of hurricanes, etc. Students in collaborative teams choose a fluids topic from the article and prepare a presentation for the class. All topics involve the impact of fluid mechanics in a social setting. Presentations can involve role-play and may be live or recorded on video. Historical research on the selected topic is necessary for each project.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from the practice exam provided by the College Board.

I use a rubric-based grading scheme to evaluate students' depth of understanding and ability to explain how physics laws and principles were involved in this historical event. Students are given feedback on their ability to apply relevant physics principles and to convey them in presentation form.

All of the guiding questions for this unit are addressed in this summative assessment.

Laboratory Investigations:

- Calculating Thermal Conductivity
- Heat Engine
- Hair Dryer Efficiency

Estimated Time: *20 days*

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed. [LO 5.D.1.6, 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.1.7, SP 2.1, SP 2.2] 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]	**Web** "Collision Lab"	**Instructional Activity:** Students individually work with the simulation to explore the characteristics of one-dimensional elastic and inelastic collisions. They collect data to calculate and compare system momentum and system kinetic energy before and after collisions with varying degrees of inelasticity. Students then write a paragraph defining the characteristics of elastic collisions, and they justify their claims about elastic collisions with evidence from their data.
		Instructional Activity: Students in small lab groups work with the advanced activity in the simulation to explore the characteristics of two-dimensional elastic and inelastic collisions. After they have compared system momentum and kinetic energy for different collision types, they use the simulation to construct a model that would represent an ideal gas in a container. They must describe in writing how their model is representative and what its limitations are.
		Formative Assessment: Students individually describe in writing the type of collision they think occurs in a container of ideal gas. They consider collisions between individual gas molecules and collisions between gas molecules and the walls of the container. They must articulate the reasons they have selected a particular collision type. After writing their individual statements, students in small groups combine their descriptions to produce group reports, which are presented to the class for discussion.

I monitor the discussion, guiding it where necessary, to ensure the class understands that collision of ideal gas molecules is elastic. The discussion informs my decisions about next instructional steps.

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Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables. [LO 7.A.3.2, SP 3.2, SP 4.2] Analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$. [LO 7.A.3.3, SP 5.1] Treating a gas molecule as an object, analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables. [LO 7.A.1.2, SP 1.4, SP 2.2] Extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. [LO 7.A.3.1, SP 6.4, SP 7.2] Make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container, and how changes in pressure affect the thermal equilibrium of the system. [LO 7.A.1.1, SP 6.4, SP 7.2]	**Web** "Gas Properties"	**Instructional Activity:** Students first use the simulation to visualize the behavior of an ideal gas at the molecular level. They then propose a mechanism, consistent with considering molecules as objects, by which the ideal gas exerts pressure on the container walls. They also make claims based on evidence for a specific collision type (elastic or inelastic) between molecules in an ideal gas and between gas molecules and the container wall. **Instructional Activity:** Students investigate the interdependence of volume, pressure, and temperature for an ideal gas, using measurement tools in the simulation to collect data and create graphs. Students construct written responses describing what the physical consequences would be if (a) gas molecules underwent inelastic collisions, (b) gas molecules did not exert forces on each other during collisions, and (c) gas molecules exerted long-range attractive forces on each other. Students also identify what they think is the cause of the repulsive force that exists between molecules of an ideal gas and other gas molecules and between gas molecules and the container wall. They must justify their answers.

During this activity, I encourage students to apply classical mechanics concepts of Newton's third law, conservation of linear momentum, and conservation of energy to the molecular level.

Students should remember ideal gas laws from chemistry. It is advisable to remind them of ideal gas behavior but not to spend too much time on it. In AP Physics, we are more interested in how a container of ideal gas can function as a heat engine.

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

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	Print O’Kuma, Maloney, and Hieggelke, Heat and Thermodynamics Ranking Tasks, pp. 110, 114, 118, 120–121	**Formative Assessment:** Working in groups, students solve and present the solutions to different ranking task problems involving heat and thermodynamics.

I encourage discussion during the presentations and monitor explanations for correct use of the ideal gas law. The discussion informs my decisions about next instructional steps.

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level [LO 4.C.3.1, SP 6.4] Describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation. [LO 5.B.6.1, SP 1.2] Construct an explanation, based on atomic-scale interactions and probability, of how a system approaches thermal equilibrium when energy is transferred to it or from it in a thermal process. [LO 7.B.1.1, SP 6.2] Design an experiment and analyze data from it to examine thermal conductivity. [LO 1.E.3.1, SP 4.1, SP 4.2, SP 5.1]		**Instructional Activity:** I show video clips of “Demonstrations in Physics with Julius Sumner Miller – Heat and Temperature Parts 1 and 2.” (These videos can easily be found online.) Miller is particularly good at explaining thermodynamics concepts. After watching the video clips, students use appropriate physics concepts to discuss each of the demonstrations.
	Web “Physics/Chemistry – Heat Energy”	**Instructional Activity:** In teams, students explore this site to answer questions such as the following: (a) How does temperature difference affect heat transferred between two systems in contact? (b) By what mechanism do the molecules of one system transfer heat to the molecules of another system? (c) How does conservation of momentum apply to heat transfer? (d) How does conservation of energy apply to heat transfer? (e) What conditions must exist for thermal equilibrium to be established? (f) How do conduction, convection, and radiation differ in the way they cause heat to be transferred from one system to another? Student teams focus on the questions that interest them the most and report their findings to the class for discussion.
	Supplies Polystyrene cups, glass beakers, steel cups, aluminum cups, water, thermometers, calipers, hot-water baths, ice baths, stopwatches	**Instructional Activity:** Students in collaborative lab groups design a procedure to collect data that can be used to calculate the thermal conductivity of Styrofoam, glass, steel, and aluminum. They collect data, perform calculations, and compare the results to standard values. A full or partial written lab report is submitted.

I evaluate student discussion for understanding that elastic collisions between molecules are involved in the transfer of thermal energy. Students should also understand that thermal equilibrium does not mean that all molecules have the same kinetic energy but rather that there is an average kinetic energy for all molecules in the system.

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. [LO 7.A.2.1, SP 7.1] Connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and relate this to thermodynamic processes. [LO 7.A.2.2, SP 7.1]	**Web** "Gas Properties"	**Instructional Activity:** Students use the simulation introduced earlier in this unit for another study. After they add gas molecules to the chamber, they add or remove heat and collect data on molecular speed, kinetic energy, and temperature. Groups present answers to the following questions: (a) How does molecular speed depend upon temperature? (b) How does molecular kinetic energy depend upon temperature? (c) Do all the molecules have the same speed or kinetic energy? (d) Does a given molecule have the same speed or kinetic energy over time? (e) How does the average speed and kinetic energy vary over time at constant temperature? (f) What differences do you observe between light and heavy gas molecules at the same temperature? (g) How is energy transferred from one molecule to another?
Describe and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. [LO 5.B.7.1, SP 6.4, SP 7.2]		**Instructional Activity:** I explain to students that the "internal energy" of a gas describes the energy it can exchange in the form of heat or work. They use their understanding of the molecular model of an ideal gas to propose which of the variables in $PV = nRT$ are most directly related to internal energy.
	Print O'Kuma, Maloney, and Hieggelke, Heat and Thermodynamics Ranking Tasks, pp. 113, 115–117, 121	**Formative Assessment:** In small collaborative groups of two or three, students construct answers in writing to these conceptual exercises. Students present their answers to the class, prompting discussion.

I offer direct feedback on the exercise to individual students or to the entire class when the class is unable to arrive at a correct consensus answer.

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. [LO 5.B.7.1, SP 6.4, SP 7.2]		**Instructional Activity:** I explain that the first law of thermodynamics is a version of the law of conservation of energy in which heat and mechanical work are both taken into account. Assuming a container of ideal gas as a system, students draw a graphic model representing the first law of thermodynamics, using arrows to represent energy exchange as heat or work between the system and its environment. Students then express the first law of thermodynamics in equation form.
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. [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] Design an experiment and analyze graphical data in which interpretations of the area under a pressure-volume curve are needed to determine the work done on or by the object or system. [LO 5.B.5.6, SP 4.2, SP 5.1] Create a plot of pressure versus volume for a thermodynamic process from given data. [LO 5.B.7.2, SP 1.1] Use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). [LO 5.B.7.3, SP 1.1, SP 1.4, SP 2.2]	**Supplies** Heat engine/gas law apparatus (e.g., the PASCO TD-8572, a commercial gas law apparatus consisting of a piston with a platform that can raise and lower weights, a submersible air chamber, tubing, and one-way check valves), two 1000 mL beakers for hot and cold water, ruler, pressure gauge, calipers, masses (20, 50, 100, 200 g), hot plate, ice	**Instructional Activity:** Using the apparatus in combination with hot- and cold-water reservoirs, students demonstrate how the flow of heat through a heat engine can be harnessed to perform mechanical work by lifting a weight. Students collect and graph pressure-versus-volume data for the gas (air). They compare the work done in lifting the weight, $F(\Delta y)$, to the area under the *PV* curve for a complete cycle and estimate thermodynamic efficiency. Students explain in writing how their mathematically and graphically determined mechanical work for each process is related to the fundamental concept that work is force multiplied by distance.
	Web "The AP Physics B Exam": 2010 Form B, Question 4; 2009 Form B, Question 4; 2007 Form B, Question 5; 2006 Form B, Question 5	**Formative Assessment:** I provide practice problems from published AP examinations. Students use accompanying scoring rubrics to correct their own work. It is important to continue emphasizing fundamental concepts of molecular kinetic energy and its relationship to internal energy and temperature throughout formative assessment exercises.

If you have only one gas law apparatus, the investigation may be done as a demonstration during which data is collected for independent analysis by students. Remind students that the bounded area on a PV graph is related to net work, and ask them to tell you why this is so. Using the definitions of pressure and work, guide them to show that $W_g = P\Delta V$.

While Physics B free-response questions are not reliable representatives of the questions on the AP Physics 2 Exam, some Physics B questions, such as those cited here, can provide a starting point for physics teachers to develop their own formative assessment questions.

Students submit their corrected problems, including a verbal analysis of mistakes they made. I provide feedback on their original work and their analysis.

Thermodynamics

(continued)

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Connect qualitatively the second law of thermodynamics in terms of the state function called entropy and how it (entropy) behaves in reversible and irreversible processes. [LO 7.B.2.1, SP 7.1]	**Supplies** Pieces of cotton fabric (old T-shirts may be used), water, mass balances, hair dryers with known power ratings, timers	**Instructional Activity:** In small groups, students use hair dryers to partially dry wet fabric; from the power rating of the hair dryers, the drying time, and the amount of water evaporated, students determine hair-dryer efficiency. They discuss whether a hair dryer that is 100 percent efficient could be invented.
	Web "Second Law of Thermodynamics"	**Instructional Activity:** Working in small groups, students explore the Web, beginning with the resource given, for information on the second law of thermodynamics, entropy, and reversible and irreversible processes. Each group of students researches all three topics and is responsible for coming up with examples of reversible and irreversible processes, which they must describe in terms of the associated entropy changes. The students return to the hair-dryer discussion and assess the feasibility of a 100 percent efficient hair dryer in terms of the second law of thermodynamics. I monitor discussions for correct application of the concepts of entropy (disorder) and irreversibility.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from the practice exam provided by the College Board.

All of the guiding questions for this unit are addressed in this summative assessment.

Unit 3:

Electrostatics

Laboratory Investigations:

- Balloons and Static Charge
- Electroscope Polarization
- Estimated Electrons on Charged Beads
- Mapping the Electric Field Around a Dipole
- Mapping the Electric Field Between Parallel Plates

Estimated Time:

20 days

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict electric charges on objects within a system by application of the principle of charge conservation within a system. [LO 5.C.2.1, SP 6.4] Make predictions about the redistribution of charge during charging by friction, conduction, and induction. [LO 4.E.3.1, SP 6.4] Make claims about natural phenomena based on conservation of electric charge. [LO 1.B.1.1, SP 6.4] 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]	**Supplies** Balloons, pieces of tissue paper	**Instructional Activity:** Students are provided with inflated balloons and are instructed to pick up small pieces of tissue paper from their desks with the balloons. They rub the balloons on a sweater or on their hair, charging them, and then they can pick up the paper pieces. They can also stick the balloons to their hair or sweaters and to walls. Students then draw diagrams that depict their idea of a model that explains what happens (a) when the balloon is charged, and (b) when the charged balloon picks up the paper. Students work in small groups on large whiteboards or large sheets of butcher paper. The students then do a gallery walk, using sticky notes to place comments on their classmates' work.
	Web "Balloons and Static Electricity"	**Formative Assessment:** Students discuss and construct a written response to what they think happens in the balloon experiment. They then use this simulation to help clear up misconceptions that might have been revealed in their written response. Some students will likely believe that positive charge is transferred when the balloon is charged; it is important they be reminded that positive charge is in the atomic nucleus and does not move around. The simulation can also help students visualize the polarization of neutral objects such as pieces of paper or a wall. Following the simulation, students revisit their explanations for the balloon investigation and modify their written explanations based on what they observed in the simulation.

All electrostatic experiments are best done on cool, dry days.

I monitor student responses and provide direct feedback to students during this activity. It is important that students identify the electrons as the movable charged particle during charge transfer and polarization activities.

Electrostatics

(continued)

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data. [LO 5.C.2.2, SP 4.2, SP 5.1] Make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. [LO 1.B.2.2, SP 6.4, SP 7.2] Challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object. [LO 1.B.2.3, SP 6.1] Construct a representation of the distribution of fixed and mobile charge in insulators and conductors. [LO 4.E.3.3, SP 1.1, SP 1.4, SP 6.4] Construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction. [LO 4.E.3.4, SP 1.1, SP 1.4, SP 6.4] Make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects. [LO 4.E.3.2, SP 6.4, SP 7.2] Plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure. [LO 4.E.3.5, SP 3.2, SP 4.1, SP 4.2, SP 5.1, SP 5.3]	**Supplies** Electroscopes, rubber rods, glass rods, rabbit fur, silk	**Instructional Activity:** Student teams conduct the following short experiments: 1. Rub the rubber rod with rabbit fur. Bring the rod toward the pole of the electroscope without touching it, and move it away again. 2. Rub the glass rod with silk. Bring the rod toward the pole of the electroscope without touching it, and move it away again. 3. Rub the rubber rod with rabbit fur. Touch the pole of the electroscope with the rod, and move it away again. Student teams record their observations and construct explanations using atomic-level physics. The explanations must include a sketch describing charge distribution on the nonconducting rods and the initially uncharged electroscope. In written form, students defend their ideas about whether there is charge transfer, using evidence from the experiments.

Focus on students' verbal descriptions as well as sketches to be sure charging and polarization are understood. For the first two experiments described, be alert to students who think the electroscope is charged or that protons are moving.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Qualitatively and semi-quantitatively apply the vector relationship between the electric field and the net electric charge creating that field. [LO 2.C.2.1, SP 2.2, SP 6.4] Explain the inverse square dependence of the electric field surrounding a spherically symmetric electrically charged object. [LO 2.C.3.1, SP 6.2]	**Web** "Charges and Fields"	**Instructional Activity:** Students use the simulation to measure the field strength at various distances from a defined point charge and to measure how the field strength varies with charge at constant radius. The simulation also allows for the visualization of field vectors. I guide students to collect enough data to clearly suggest an inverse squared dependency of field with radius, and a direct linear relationship of field with charge. Students produce graphs to show functional dependencies and explain why the electric field varies inversely with the surface area of a sphere. They also identify other physical systems that show this dependence (e.g., gravitational fields, light intensity).

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict the direction and the magnitude of the force exerted on an object with an electric charge *q* placed in an electric field *E* using the mathematical model of the relation between an electric force and an electric field: $\vec{F} = q\vec{E}$ a vector relation. [LO 2.C.1.1, SP 6.4, SP 7.2] Challenge a claim that an object can exert a force on itself. [LO 3.A.3.2, SP 6.1] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] Calculate any one of the variables — electric force, electric charge, and electric field — at a point given the values and sign or direction of the other two quantities. [LO 2.C.1.2, SP 2.2] Make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge. [LO 3.A.3.4, SP 6.1, SP 6.4] 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] Use mathematics to describe the electric force that results from the interaction of several separated point charges. [LO 3.C.2.3, SP 2.2] Justify the selection of data relevant to an investigation of the electrical charging of objects and electric charge induction on neutral objects. [LO 5.C.2.3, SP 4.1]	**Print** O'Kuma, Maloney, and Hieggelke, Electrostatics Ranking Tasks, pp. 136–138 Hieggelke, Maloney, Kanim, and O'Kuma, Conflicting Contention Tasks eT3-CCT1 and eT6-CCT1	**Instructional Activity:** Students work in pairs on conceptual exercises that emphasize the direct relationship between electric field and force. Many of these exercises require students to go beyond a simple calculation and invoke Newton's laws or graphical interpretation. The exercises also include conflicting contention tasks, which involve students evaluating correct and incorrect arguments and encourage discussion of common misconceptions. One clarification that may be necessary is an explanation that the electric field itself arises from a charge configuration; therefore, the requirement that forces must arise from the interaction of bodies with the same property (in this case, electric charge) is not violated when forces are calculated from fields.
	Supplies Small plastic beads, string, rubber rods, balances, metersticks	**Instructional Activity:** A student holds two strings, each connected to a small plastic bead, such that the beads hang straight down. Another student charges a rubber rod and touches the rod to the beads. The beads repel each other. Students must explain the phenomenon qualitatively in terms of charge transfer and approximate the number of extra electrons on each bead, assuming each bead has an identical number of electrons. Measurements must be taken of bead mass, string length, and the distance between the beads. Students calculate electric force on one bead, assuming gravitational force and tension are the two other forces. Students draw free-body diagrams in this analysis, and I ensure that measurements are recorded as accurately as possible.

Ranking tasks and TIPERs are most valuable when used not for grades but for sparking discussions that develop conceptual understanding. Evaluation of student work should go beyond the correct answer and focus on the reasoning behind its selection. Addressing misconceptions such as those in conflicting contention tasks is an integral part of a constructivist approach to mastering difficult content and has been shown consistently to be effective in PER (Physics Education Research).

The calculation performed in this activity reminds students that Newton's first law is still useful in electrostatics.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semi-quantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. [LO 2.C.4.1, SP 6.4, SP 7.2] Apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points. [LO 2.C.4.2, SP 1.4, SP 2.2]	**Web** "Charges and Fields"	**Instructional Activity:** Students use this simulation to compare the electric field resulting from a single point charge to that resulting from a system of two charges. Students must explain, using vector addition, what is meant when we say that the electric field due to multiple charges is a result of superposition of the electric field due to each individual charge. Students must consider the magnitude and direction of the fields produced by individual charges and perform graphical vector addition properly. Students must be able to distinguish between the lines of force of a typical field map and the field vector at a given point.
	Print O'Kuma, Maloney, and Hieggelke, Electrostatic Ranking Tasks, p. 141 Hieggelke, Maloney, Kanim, and O'Kuma, Ranking Tasks eT5-RT6, eT5-RT8, and eT5-RT12; Conflicting Contention Tasks eT5-CCT4 and eT5-CCT5	**Formative Assessment:** Groups of students use superposition to solve various ranking task or conflicting contention problems. Each group is responsible for presentation of a solution and for managing the ensuing discussion. Large sheets of butcher paper or newsprint make ideal "panels" for a "panel discussion." Groups are expected to show clearly how they arrived at their conclusions.
	Web "The AP Physics B Exam": 2001 Form B, Question 3; 2005 Form B, Question 3	**Formative Assessment:** Once we have reviewed the process of vector addition and I am confident that students understand the concept of superposition, the students individually solve quantitative problems drawn from AP Physics B exams.

It is important to scaffold superposition concepts. Begin with graphical vector addition of fields from just two charges to get the resultant field. The graphical method is more conceptual than the trigonometric method and does not tempt students to focus on the math rather than the physics.

I monitor students' work for demonstration of correct thinking regarding magnitude and especially direction of the fields that are added in these largely conceptual superposition problems, and I provide verbal feedback as problems are solved and then presented to the class.

I provide feedback to students on the accuracy of their work, but students also use provided rubrics to assess their own understanding.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	**Web** Bertrand, "Conceptual Links in Electrostatics" Wells, "Electric Potential and Potential Energy"	**Instructional Activity:** Students consider a model in which a static charge configuration modifies the empty space around it and produces an electric field and electric potential at a point in space that can be used to calculate the electric force and electric potential energy, respectively, of a charged particle placed at that point. Students discuss whether this model is consistent with the classical understanding that forces and potential energies cannot exist for one particle alone. I monitor the discussion and guide students to acknowledge that fields and potentials imply the existence of other particles, which may be outside of the immediate field of view, that interact with a particle placed in the field. Therefore, the field model does not violate the necessity to have multiple particles interacting.
Determine the structure of isolines of electric potential by constructing them in a given electric field. [LO 2.E.2.1, SP 6.4, SP 7.2] Predict the structure of isolines of electric potential by constructing them in a given electric field and make connections between these isolines and those found in a gravitational field. [LO 2.E.2.2, SP 6.4, SP 7.2] Qualitatively use the concept of isolines to construct isolines of electric potential in an electric field and determine the effect of that field on electrically charged objects. [LO 2.E.2.3, SP 1.4] Apply the concept of the isoline representation of electric potential for a given electric charge distribution to predict the average value of the electric field in the region. [LO 2.E.3.2, SP 1.4, SP 6.4] ***(learning objectives continue)***	**Supplies** Conducting paper with two circular electrodes painted on it at opposite ends with silver conducting ink, cork or wood boards, thumbtacks, batteries or power supplies, electrical leads, digital multimeters **Web** "The Electric Force Field"	**Instructional Activity:** In pairs or small groups, students connect silver electrodes to positive and negative terminals of a potential source by driving thumbtacks through leads and into paint, thus creating a dipole. A potential of between 3 to 10 volts is applied between the electrodes. The field is mapped by holding the digital multimeter probes a small fixed distance apart and, starting with the negative probe on the positive electrode, marking the path of the greatest negative potential change from the positive to the negative electrode. Students mark dots on the conducting paper with pencils, and after the path has been identified, they connect the marks with a smooth curve. The direction of the field line, from positive to negative, is identified with arrowheads. Several field lines are marked.

It is helpful for students to draw parallels between calculation of force ($\vec{E} = \frac{\vec{F}_E}{q}$) and potential energy ($\Delta U_E = q\Delta V$), always being mindful that the existence of the field or potential implies the existence of particles with which a particle placed at a given location can interact.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) Apply mathematical routines to calculate the average value of the magnitude of the electric field in a region from a description of the electric potential in that region using the displacement along the line on which the difference in potential is evaluated. [LO 2.E.3.1, SP 2.2]		**Instructional Activity:** After the field is mapped in the preceding activity, students in lab groups of two or three map the isolines of electric potential by marking points that are at a constant potential difference from one electrode or the other. Several potential isolines should be marked.
	Print O'Kuma, Maloney, and Hieggelke, Electrostatics Ranking Tasks, pp. 145–146 Hieggelke, Maloney, Kanim, and O'Kuma, Ranking Tasks eT5-RT9, eT5-RT0, and eT5-RT11; Changing Representation Tasks eT3-CRT1 and eT5-CRT2	**Instructional Activity:** The concept of the "greatest negative potential change," or $\frac{-\Delta V}{\Delta x}$, may now be equated to the magnitude and direction of the electric field ($\vec{E}$). Students collaboratively work through numeric and symbolic problems linking field to potential change. I monitor student discussion and review the written answers that student teams submit to ensure that they understand the fundamental concept: the field is the negative gradient of the potential. For students who demonstrate understanding of this concept, I show how it can be extended to the directly analogous concept of force being related to potential energy change.
Create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and recognize that the assumption of uniform field is not appropriate near edges of plates. [LO 2.C.5.1, SP 1.1, SP 2.2]	**Web** "Charges and Fields"	**Instructional Activity:** Using this simulation, students individually align a straight row of positive charges across from a parallel row of an equal number of negative charges to simulate a parallel plate capacitor. The space between the "plates" exhibits linear field lines, and fringe effects near the edges are clearly visible.
	Supplies Conducting paper with parallel straight plates painted on it at opposite ends with silver conducting ink, cork or wood boards, thumbtacks, batteries or power supplies, electrical leads, digital multimeters	**Instructional Activity:** Students in lab groups of two or three repeat the field-mapping lab, with the variation that they investigate the field between and around parallel straight plates painted with silver ink on the conducting paper. The mapping will clearly show the uniform field between the plates and the fringe effects near the edges. Students may also map the isolines of potential, which will clearly show even spacing between isolines with the same potential difference between them.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Calculate the magnitude and determine the direction of the electric field between two electrically charged parallel plates, given the charge of each plate, or the electric potential difference and plate separation. [LO 2.C.5.2, SP 2.2] Represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field. [LO 2.C.5.3, SP 1.1, SP 2.2, SP 7.1]		**Formative Assessment:** Students individually apply $E = \frac{-\Delta V}{\Delta x}$ to a dynamics problem. They are given a sketch of a parallel plate capacitor with the potential between the plates, ΔV, and plate spacing, Δx, clearly marked. Students predict the behavior of a particle of known mass and charge when it is placed at various locations between the plates, and when it is projected between the plates at a given velocity. I check for correct calculation of the field, determination of force, application of Newton's first or second law, and correct calculation of the position and velocity of the particle at various elapsed times and distances.
Construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential. [LO 2.E.1.1, SP 1.4, SP 6.4, SP 7.2] Connect the strength of electromagnetic forces with the spatial scale of the situation, the magnitude of the electric charges, and the motion of the electrically charged objects involved. [LO 3.G.2.1, 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] 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] Connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces. [LO 3.G.1.2, SP 7.1]	**Supplies** Topographical maps (three-dimensional, if available)	**Instructional Activity:** Students individually compare a topographical map to an electric potential isoline map and construct written responses to the following: (a) Describe how the direction of the force on a particle with mass or charge placed on an appropriate map is related to the isolines. (b) Describe how the gravitational or electric field is related to the force and to the isolines. (c) How can we use gravitational and electric isolines in applying conservation of energy to particles released in gravitational or electric fields?

I provide verbal feedback directly to students during the activity. This assessment helps me determine whether any reteaching is necessary before we move on to the next topic.

For this activity, students should know that on a topographical map, points on an isoline have the same elevation, which is proportional to gravitational potential energy. Thus, the concept of gravitational potential is more easily developed and can be used to help students visualize electric potential.

Guiding Questions: ▼ What happens at the atomic level when an object is charged or polarized? ▼ What is an electric field, and how can it be used to calculate force? ▼ What is an electric potential, and how is it related to potential energy? ▼ How can we visualize the electric field and electric potential produced by a charge configuration?

Learning Objectives	Materials	Instructional Activities and Assessments
Construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential. [LO 2.E.1.1, SP 1.4, SP 6.4, SP 7.2] Connect the strength of electromagnetic forces with the spatial scale of the situation, the magnitude of the electric charges, and the motion of the electrically charged objects involved. [LO 3.G.2.1, 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] 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] Connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces. [LO 3.G.1.2, SP 7.1]	**Supplies** Models of the Earth-moon system or our solar system	**Instructional Activity:** Using a planetary model, students collaborate to write responses to the following: (a) What does Earth's gravitational field look like at a radius equal to the moon's orbital radius, and what kind of electric field does this resemble? (b) What does the gravitational field look like close to Earth's surface, and what type of electric field does it resemble? (c) How do gravitational and electric forces compare in terms of relative strength and the distance over which they are significant? (d) Create and solve two parallel problems, one involving gravitational force and the other involving electrostatic force, in which the force accelerates a particle. Describe similarities and differences in these problems, with an emphasis on particle properties and scale.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from practice examinations provided by the College Board.

Focusing on a planet–satellite system will remind students of the inverse square dependency of the gravitational force. Students should be able to identify both forces as acting over a distance, without contact. They should be able to see that the gravitational force acts over longer distances but is weaker on the laboratory scale than the electrostatic force.

All of the guiding questions for this unit are addressed in this summative assessment.

Unit 4: Electric Current

Laboratory Investigations:

- Resistivity of Conductive Paper
- Kirchhoff's Rules (Multiple Investigations)
- Bulb Brightness in Parallel and Series Circuits
- Ohm's Law

Estimated Time:

20 days

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Choose and justify the selection of data needed to determine resistivity for a given material. [LO 1.E.2.1, SP 4.1] Design a plan for the collection of data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. [LO 4.E.4.2, SP 4.1, SP 4.2] Make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. [LO 1.B.1.2, SP 6.4, SP 7.2] Analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. [LO 4.E.4.3, SP 5.1] Make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships. [LO 4.E.4.1, SP 2.2, SP 6.4]	**Supplies** Conductive paper, scissors, rulers, Vernier calipers, digital multimeters **Web** "Episode 112-2: Introduction to Resistivity Using Conducting Paper"	**Instructional Activity:** Students make model resistors out of strips of conductive paper and measure the dimensions and resistance of each paper resistor. From their data, they illustrate graphically the dependence of resistance on geometry and estimate the resistivity of the carbonized paper. A graph of resistance versus length should be linear, and its slope should yield resistivity divided by cross-sectional area. A graph of resistance versus 1/area should have a slope of resistivity multiplied by length. Students explain how the paper resistor model can be extrapolated to the construction of resistors for circuit boards, where space and size are limited. I monitor students' work for correct use of SI units, scientific notation, and an understanding of the limits of experimental precision.
	Web "Capacitor Lab"	**Instructional Activity:** Teams of two or three students experiment with capacitors using the online simulation to determine how the capacitance and charge on a capacitor varies with voltage, plate area, and plate spacing. They then explore the effects of adding a dielectric to the capacitor. Students illustrate their understanding of the relationships they uncover by sketching graphs. During this activity, students use physical arguments to construct written answers to questions such as these: (a) How does a battery charge a capacitor? (b) How do the positive and negative plates assume equal quantities of charge? (c) Why does charge seem to flow through a capacitor? When necessary, I help students apply conservation of charge to answer each of these questions.
Translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor. [LO 5.B.9.8, SP 1.5]	**Web** "Circuit Construction Kit (DC Only)"	**Instructional Activity:** Students use the online simulation to collect and tabulate data for potential, current, and resistance. They then graph potential as either a function of current or as a function of resistance and explain how their linear graph relates to the symbolic expression of Ohm's law.

An explanation of how a multimeter measures resistance is generally necessary prior to performing this laboratory. Graphical linearization techniques may also require explanation. In a modification of this lab, students use modeling clay to build model resistors.

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor. [LO 5.B.9.8, SP 1.5]		**Instructional Activity:** Using $\Delta U = q\Delta V$, $P = \frac{\Delta U}{\Delta t}$, and $I = \frac{q}{\Delta t}$, students derive the power equation $P = I\Delta V$. They then combine that with Ohm's law to derive $P = I^2 R$ and $P = \frac{V^2}{R}$. Students then sketch graphs that depict the relationships between power and potential, current, and resistance. Students should be reminded that the fundamental relationship between potential energy and potential they learned in electrostatics applies to circuits as well.
Predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation. [LO 5.C.3.4, SP 6.4, SP 7.2] Determine missing values and direction of electric current in branches of a circuit with resistors and NO capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule. [LO 5.C.3.5, SP 1.4, SP 2.2]	**Web** "Circuit Construction Kit (DC Only)"	**Instructional Activity:** Students use the simulation to construct a circuit with one battery, one bulb, and one switch. They must explain (a) why the bulb lights instantly when the switch is closed, (b) whether electrons are "disappearing" as they move through the circuit, and (c) what the slow motion of electrons along the wire is intended to illustrate. Students are also challenged to come up with a mechanical model that illustrates the almost instantaneous transmission of an electrical signal.
	Supplies Batteries (D-cells), resistors (100 Ω – 1000 Ω), wires, digital multimeters	**Instructional Activity:** Students in pairs build a circuit with one battery and three resistors in series and measure the current through each resistor. They then arrange the resistors in parallel and measure the current through each resistor. I provide detailed instructions on using the digital multimeter at this point, so students don't measure current as if they were measuring potential, which is likely to burn out the fuse. Students explain their measurements using conservation of charge and Kirchhoff's junction rule.

Students usually assume electrons travel through a circuit at nearly the speed of light instead of at the much slower drift velocity. A Newton's cradle is useful for demonstrating how a signal can travel faster than the particles transmitting it. Another prevalent misconception is that current "disappears" in a circuit. The simulation helps you identify and correct student misconceptions such as these.

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation. [LO 5.C.3.4, SP 6.4, SP 7.2] Determine missing values and direction of electric current in branches of a circuit with resistors and NO capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule. [LO 5.C.3.5, SP 1.4, SP 2.2]	**Web** "Kirchhoff's Rules"	**Formative Assessment:** Students find the missing currents in the five-loop circuit problem (Problem 1) from the online resource. While the problem appears challenging, it can easily be solved with correct application of Kirchhoff's junction rule. Students who are observed to struggle with this task are encouraged to focus on one junction at a time, beginning with those junctions for which only one current is unknown.
Determine missing values and direction of electric current in branches of a circuit with both resistors and capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule. [LO 5.C.3.6, SP 1.4, SP 2.2] Determine missing values, direction of electric current, charge of capacitors at steady state, and potential differences within a circuit with resistors and capacitors from values and directions of current in other branches of the circuit. [LO 5.C.3.7, SP 1.4, SP 2.2]	**Web** "Circuit Construction Kit (AC+DC)"	**Instructional Activity:** This more complete version of the online circuit construction kit provides capacitors as well as resistors, cells, and switches. By constructing virtual circuits and placing a virtual ammeter in various branches of those circuits, students can verify two important principles: (a) current on either side of a capacitor that is charging or discharging is equal and (b) current entering a junction is equal to current leaving a junction, just as it is in a resistor-only circuit.
		Formative Assessment: Students are given diagrams of circuits containing batteries, switches, capacitors, and resistors in series and parallel arrangements. Working individually, they must calculate the current through some components when the current through other components is defined. Students who understand conservation of charge and current should be able calculate currents correctly. Some students may need to be reminded that potential is proportional to current for resistors and to charge for capacitors.

I provide verbal feedback directly to the students as they work through the five-loop circuit problem. This activity helps me determine whether students are ready to move on to the next topic.

I provide verbal feedback directly to students as they work to calculate current in the components. When I observe that students have mastered this skill, I have them work on similar problems in which no currents are given but capacitors are either uncharged or in steady state.

Electric Current

(continued)

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule $\sum \Delta V = 0$. [LO 5.B.9.4, SP 5.1] Use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. [LO 5.B.9.5, SP 6.4] Refine and analyze a scientific question for an experiment using Kirchhoff's loop rule for circuits that includes determination of internal resistance of the battery and analysis of a non-ohmic resistor. [LO 5.B.9.7, SP 4.1, SP 4.2, SP 5.1, SP 5.3] Mathematically express the changes in electric potential energy of a loop in a multiloop electrical circuit and justify this expression using the principle of the conservation of energy. [LO 5.B.9.6, SP 2.1, SP 2.2]	**Supplies** Batteries (D-cells), resistors ($100\ \Omega - 1000\ \Omega$), wires, digital multimeters, capacitors ($100\ \mu F - 330\ \mu F$)	**Instructional Activity:** Student lab teams design and construct single-loop circuits with one D-cell and multiple resistors. They predict potential across each circuit element using Kirchhoff's loop rule, measure the potential, and compare the two. I monitor the tabulated data and ask students to explain differences in ΔV. If the measured ΔV is consistently lower than expected for low-resistance circuits, the students should surmise there is resistance in the circuit that is not accounted for.
		Instructional Activity: Student lab teams add one or two capacitors to their single-loop circuits, predict potential across each circuit element using Kirchhoff's loop rule, measure the potential, and compare the two. They calculate the charge and energy in the capacitors. I review their data for correctness. Students should be able to explain why there is no potential across the resistors and what this implies in terms of energy dissipation.
		Formative Assessment: I pose this question: When is an incandescent light bulb in your home most likely to burn out? Students probably know bulbs usually burn out when first turned on, but they may not know why. The incandescent bulb is the most familiar example of a non-ohmic resistor whose resistance increases dramatically with temperature. Students then explain the phenomenon; this may be done in class discussion or by students conducting online research (in class or as homework) and then writing a brief report.

The difference between predicted and measured ΔV values should be small; however, variance is likely to be larger when resistance is low and current is high due to internal resistance in the cell, especially if it is not new.

I provide verbal feedback during the class discussion or provide written feedback on students' reports.

Electric Current

(continued)

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule $\sum \Delta V = 0$. [LO 5.B.9.4, SP 5.1] Use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. [LO 5.B.9.5, SP 6.4] Refine and analyze a scientific question for an experiment using Kirchhoff's loop rule for circuits that includes determination of internal resistance of the battery and analysis of a non-ohmic resistor. [LO 5.B.9.7, SP 4.1, SP 4.2, SP 5.1, SP 5.3] Mathematically express the changes in electric potential energy of a loop in a multiloop electrical circuit and justify this expression using the principle of the conservation of energy. [LO 5.B.9.6, SP 2.1, SP 2.2]	**Supplies** Batteries (D-cells), resistors (100 Ω – 1000 Ω), wires, digital multimeters, capacitors (100 μF – 330 μF)	**Instructional Activity:** Students in teams of two or three construct multiloop circuits with D-cells and resistors. They predict the currents using Kirchhoff's rules, measure the currents, tabulate the data, and compare predicted and measured currents. Once I observe that currents have been appropriately determined, I assign an extension activity in which the students must add one capacitor to a parallel branch of the circuit and repeat the activity under steady state conditions. Charge and energy for the capacitor must be calculated.
		Formative Assessment: Students individually produce full lab reports displaying correct Kirchhoff's analysis, including simultaneous solution of Kirchhoff's equations. The connection to conservation of energy must be evident, including energy put into the circuit by the cell, dissipated by the resistors, and stored in the capacitors. Error analysis must be performed.

I provide written feedback on all reports and allow a second submission for students to address errors.

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
Make and justify a qualitative prediction of the effect of a change in values or arrangements of one or two circuit elements on currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. [LO 4.E.5.2, SP 6.1, SP 6.4] Make and justify a quantitative prediction of the effect of a change in values or arrangements of one or two circuit elements on the currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. [LO 4.E.5.1, SP 2.2, SP 6.4] Plan data collection strategies and perform data analysis to examine the values of currents and potential differences in an electric circuit that is modified by changing or rearranging circuit elements, including sources of emf, resistors, and capacitors. [LO 4.E.5.3, SP 2.2, SP 4.2, SP 5.1]	**Supplies** Batteries (D-cells), miniature bulbs (2.5 V), wires, digital multimeters	**Instructional Activity:** Students working in small groups predict the difference in bulb brightness for circuits with (a) one bulb and different numbers of cells in series, (b) one bulb and different numbers of cells in parallel, (c) one cell and different numbers of bulbs in series, (d) one cell and different numbers of bulbs in parallel, and (e) a combination of two bulbs in parallel and one in series. They write their predictions and justify their reasoning. They then build circuits and compare observations with predictions. I prompt students to write physical explanations for all observations, especially those for which prediction and observation are discrepant. Students write their findings and explanations on large whiteboards. To conclude, they review each others' work, using sticky notes to post comments and questions.
	Print O'Kuma, Maloney, and Hieggelke, DC Circuit Ranking Tasks, pp. 155–179	**Formative Assessment:** Ranking task exercises are used to assess students' depth of conceptual knowledge of circuits. Students work in pairs so they can challenge each other's ranking of the tasks.
	Print Polley, "Lab Seven: Ohm's Law" **Supplies** Power supplies (D-cells, 9-volt batteries, or variable-current power supply), wires, resistors, digital multimeters, potentiometers (optional)	**Instructional Activity:** This resource provides two versions of an Ohm's law lab: one in which students determine an unknown resistance by varying the resistance in a potentiometer, or variable resistor, and a second in which the internal resistance of digital multimeters is explored. In either case, student lab teams must plan an investigation, write an experimental procedure, collect and record data, perform an analysis of the data to determine an unknown resistance value, and submit a full written lab report that describes their findings. Students should explicitly use conservation of energy and conservation of charge as part of their discussion. I comment on the lab reports and have students edit and resubmit them as appropriate.

I walk around the room during the activity and provide specific feedback to students about their rankings. If I see common mistakes being made on similar questions, I may stop the class and address that particular question to provide clarity.

Electric Current

(continued)

Guiding Questions: ▼ What factors affect the resistance of a material? ▼ How do charge conservation and energy conservation apply to direct current circuits? ▼ What is common to elements in series and parallel circuits? ▼ How do capacitors affect current in a circuit immediately after a switch is closed, as well as under steady-state conditions?

Learning Objectives	Materials	Instructional Activities and Assessments
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from practice examinations provided by the College Board.

All of the guiding questions for this unit are addressed in this summative assessment.

Laboratory Investigations:

- Mapping a Magnetic Field with Iron Filings
- Mapping a Magnetic Field with Compasses
- Compound Magnets
- Magnetic Force and Current
- Evidence of Electromagnetic Induction

Estimated Time:

20 days

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. [LO 2.D.3.1, SP 1.2] Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semi-quantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. [LO 2.C.4.1, SP 2.2, SP 6.4, SP 7.2] Create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires. [LO 2.D.2.1, SP 1.1]	**Supplies** Bar magnets, horseshoe magnets, iron filings, heavy paper	**Instructional Activity:** Students in small lab groups place a permanent magnet (bar or horseshoe) flat on a desk, place a sheet of heavy paper on top of the magnet, and sprinkle iron filings on top of the paper. They tap the paper a few times and observe the alignment of the filings on the paper. Students interpret what the alignment of the filings suggests about the interaction between shavings of iron and a magnetic field.
	Supplies Small compasses, permanent bar magnets, solenoids, batteries, connecting wire, large sheets of paper	**Instructional Activity:** Students in small lab groups place a permanent bar magnet on top of a large sheet of paper on a desk, trace the magnet, and clearly mark the position of the north and south poles. They then mark the direction a compass north pole points at various locations around the magnet to map the magnetic field. The investigation is repeated with a hollow-core solenoid connected to a battery. The solenoid allows for students to investigate the magnetic field inside as well as outside the solenoid. The activity helps students see a compass as a freely rotating magnetic dipole that aligns so its north pole indicates the direction of the magnetic field.
	Supplies Compound magnets (each consisting of stacks of eight small identical magnetic disks), bar magnets (for testing the compound magnet), steel paper clips	**Instructional Activity:** Students in small lab groups are given a column of magnets stacked together so the dipoles are aligned. Using a test magnet, they identify the north and south poles of the compound magnet, and by lifting chains of paper clips they test its strength. The students write hypotheses predicting what will happen to the poles and strength when the column of magnets is divided into two, four, and eight identical smaller magnets; they test their hypotheses with experimentation. They then describe how this model may be used to suggest that magnetic monopoles do not exist, and what the limits of validity of this model may be. They then design other experiments that may have greater validity.

Mapping exercises help students visualize the geometry of a field and understand that the magnetic field enters the south pole and exits the north pole of a magnetic field, including that of the Earth.

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. [LO 2.D.3.1, SP 1.2] Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semi-quantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. [LO 2.C.4.1, SP 2.2, SP 6.4, SP 7.2] Create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires. [LO 2.D.2.1, SP 1.1]	**Print** O'Kuma, Maloney, and Hieggelke, Magnetism and Electromagnetism Ranking Tasks, pp. 182–183 Hieggelke, Maloney, Kanim, and O'Kuma, Ranking Tasks mT6-RT1, mT6-RT2, mT7-RT1, mT8-RT1, and mT8-RT2	**Formative Assessment:** In small groups, students work a ranking task exercise that requires use of the right-hand rule combined with vector superposition. In working the problem, students must use the fact that the field is proportional to current and inversely proportional to distance from the wire. Each group is provided with a different problem, which they must solve and present to the class.
Apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. [LO 2.D.1.1, SP 2.2]	**Supplies** Basic current balance (PASCO SF-8607), electronic mass balance (sensitive to 0.01 gram)	**Instructional Activity:** A commercial current balance, paired with a sensitive electronic mass balance, can help students measure the relationship between electric current and magnetic force. Both magnitude of current and angle between field and current can be measured. I evaluate student lab reports of the data to ensure that the direct relationship between current and magnetic force is recognized.

The class and I watch the solution presentations, ask questions, and offer constructive critique of the solutions. This activity helps me determine whether any reteaching is necessary before moving on to the next topic.

It is possible to build current balances economically; I've had my students build their own versions of this device. Because a new current balance costs around $300, a single balance can be used to collect data in a demonstration that students can subsequently analyze.

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor. [LO 3.C.3.1, SP 1.4] Plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion. [LO 3.C.3.2, 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] 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. [LO 3.B.1.4, SP 6.4, SP 7.2]	**Print/CD** Christian and Belloni, Exploration 27.1: "Map Field Lines and Determine Forces"	**Instructional Activity:** In this Physlet exploration, students in small lab groups must first use a compass to map a magnetic field around a central object. In Configuration 1 of the simulation, the central object happens to be a current-carrying wire. Students then add another current-carrying wire to the simulation and determine the magnitude and direction of the magnetic force on the added wire due to the central current.
		Formative Assessment: Based on the preceding Physlet activity, students should now be able to provide a written explanation of the force on the second current due to the first. I expect high-quality written explanations that involve (a) the direction of magnetic field created by the central current, (b) the motion of charge carriers in the second wire, and (c) the resulting magnetic force on the charge carriers due to the magnetic field. I have students write their explanations individually, refine their written explanations in small groups, and then engage in a whole-class discussion.
	Print/CD Christian and Belloni, Exploration 27.2: "Velocity Selector"	**Instructional Activity:** In this Physlet exploration, students work individually to find the speed at which a charged particle moves through crossed magnetic and electric fields without deflection. The activity requires students to make and explain predictions. I require students to use Newton's first and second laws, with an analysis that includes free-body diagrams and the mathematical relationship of the magnetic and electric forces.

I provide feedback to the entire class during the discussion. Their presentations and responses inform my decisions about next instructional steps.

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor. [LO 3.C.3.1, SP 1.4] Plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion. [LO 3.C.3.2, 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] 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. [LO 3.B.1.4, SP 6.4, SP 7.2]	**Print/CD** Christian and Belloni, Exploration 27.3: "Mass Spectrometer"	**Instructional Activity:** Students working in small lab groups use this Physlet to explore the functioning of a mass spectrometer in which charged particles of different charge/mass ratios move through curved paths of different radii in a magnetic field. I require students to use Newton's second law with centripetal acceleration in their analysis. Students must be able to explain the difference in radius of curvature for objects of different charge/mass ratios using a clear dynamics analysis.
Construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area. [LO 4.E.2.1, SP 6.4] 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]	**Supplies** Conducting pipe, bar magnet, nonmagnetized metal object of similar size and mass **Print** Lietz, Bertrand, and Friedlander, *AP Physics Curriculum Module: Electromagnetic Induction*	**Instructional Activity:** In this demonstration, students observe the difference in how long it takes magnetized and nonmagnetized objects to fall through a conducting pipe. They construct explanations in terms of magnetic force generated by current flow in the pipe. This serves as a qualitative introduction to Lenz's law. Students answer questions to explain what they observe in terms of acceleration, force, and induced current direction. I monitor students' answers for conceptual understanding. For an additional twist to this demonstration, I hang the tube from a spring scale. Deflection of the spring scale while the magnet falls enables an estimation of the magnitude of the force, which can be compared to the magnet's weight. Students can explain this using Newton's laws.

After doing this demonstration for years, I still find it amazing. It is powerful, visual evidence that an induced current, which I cannot feel with my hand, generates a strong enough magnetic force to reduce or eliminate the acceleration of a falling magnet.

Magnetism

(continued)

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area. [LO 4.E.2.1, SP 6.4] 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]	**Supplies** Galvanometers, solenoids, bar magnets, connecting wires **Web** "Faraday's Electromagnetic Lab" (as an alternative to the hands-on lab)	**Instructional Activity:** Using simple equipment, students in small lab groups investigate electromagnetic induction by performing qualitative experiments to determine what factors affect induced potential. The PhET simulation offers an online alternative to the hands-on investigation.
	Web "Faraday's Law"	**Formative Assessment:** Students write paragraphs describing how induction is affected by the number of loops in a solenoid, the speed at which a magnet is moved through the solenoid, and the field strength of the moving magnet. They sketch qualitative graphs consistent with their verbal descriptions.
	Web "Generator"	**Instructional Activity:** Working individually, students use quantitative measurements from the simulation, which is a model of hydroelectric generation, to investigate mathematical relationships.
	Web "2 Student Directions Faraday Induction"	**Formative Assessment:** Students individually complete the writing activities that accompany the generator simulation used in the previous activity. Students then share their answers in a whole-class discussion.

I evaluate students' written work and graphs for correctness and clarity and provide them with written feedback.

I monitor the discussion as students develop understanding of the concepts, clarifying student explanations when necessary.

Guiding Questions: ▼ How can we describe a magnetic field due to single or multiple sources? ▼ How does a magnetic field interact with electric charge? ▼ How can we combine a magnetic field with an electric field to produce a beam of charged particles with a single velocity? ▼ How can changing magnetic flux produce an electric potential?

Learning Objectives	Materials	Instructional Activities and Assessments
Use the representation of magnetic domains to qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material. [LO 2.D.4.1, SP 1.4] Use representations and models to qualitatively describe the magnetic properties of some materials that can be affected by magnetic properties of other objects in the system. [LO 4.E.1.1, SP 1.1, SP 1.4, SP 2.2]	**Online video** "Lecture 21: Magnetic Materials"	**Instructional Activity:** Walter Lewin of MIT describes the origin of the magnetic force on a dipole in a nonuniform field, using basic E&M. He explains what is meant by *dia-*, *para-*, and *ferromagnetism*; describes magnetic domains; and demonstrates alignment of domains in ferromagnetic materials. Demonstrations conducted in the video support students' visualization of the concepts involved. This culminating activity requires a basic qualitative understanding of magnetic field, force, dipoles, and dipole moment. I pause the video periodically to ask students how Lewin's comments are linked to concepts learned earlier in the unit.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from the practice examination provided by the College Board.

All of the guiding questions for this unit are addressed in this summative assessment.

Unit 6:

Waves and Optics

Laboratory Investigations:

- Diffraction Laser Lab
- Polarizing Filters
- Law of Reflection
- Determining the Index of Refraction
- Spherical Mirror
- Lenses

Estimated Time:

20 days

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe representations of transverse and longitudinal waves. [LO 6.A.1.2, SP 1.2] Use a visual representation of a periodic mechanical wave to determine wavelength of the wave. [LO 6.B.2.1, SP 1.4] Contrast mechanical and electromagnetic waves in terms of the need for a medium in wave propagation. [LO 6.A.2.2, SP 6.4, SP 7.2] Describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present. [LO 6.F.2.1, SP 1.1]	**Supplies** Long demonstration helical spring toy (PASCO SE-8760)	**Instructional Activity:** Students place a spring toy on a long table or the floor and stretch it about three meters, with one student holding each end. Students create transverse wave pulses by having one person slide an end of the spring toy quickly to one side and back. They create longitudinal pulses by having one person quickly push an end of the spring toy in the direction of the other person and pull it back. Reflection of the pulses when they reach the end of the spring toy is generally quite clear.
	Print/CD Christian and Belloni, Chapter 17: "Waves," Chapter 18: "Sound," and Chapter 32: "Electromagnetic Waves"	**Instructional Activity:** Working individually, students explore several Physlets involving various periodic wave properties. Of particular interest is the animation of the electromagnetic wave, which may help students visualize how oscillating electric and magnetic fields propagate EM waves through a vacuum. The variety of waves explored helps students visualize the similarities and differences between various wave types.
		Formative Assessment: After exploring Physlets in the previous activity, students individually work through the problems that accompany each chapter.
Make claims and predictions about the net disturbance that occurs when two waves overlap. Examples should include standing waves. [LO 6.C.1.1, SP 6.4, SP 7.2] Construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. [LO 6.C.1.2, SP 1.4]	**Print/CD** Christian and Belloni, Illustration 17.4: "Superposition of Traveling Waves"	**Instructional Activity:** Students individually interact with this Physlet to help them visualize the production of standing waves. Interference is represented in animated form for wave pulses as well as for periodic waves. The production of standing waves is clearly illustrated by the interference of periodic waves. Each student writes a description about what causes standing waves to exist, and how their wavelength depends upon frequency and the length of the chamber.

Students love this activity! It is important to ensure they are careful with the spring toy, as it is easily twisted.

I evaluate individual student performance on these problems by reviewing their written work and then reteach concepts as necessary.

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims and predictions about the net disturbance that occurs when two waves overlap. Examples should include standing waves. [LO 6.C.1.1, SP 6.4, SP 7.2] Construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. [LO 6.C.1.2, SP 1.4]	**Print** O'Kuma, Maloney, and Hieggelke, Wave and Optics Ranking Tasks, pp. 201–204	**Formative Assessment:** Students collaboratively solve these ranking task problems. Student teams present solutions to different problems to the class. Classmates and I ask questions and offer constructive comments.
Make claims about the diffraction pattern produced when a wave passes through a small opening, and qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave. [LO 6.C.2.1, SP 1.4, SP 6.4, SP 7.2] Qualitatively apply the wave model to quantities that describe the generation of interference patterns to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small, but larger than the wavelength. [LO 6.C.3.1, SP 1.4, SP 6.4] Predict and explain, using representations and models, the ability or inability of waves to transfer energy around corners and behind obstacles in terms of the diffraction property of waves in situations involving various kinds of wave phenomena, including sound and light. [LO 6.C.4.1, SP 6.4, SP 7.2]	**Web** "Wave Interference"	**Instructional Activity:** Students use this comprehensive and engaging simulation to investigate diffraction and interference of water, sound, and light waves. For diffraction of water waves, the students control the frequency of water dripping into a ripple tank and examine the effect of adding barriers and slits into the tank. For sound waves, they are provided one or two speakers, barriers, audio, and an optional view of the air molecules moving. For light, they are provided with one or two light sources with color control, and a screen upon which to view the diffraction pattern created when slits are placed between the light source and the screen. Several lesson plans are available that provide suggested investigations and inquiry-based activities. **Formative Assessment:** Conceptual questions are available with the PhET simulation for use in formative assessment activities. I pose these questions to the whole class. Students respond using clickers or by writing the answer on small whiteboards. Disagreements about the answers are resolved in whole-class discussion.

During the discussion of solutions, I provide feedback to the groups and entire class. Monitoring the discussion helps me determine whether any reteaching is necessary before we move on to the next topic.

This simulation is particularly valuable because it underscores the commonality between diffraction and interference phenomena for three different wave types, avoiding the misconception students sometimes have that diffraction occurs only for light. Sound is introduced in the Physics 1 curriculum and is used here as review to build students' knowledge of diffraction using a more familiar model.

I provide feedback to students during the class discussion. Their comments and responses help me determine whether reteaching is necessary.

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims about the diffraction pattern produced when a wave passes through a small opening, and qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave. [LO 6.C.2.1, SP 1.4, SP 6.4, SP 7.2] Qualitatively apply the wave model to quantities that describe the generation of interference patterns to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small, but larger than the wavelength. [LO 6.C.3.1, SP 1.4, SP 6.4] Predict and explain, using representations and models, the ability or inability of waves to transfer energy around corners and behind obstacles in terms of the diffraction property of waves in situations involving various kinds of wave phenomena, including sound and light. [LO 6.C.4.1, SP 6.4, SP 7.2]	**Supplies** Diffraction gratings with different line spacing, small low-powered red and green lasers, metersticks, cardboard screens **Print** Polley, "Lab Twelve: The Diffraction Grating"	**Instructional Activity:** Students in small lab groups investigate the effects of wavelength and slit spacing on diffraction geometry. Using a single diffraction grating, they shine the red and green lasers separately through the grating onto the screen and record the angle between the central bright spot, the diffraction grating, and the first and second order bright fringes. Students then repeat the investigation, this time keeping the wavelength constant and using different diffraction gratings. Students should conclude from their data that as wavelength increases so does the angle. They should also conclude that as slit spacing increases the angle decreases. I ask the students to link what they observed in the PhET simulation to what they observe in this investigation.
Make qualitative comparisons of the wavelengths of types of electromagnetic radiation. [LO 6.F.1.1, SP 6.4, SP 7.2] Analyze data (or a visual representation) to identify patterns that indicate that a particular mechanical wave is polarized and construct an explanation of the fact that the wave must have a vibration perpendicular to the direction of energy propagation. [LO 6.A.1.3, SP 5.1, SP 6.2] Construct an equation relating the wavelength and amplitude of a wave from a graphical representation of the electric or magnetic field value as a function of position at a given time instant and vice versa, or construct an equation relating the frequency or period and amplitude of a wave from a graphical representation of the electric or magnetic field value at a given position as a function of time and vice versa. [LO 6.B.3.1, SP 1.5]	**Web** "Introduction to the Electromagnetic Spectrum"	**Instructional Activity:** This NASA website provides a beautifully illustrated, comprehensive, and readable introduction to electromagnetic radiation. Student groups are given topics to research, and using this site and other Web resources, they construct presentations. Examples of presentation topics include (a) describing the range of wavelengths of EM radiation in nonmathematical terms, (b) describing some useful applications of various forms of EM radiation, (c) explaining the wave model of EM radiation in terms of electromagnetic fields, and (d) explaining how the polarization of EM radiation works.

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Make qualitative comparisons of the wavelengths of types of electromagnetic radiation. [LO 6.F.1.1, SP 6.4, SP 7.2] Analyze data (or a visual representation) to identify patterns that indicate that a particular mechanical wave is polarized and construct an explanation of the fact that the wave must have a vibration perpendicular to the direction of energy propagation. [LO 6.A.1.3, SP 5.1, SP 6.2] Construct an equation relating the wavelength and amplitude of a wave from a graphical representation of the electric or magnetic field value as a function of position at a given time instant and vice versa, or construct an equation relating the frequency or period and amplitude of a wave from a graphical representation of the electric or magnetic field value at a given position as a function of time and vice versa. [LO 6.B.3.1, SP 1.5]	**Online video** "Circular Polarization"	**Instructional Activity:** This beautiful simulation clearly shows the orthogonal electric and magnetic fields oscillating as light propagates. The first half of the video illustrates plane polarization, and the second half shows circular polarization; you may choose to show only the first half of the video. Students write a paragraph explaining how induction can be used to explain the interdependence of changing magnetic and electric fields in electromagnetic radiation. I ask students how light propagation is similar to and different from other types of induction with which they are familiar, such as the generation of current.
	Supplies Polarizing filters, incandescent light sources, white paper	**Instructional Activity:** Students experiment with two polarizing filters and a light source. I guide them to discover that light passes through the filters when the filters are aligned, and light is completely blocked when the filters are at right angles to each other. Students must explain how polarizing filters work, using the model shown in the simulation from the previous activity. Students should be able to articulate that a polarizing filter transmits only light in which the electric field is oscillating in a given plane. A second filter can transmit light only if it is in the same orientation as the first filter.
	Print/CD Christian and Belloni, Illustration 17.2: "Wave Functions" and Chapter 32: "Electromagnetic (EM) Waves"	**Instructional Activity:** Using animated models of electromagnetic radiation, the Physlets help students see how a sinusoidal function mathematically describes light. Students perform the assignments that accompany each of the Physlet activities.
		Formative Assessment: Working in groups, students collaboratively solve various problems accompanying the Physlets. Each group presents to the class a solution to a different problem, and their classmates ask questions and offer constructive feedback.

I provide feedback either during student presentations or directly on work that has been turned in.

Waves and Optics

(continued)

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims using connections across concepts about the behavior of light as the wave travels from one medium into another, as some is transmitted, some is reflected, and some is absorbed. [LO 6.E.1.1, SP 6.4, SP 7.2] Describe models of light traveling across a boundary from one transparent material to another when the speed of propagation changes, causing a change in the path of the light ray at the boundary of the two media. [LO 6.E.3.1, SP 1.1, SP 1.4] Plan data collection strategies as well as perform data analysis and evaluation of the evidence for finding the relationship between the angle of incidence and the angle of refraction for light crossing boundaries from one transparent material to another (Snell's law). [LO 6.E.3.2, SP 4.1, SP 5.1, SP 5.2, SP, 5.3] Make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation. [LO 6.E.3.3, SP 6.4, SP 7.2]	**Supplies** Plane mirrors with vertical mount, photocopies of a protractor, lasers (or pins as an alternative to lasers) **Web** "Reflection Lab: Teacher's Guide"	**Instructional Activity:** Students align an upright mirror along the bottom of a photocopy of a protractor. They aim the laser at the origin of the protractor and mark the incident and reflected rays. They repeat this for several angles. Based on their observations, students create a statement for the law of reflection.
	Supplies Cardboard, semicircular plastic dishes filled with water or transparent glass blocks, lasers (or pins as an alternative to lasers) **Print** Polley, "Lab Eleven: Geometrical Optics – Determining the Index of Refraction"	**Instructional Activity:** Students design an investigation to collect data to determine the index of refraction of water or glass. To do so, they must plan how to accurately measure angles of incidence and refraction of light as it travels through the material. Students then run the experiment they have designed. They will generally trace objects on paper and run several trials at different angles of incidence. Marking the path of light can be done with pins, some placed in front and some behind a glass block or semicircular dish filled with water, which students align while looking through the material. If a laser is used, students can mark the path of the light with a pencil. Angle determination can be done with protractors or with trigonometry.
	Web "The AP Physics B Exam": 1999 Form B, Question 6; 2006 Form B, Question 4	**Formative Assessment:** I provide practice problems from published AP examinations. Students use the published scoring rubrics for those exams to correct their own work.

This reflection lab and the refraction lab below can both be done without using lasers, by the apparent alignment of pins. Labs done this way are safer and lower cost; however, the results are less accurate.

Consider requiring students to graph the data such that the index of refraction is obtained from the slope of a best-fit straight line. Ideally, students will recognize that the sine of the angle of incidence is the independent variable, and the sine of the angle of refraction is the dependent variable. You may need to remind students that the slope-intercept form of a linear equation is often used by scientists to extract physical constants.

While Physics B free-response questions are not reliable representatives of the questions on the AP Physics 2 Exam, some Physics B free-response questions, such as those cited here, can provide a starting point for physics teachers to develop their own formative assessment questions.

I provide written feedback to students' responses. This assessment helps me determine whether any reteaching is necessary before we move on to the next topic.

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface. [LO 6.E.2.1, SP 6.4, SP 7.2] Plan data collection strategies, and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors. [LO 6.E.4.1, SP 3.2, SP 4.1, SP 5.1, SP 5.2, SP 5.3] Use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces. [LO 6.E.4.2, SP 1.4, SP 2.2]	**Supplies** Meterstick optics benches, spherical concave mirrors, light sources, screens	**Instructional Activity:** In lab teams, students use inexpensive meterstick optics benches to create real images on screens using light sources and spherical concave mirrors. They use the data collected to determine the focal length of the mirror by using the thin lens/mirror equation. I require students to draw ray diagrams as part of their analysis. Typically, students will construct ray diagrams using principal rays. Students should record mirror, object, and screen locations on the meterstick, not the distances from mirror to object and mirror to screen.
		Formative Assessment: Working individually, students demonstrate clearly how principal rays used in ray diagrams obey the law of reflection by providing a similar mirror problem. To do this correctly, the student will need to draw a large diagram of a mirror, construct a normal to the surface at the point each ray touches the mirror, and compare the resulting angles of incidence and reflection. This analysis is far more fundamental than the shortcut of using principal rays, so it is important for students to perform it; otherwise, they may not realize that principal rays are simply shortcuts and that the law of reflection is followed always.

I provide written feedback to the students when analyzing their diagrams.

Guiding Questions: ▼ How do mechanical waves and electromagnetic waves propagate? ▼ What causes light to bend as it exits one medium and enters another? ▼ How can we use the thin lens (or mirror) equation to predict the size and location of an image? ▼ How do the principal rays commonly used in ray diagrams obey the law of reflection for mirrors and the law of refraction for lenses?

Learning Objectives	Materials	Instructional Activities and Assessments
Use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses. [LO 6.E.5.1, SP 1.4, SP 2.2] Plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses. [LO 6.E.5.2, SP 3.2, SP 4.1, SP 5.1, SP 5.2, SP 5.3]	**Supplies** Meterstick optics benches, converging lenses, light sources, screens	**Instructional Activity:** Students in lab teams use inexpensive meterstick optics benches to create real images on screens using light sources and converging lenses. Students should plan a data collection strategy to determine the focal length of the lens using the thin lens/mirror equation. Students must draw ray diagrams as part of their analysis; it is expected that students will use principal rays. I emphasize that the bending of light occurs at the surfaces of the lens, upon entry and exit, and that principal rays are simply convenient shortcuts. Students should record lens, object, and screen locations on the meterstick, not the distances from lens to object and mirror to screen.
	Web *AP Physics 1 and 2 Curriculum Framework*, p. 147	**Formative Assessment:** I present students with a sample free-response problem from the *AP Physics Curriculum Framework* to assess their mastery of the material covered in the unit. Assessment questions from the framework are comparable to what students will encounter on the exam. The questions assess students' conceptual understanding and their ability to explain their reasoning, both of which are emphasized in the redesigned course.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from practice examinations provided by the College Board.

I collect the work and provide written feedback to the students.

All of the guiding questions for this unit are addressed in this summative assessment.

Unit 7: Modern Physics

Laboratory Investigations:

- Determination of Planck's Constant
- Photoelectric Effect (Simulation Lab)
- Electron Diffraction (Simulation Lab)
- Nuclear Decay (Simulation Lab)
- Nuclear Fission (Simulation Lab)

Estimated Time:

20 days

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Construct representations of the differences between a fundamental particle and a system composed of fundamental particles and relate this to the properties and scales of the systems being investigated. [LO 1.A.2.1, SP 1.1, SP 7.1] 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] Construct representations of how the properties of a system are determined by the interactions of its constituent substructures. [LO 1.A.5.2, SP 1.1, SP 1.4, SP 7.1] Use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region. [LO 7.C.1.1, SP 1.4] Use a standing wave model in which an electron orbit circumference is an integer multiple of the de Broglie wavelength to give a qualitative explanation that accounts for the existence of specific allowed energy states of an electron in an atom. [LO 7.C.2.1, SP 1.4]	**Online video** "Atoms: The Space Between" "Quarks: Inside the Atom" "Quantum Mechanics"	**Instructional Activity:** I use these video clips to introduce the unit on modern physics. They are good introductions to the size and scale of atoms, the existence of fundamental particles such as quarks, and problems with the classical model of the atom developed by Rutherford. Quantum mechanics is introduced. The students respond to guided-viewing questions during the video activity and engage in class discussion about important or surprising points in the videos.
	Web "Atom Builder"	**Instructional Activity:** Using this simulation, students working in teams construct atoms from fundamental particles. Neutrons and protons must be built from up and down quarks, and electrons must be added. The atom will be identified as an ion or as a radioactive nuclide. Following this exploratory activity, student teams are each given an atom or ion for which they must describe physical properties and prepare visual representations of its construction from component parts. They must show in their representations how charge, mass, and energy are conserved or converted to other forms in the process of constructing their atom or ion.
	Web "Models of the Hydrogen Atom"	**Instructional Activity:** In this simulation students compare different theoretical models of the hydrogen atom, including the billiard ball, plum pudding, classical solar system, Bohr, de Broglie, and Schrödinger models. The simulation allows students to see the type of emission spectra that would accompany the different theoretical models. Photon absorption and emission are displayed in a way that helps students visualize these phenomena. Additionally, an electron energy-level diagram view is provided, so students can link the absorption and emission of photons to changes within the atom.

It is important for students to understand that models are constructs that help scientists understand abstract phenomena in more concrete ways. Point out that models may be replaced by more appropriate ones as scientists gain new knowledge and develop new ways of explaining abstract scientific concepts.

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Construct representations of the energy-level structure of an electron in an atom and relate this to the properties and scales of the systems being investigated. [LO 1.A.4.1, SP 1.1, SP 7.1] Describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed. [LO 5.B.8.1, SP 1.2, SP 7.2] Construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [LO 7.C.4.1, SP 1.1, SP 1.2] Select a model of radiant energy that is appropriate to the spatial or temporal scale of an interaction with matter. [LO 6.F.4.1, SP 6.4, SP 7.1] Support the photon model of radiant energy with evidence provided by the photoelectric effect. [LO 6.F.3.1, SP 6.4]	**Supplies** LEDs, D-cells or 9-V batteries, wires, 1 kΩ resistors, digital multimeters **Print** Polley, "Lab Thirteen, Planck's Constant on the Cheap"	**Instructional Activity:** Students construct simple circuits with light emitting diodes. By comparing the LED color to a printed visible-light spectrum, they estimate the wavelength and frequency of the light. With a digital multimeter, students determine the potential drop across the diode. Ideally, several LEDs with colors in the red, yellow, green, and blue spectral regions should be used. From these measurements, students estimate Planck's constant, ideally by graphing the frequency versus potential drop, or vice versa. Students must consider conservation of energy in their analysis. As each electron drops in energy ($E = e\Delta V$), it emits a photon ($E = hf = hc/\lambda$). A linear equation is constructed and graphed; from the slope of a best-fit straight line, Planck's constant is estimated.
	Web "Photoelectric Effect"	**Instructional Activity:** In this simulated experiment, students find stopping potential for various emitted wavelengths. They analyze data graphically to extract Planck's constant, cut-off frequency, and work function. I determine whether students can make the correct calculations to produce the linear graph, and I probe conceptual knowledge by asking questions such as these: (a) How does the stopping potential relate to maximum electron kinetic energy? (b) Why do we emphasize that this is "maximum" kinetic energy and not just kinetic energy? (c) Why do we graph frequency and not wavelength? (d) What is the physical significance of the cut-off frequency? (e) What is the significance of the work function? (f) Do you expect all metals to exhibit the photoelectric effect? Why or why not?

This lab brings together fundamental relationships: that potential energy change of electrons in a circuit is proportional to potential change, and that the energy of a photon is proportional to its frequency. The charge of the electron and Planck's constant are, of course, constants. This lab is a good way to underscore that conservation of energy is still valid on the atomic scale.

This simulation is a particularly valuable learning tool because it provides a good visual representation of the motion of electrons accompanying the photoelectric effect, making the phenomenon less abstract.

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain why classical mechanics cannot describe all properties of objects by articulating the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties. [LO 1.D.1.1, SP 6.3] Articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal. [LO 6.G.2.1, SP 6.1] Predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. [LO 6.G.2.2, SP 6.4] Make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate. [LO 6.G.1.1, SP 6.4, SP 7.1]	**Web** "Quantum Wave Interference"	**Instructional Activity:** Students use this simulation to explore how quantum effects and probability play a role in the behavior of photons and small particles (electrons, neutrons, and helium nuclei) on the atomic scale. The site provides excellent instructional support for the introduction to wave-particle duality, including a PowerPoint presentation and possible student assignments.
	Web "Davisson-Germer: Electron Diffraction"	**Instructional Activity:** Students perform their own Davisson-Germer electron diffraction experiment using this excellent simulation. They are provided with an electron gun with controllable electron speed, a protractor, and a ruler. The atom separation and atomic radius in the target crystal can be adjusted. A lesson plan for the teacher is provided, complete with a PowerPoint presentation and homework assignment.
		Formative Assessment: In small groups, students construct verbal and mathematical descriptions of how diffraction depends on particle speed, material structure, and de Broglie wavelength. They compare diffraction of light to diffraction of particles and explain the characteristics of a particle that make it suitable for diffraction by a certain material. I evaluate student responses for conceptual clarity and understanding, and I select some of the responses to present to the class for discussion and critique. I guide the discussion to ensure that students can articulate a correct understanding of how the various parameters affect the spacing between interference maxima in the diffraction pattern.

This activity is helpful in preparing students for the upcoming electron diffraction lab.

During the class discussion about students' responses, I provide verbal feedback regarding students' performance on this assessment. This activity helps me determine whether any reteaching is necessary before we move on to the next topic.

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Articulate the reasons that classical mechanics must be replaced by special relativity to describe the experimental results and theoretical predictions that show that the properties of space and time are not absolute. [LO 1.D.3.1, SP 6.3, SP 7.1] Apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale. [LO 4.C.4.1, SP 2.2, SP 2.3, SP 7.2]	**Web** "Einstein Light"	**Instructional Activity:** Using resources on the Web, students in small groups prepare presentations describing the various aspects of special relativity, such as (a) Galileo and relativity, (b) Maxwell and relativity, (c) Einstein and relativity, (d) time dilation, (e) length contraction, and (f) mass/energy equivalence. Students must illustrate their presentations by showing video clips or simulations that help describe their topic. The website "Einstein Light" can serve as a starting point, although the students should be expected to find additional resources for their presentations.
		Formative Assessment: As students observe the presentations described above, they construct assessment questions that they think emphasize the major ideas in each presentation. I collect the student-constructed questions and select some to present to the class in a formative assessment activity.

The student group that presented each topic will be expected to evaluate the answers to questions pertaining to that topic and reteach as necessary. My role is to ensure proper physics understanding is demonstrated throughout the process.

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
Apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay. [LO 5.G.1.1, SP 6.4] Predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay. [LO 7.C.3.1, SP 6.4] Apply conservation of mass and conservation of energy concepts to a natural phenomenon and use the equation $E = mc^2$ to make a related calculation. [LO 5.B.11.1, SP 2.2, SP 7.2] 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.2.6, SP 6.4, SP 7.2] Make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system. [LO 5.D.3.2, SP 6.4] Make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system. [LO 5.D.3.3, SP 6.4] Analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge. [LO 5.C.1.1, SP 6.4, SP 7.2] Identify the strong force as the force that is responsible for holding the nucleus together. [LO 3.G.3.1, SP 7.2] Articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass-energy. [LO 1.C.4.1, SP 6.3]	**Web** "Alpha Decay" "Beta Decay"	**Instructional Activity:** Half the class qualitatively investigates alpha decay and the other half qualitatively investigates beta decay, using these simulations. The students individually explain in writing how each of the following applies to decay reactions: (a) conservation of nucleon number, (b) conservation of charge, (c) conservation of momentum, and (d) center of mass velocity. Individual work is followed by a collaborative activity, in which groups of students combine their individual responses to construct explanations for presentation to the class. I guide discussion and correct misconceptions as necessary during group collaboration and presentation activities.
	Web "Nuclear Fission"	**Instructional Activity:** All students qualitatively explore nuclear fission using this simulation. The students individually explain how each of the following applies to fission: (a) conservation of nucleon number, (b) conservation of charge, (c) conservation of momentum, (d) center of mass velocity, and (e) special relativity. Individual work is followed by a collaborative activity, in which groups of students construct explanations and present them to the class. I guide the discussions and correct misconceptions as necessary during group collaboration and presentation activities.
		Instructional Activity: Students individually explain in writing why, in terms of forces, nuclear particles fly apart with so much energy after nuclear decay or fission occurs, and yet are able to stay extremely close together in a stable nucleus. Their explanations must be consistent with the fact that nuclei larger than hydrogen must contain neutrons in addition to protons. I evaluate whether students understand that electrostatic repulsive forces cause positive particles to fly apart during alpha decay or fission.

It should be pointed out to students that in order to hold a nucleus together, there must be a very strong force, attractive in nature, to overcome proton-to-proton electrostatic repulsion. Neutrons stabilize the nucleus by providing additional nuclear strong force and simultaneously allowing protons to separate more, reducing electrostatic repulsion.

Guiding Questions: ▼ What is the photoelectric effect? ▼ Under what conditions does a particle act like a wave or a wave act like a particle? ▼ What are the major implications of the theory of relativity? ▼ What quantities are conserved in a nuclear reaction?

Learning Objectives	Materials	Instructional Activities and Assessments
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from the practice examination provided by the College Board.

All of the guiding questions in the unit are addressed in this summative assessment.

Resources

General Resources

"AP Physics 2 Practice Exam." The College Board. Available summer 2014. http://www.collegeboard.com/html/apcourseaudit/teacher.html.

"The AP Physics B Exam." The College Board. Accessed March 12, 2013. http://apcentral.collegeboard.com/apc/members/exam/exam_information/2007.html.

Christian, Wolfgang, and Mario Belloni. *Physlet® Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics.* Boston: Addison-Wesley, 2003.

Hieggelke, Curtis J., David P. Maloney, Stephen E. Kanim, and Thomas L. O'Kuma. *E&M TIPERs: Electricity and Magnetism Tasks.* Boston: Addison-Wesley, 2005.

Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach.* 2nd ed. Boston: Addison-Wesley, 2012.

O'Kuma, Thomas L., David P. Maloney, and Curtis J. Hieggelke. *Ranking Task Exercises in Physics.* Student ed. Boston: Addison-Wesley, 2004.

Walker, James. *Physics.* 4th ed. Boston: Addison-Wesley, 2009.

Unit 1 (Fluid Mechanics) Resources

"27: Gases and Incompressible Liquids." Walter Lewin. MIT Video. Accessed August 11, 2012. http://video.mit.edu/watch/27-gases-and-incompressible-liquids-1743.

"Bernoulli Principle Animation." mitchellscience.com. Accessed August 11, 2012. http://mitchellscience.com/bernoulli_principle_animation.

Bertrand, Peggy. "Hurricane Katrina: A Teachable Moment." *The Science Teacher* 76, no. 7(2009): 30–35. http://learningcenter.nsta.org/files/tst0910_30.pdf.

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.

"Buoyancy." PhET. University of Colorado at Boulder. Accessed August 11, 2012. http://phet.colorado.edu/en/simulation/buoyancy.

"Fluid Pressure and Flow." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/fluid-pressure-and-flow.

"Fluids Experiment: Show Relationship Between Water Pressure and Depth." Ron Kurtus. Ron Kurtus' School for Champions. Accessed August 11, 2012. http://www.school-for-champions.com/experiments/fluids_pressure_depth_relationship.htm.

Unit 2 (Thermodynamics) Resources

"Collision Lab." PhET. University of Colorado at Boulder. Accessed May 17, 2013. http://phet.colorado.edu/en/simulation/collision-lab.

"Gas Properties." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/gas-properties.

"Physics/Chemistry – Heat Energy." The Molecular Workbench Database of Curriculum, Models, and Activities. The Concord Consortium, Inc. Accessed October 14, 2012. http://workbench.concord.org/database/browse/concept/Physics%5EChemistry/502.html.

"Second Law of Thermodynamics." Tom Benson. NASA. Accessed October 14, 2012. http://www.grc.nasa.gov/WWW/k-12/airplane/thermo2.html.

Unit 3 (Electrostatics) Resources

"Balloons and Static Electricity." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/balloons.

Bertrand, Peggy. "Conceptual Links in Electrostatics." In *Special Focus: Electrostatics,* 63–74. AP Physics, 2007–2008 Professional Development Workshop Materials. New York: The College Board, 2007. Accessed March 12, 2013. http://apcentral.collegeboard.com/apc/public/repository/physics-special-focus-electrostatics.pdf.

"Charges and Fields." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/charges-and-fields.

"The Electric Force Field." Collin College Physics Department. University Physics. Accessed April 23, 2013. http://iws.collin.edu/mbrooks/physics/experiments/PHYS%202426%20Exp%202%20Manual.pdf.

Wells, Connie. "Electric Potential and Potential Energy." In *Special Focus: Electrostatics*, 30–49. AP Physics, 2007–2008 Professional Development Workshop Materials. New York: The College Board, 2007. Accessed September 4, 2013. http://apcentral.collegeboard.com/apc/public/repository/physics-special-focus-electrostatics.pdf.

Unit 4 (Electric Current) Resources

"Capacitor Lab." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/capacitor-lab.

"Circuit Construction Kit (AC+DC)." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/circuit-construction-kit-ac-virtual-lab.

"Circuit Construction Kit (DC Only)." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc-virtual-lab.

"Episode 112-2: Introduction to Resistivity Using Conducting Paper." Teaching Advanced Physics. Institute of Physics. Accessed March 12, 2013. http://tap.iop.org/electricity/resistance/112/page_45984.html.

"Kirchhoff's Rules." Glenn Elert. The Physics Hypertextbook. Accessed March 12, 2013. http://physics.info/kirchhoff/problems.shtml.

Polley, J. Patrick. "Lab Seven: Ohm's Law." In *AP Physics Lab Guide,* 30–33. New York: The College Board, 2003.

Supplementary Resources

Hewitt, Paul. "Modeling Clay Resistors." *The Physics Teacher* 41 (2003): 136.

Unit 5 (Magnetism) Resources

"2 Student Directions Faraday Induction." PhET. University of Colorado at Boulder. Accessed May 24, 2013. http://phet.colorado.edu/en/contributions/view/2827.

"Faraday's Electromagnetic Lab." PhET. University of Colorado at Boulder. Accessed June 9, 2013. http://phet.colorado.edu/en/simulation/faraday.

"Faraday's Law." PhET. University of Colorado at Boulder. Accessed April 23, 2013. http://phet.colorado.edu/en/simulation/faradays-law.

"Generator." PhET. University of Colorado at Boulder. Accessed April 23, 2013. http://phet.colorado.edu/en/simulation/generator.

"Lecture 21: Magnetic Materials." Walter Lewin. MIT OpenCourseWare. Accessed October 24, 2012. http://ocw.mit.edu/courses/physics/8-02-electricity-and-magnetism-spring-2002/video-lectures/lecture-21-magnetic-materials.

Lietz, Martha, Peggy Bertrand, and Gardner Friedlander. *AP Physics Curriculum Module: Electromagnetic Induction*. New York: The College Board, 2012. [Available on the College Board website beginning in autumn 2014.]

Unit 6 (Waves and Optics) Resources

"Circular Polarization." 0ruff0. Video, 1:37. Accessed October 29, 2012. http://www.youtube.com/watch?feature=endscreen&NR=1&v=Fu-aYnRkUgg.

College Board. *AP Physics 1 and 2 Curriculum Framework.* New York: The College Board, 2012. Accessed June 20, 2013. http://media.collegeboard.com/digitalServices/pdf/ap/2012advances/11b_4615_AP_Physics_CF_WEB_120910.pdf.

"Introduction to the Electromagnetic Spectrum." Mission: Science. NASA. Accessed October 29, 2012. http://missionscience.nasa.gov/ems/01_intro.html.

Polley, J. Patrick. "Lab Eleven: Geometrical Optics – Determining the Index of Refraction." In *AP Physics Lab Guide*, 52–56. New York: The College Board, 2003.

Polley, J. Patrick. "Lab Twelve: The Diffraction Grating." In *AP Physics Lab Guide*, 57–60. New York: The College Board, 2003.

"Reflection Lab: Teacher's Guide." The Physics Classroom. Accessed October 30, 2012. http://www.physicsclassroom.com/lab/refln/RM1tg.pdf.

"Wave Interference." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/wave-interference.

Unit 7 (Modern Physics) Resources

"Alpha Decay." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/alpha-decay.

"Atom Builder." Teachers' Domain. Accessed February 15, 2013. http://www.teachersdomain.org/resource/phy03.sci.phys.matter.atombuilder.

"Atoms: The Space Between." Teachers' Domain. Accessed February 15, 2013. http://www.teachersdomain.org/resource/phy03.sci.phys.matter.atoms.

"Beta Decay." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/beta-decay.

"Davisson-Germer: Electron Diffraction." PhET. University of Colorado at Boulder. Accessed May 21, 2013. http://phet.colorado.edu/en/simulation/davisson-germer.

"Einstein Light." Joe Wolfe and George Hatsidimitris. The University of New South Wales. Accessed November 3, 2012. http://www.phys.unsw.edu.au/einsteinlight.

"Models of the Hydrogen Atom." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/hydrogen-atom.

"Nuclear Fission." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/nuclear-fission.

"Photoelectric Effect." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/photoelectric.

Polley, J. Patrick. "Lab Thirteen: Planck's Constant on the Cheap." In *AP Physics Lab Guide*, 61–63. New York: The College Board, 2003.

"Quantum Mechanics." Teachers' Domain. Accessed February 15, 2013. http://www.teachersdomain.org/resource/phy03.sci.phys.fund.quantum.

"Quantum Wave Interference." PhET. University of Colorado at Boulder. Accessed March 12, 2013. http://phet.colorado.edu/en/simulation/quantum-wave-interference.

"Quarks: Inside the Atom." Teachers' Domain. Accessed February 15, 2013. http://www.teachersdomain.org/resource/phy03.sci.phys.matter.quark.