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

Manhattan Center for Science and Mathematics
New York, New York

School	Established in 1982, Manhattan Center is a four-year public high school that provides students with a curriculum emphasizing science and mathematics. The mission of the school is to provide a challenging academic program that enables students to compete for admission to selective, four-year, post-secondary institutions.
Student population	Manhattan Center enrolls approximately 1,600 students in grades 9–12. Located in an urban New York City community, approximate student demographics are as follows: • 58 percent Hispanic • 20 percent Asian • 19 percent African American • 2 percent Caucasian At Manhattan Center, 80 percent of students receive free or reduced-price meals.
Instructional time	The school year lasts 180 days; it begins after Labor Day and ends the last week of June. The AP Physics 2 course meets for a 48-minute period every day, with one additional period each week to accommodate the lab requirements.
Student preparation	AP Physics 2 is offered to juniors and seniors who have completed two years of science (one year of which must have been either AP Physics 1 or another year-long introductory physics course) and an Algebra 2/Trigonometry course.

Primary planning resources	"AP Physics 2 Practice Exam." The College Board. http://www.collegeboard.com/html/apcourseaudit/teacher.html. This practice exam will be available in summer 2014 through the AP Course Audit website. Baird, Dean. "The Book of Phyz." Accessed June 30, 2013. http://marge.ragesw.com/~phyzorg/phyz/BOP/. Chabay, Ruth W., and Bruce A. Sherwood. *Matter and Interactions.* 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2010. Christian, Wolfgang, and Mario Belloni. *Physlet® Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics.* Boston: Addison-Wesley Publishing, 2004. Duffy, Andrew. Physlet Simulations and Animations for First-Semester Physics. Boston University: Physics. Accessed June 30, 2013. http://physics.bu.edu/~duffy/semester1/semester1.html. Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach*. 2nd ed. AP® ed. Boston: Addison-Wesley Publishing, 2009. Laws, Priscilla. *Workshop Physics Activity Guide. Modules 3 and 4.* 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2004. Van Heuvelen, Alan, and Eugenia Etkina. *The Physics Active Learning Guide*. Boston: Addison-Wesley, 2006.

Overview of the Course

Manhattan Center for Science and Mathematics High School offers a variety of Advanced Placement classes and research opportunities to all students. By emphasizing problem-solving skills and student-centered, inquiry-based laboratory investigations, AP Physics 2 provides a challenge to students interested in a college-level science course. The relevant science practices and learning objectives from the *AP Physics 1 and 2 Curriculum Framework* guide the lab experiences. Approximately 25 percent of instructional time is dedicated to the inquiry-based activities and research opportunities. Lab activities are designed to follow the modeling approach to promote discourse and develop critical thinking skills. Each unit of study includes at least one major laboratory investigation for which students write a lab report. Main components of the lab report include purpose, procedure, data analysis, and conclusion.

I use a variety of instructional strategies to facilitate greater depth of understanding. In addition to major labs, each unit in AP Physics 2 includes hands-on activities designed to enhance students' learning experiences. Open-ended problems are solved by (and often defined by) students, who must present their solutions to other students in peer-instruction activities. Socratic seminars provide a format for discussing ideas presented in class. Instructors using a modeling approach in physics have been able to differentiate instruction to better address different learning styles. Standards-Based Grading (SBG) is another strategy I use extensively in my AP Physics 2 program. SBG reveals the level of student mastery of a concept, rather than just a grade on a test. Students who struggle receive additional instruction and can use alternate assessments to demonstrate mastery, without penalty for requiring additional time. This form of instruction and assessment has allowed students with special needs to show proficiency at their own pace and according to their own learning styles.

I implement a wide range of formative assessment tools and methods to support a "big ideas" instructional approach to the curriculum framework. Oral and written presentations, student–teacher conferences, peer instruction, and other techniques are routinely used to formatively assess student progress. Outside the classroom, students post questions and comments on an Edmodo page, which provides me with another source of feedback about student understanding. The page also contains extra material to support classroom activities.

All summative assessments are framed following the format of the AP Physics 2 Exam as described in the *AP Physics Course and Exam Description*.

Unit 1:

Thermodynamics

Laboratory Investigations:

- Developing a Model for Thermal Energy Transfer and Work on Surroundings
- Gas Properties (Virtual)
- Thermodynamics Processes

Estimated Time:

4 weeks

Guiding Questions: How do we know thermal energy is transferred or exchanged? ▼ What is the role of temperature in the transference of thermal energy? ▼ How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases? ▼ How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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 and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). [LO 5.B.5.4, SP 6.4, SP 7.2] Predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. [LO 5.B.5.5, SP 2.2, SP 6.4]	Knight, Jones, and Field, Chapter 12: "Thermal Properties of Matter" (applies to the entire unit) Laws, Module 3, Activity 17.4 **Supplies** Syringes, flasks, tubes	**Instructional Activity:** This activity, which involves both guided- and open-inquiry components, introduces the laws of thermodynamics from a conservation-of-energy approach. In the activity from Priscilla Laws's *Workshop Physics*, students investigate thermal-energy transfer and work on surroundings to illustrate a thermodynamic process. Putting the flask into hot water increases the internal energy of the gas inside the flask if the volume of the syringe is kept constant. Releasing the plunger of the syringe demonstrates that work is being done on the system. This qualitative lab experience helps students understand how the internal energy of a system can be changed. Students then design their own method to increase the internal energy of the system by doing work on the gas inside the syringe and flask.
	Knight, Jones, and Field, Chapter 12: "Thermal Properties of Matter" Student clickers **Web** Baird, "2.06 Advanced Heat" "PGP – Thermodynamics"	**Formative Assessment:** Students respond to challenging questions that require them to make connections between thermodynamic concepts and devices they use in their everyday lives. Many questions on thermal energy can be found in the textbook, on the Pretty Good Physics (PGP) wiki page, and on Dean Baird's website.
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]	**Supplies** Flinn's Conduction, Convection, and Radiation – Activity-Stations Kit	**Instructional Activity:** Working in small groups, students use the kit to explore how energy is transferred by conduction, convection, and radiation. A follow-up whole-group discussion challenges students to articulate explanations of the different processes.

A quick review of the law of conservation of energy is beneficial for understanding the law of thermodynamics. You should help students make a connection with previous cases of energy transfer from a prior physics course.

Emphasizing sign conventions is important during the introduction to the first law of thermodynamics. (Note that sign conventions used by different sources may vary.)

I employ student-response devices (clickers) to assess student understanding of thermal energy and transfer, and this helps me provide direct feedback to students. Students' responses inform my decisions about next instructional steps.

Guiding Questions: How do we know thermal energy is transferred or exchanged? ▼ What is the role of temperature in the transference of thermal energy? ▼ How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases? ▼ How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims about various contact forces between objects based on the microscopic cause of those forces. [LO 3.C.4.1, SP 6.1] 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] 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] Treating a gas molecule as an object (i.e., ignoring its internal structure), 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] 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]	Christian and Belloni, Activity 20.2	**Instructional Activity**: Working individually, students use the animation in the Physlet activity to understand the concept of pressure. In the animation, “blue” particles and “red” particles are moving in a fixed container. Because the blue particles are more massive, they exert more pressure on the walls, as indicated by the text in the animation. Students will also notice that as the particles move faster the temperature increases.

This activity helps students visualize the concept of pressure. Students can continue to develop their understanding by creating their own activities using the animation.

Guiding Questions: How do we know thermal energy is transferred or exchanged? ▼ What is the role of temperature in the transference of thermal energy? ▼ How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases? ▼ How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
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] Create a plot of pressure versus volume for a thermodynamic process from given data. [LO 5.B.7.2, SP 1.1] Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and refine a scientific question concerning a proposed incorrect relationship between the variables. [LO 7.A.3.2, SP 3.2, SP 4.2] 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] 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] 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:** This instructional activity includes both guided- and open-inquiry components. Working in small groups, students design methods to investigate properties of gases using the PhET simulation. This simulation helps students establish the relationship of pressure, temperature, and volume of gases in different conditions. Students produce graphs of volume versus pressure under constant temperature, volume versus temperature under constant pressure, and pressure versus temperature while keeping the volume constant. At this point students can derive the ideal gas equation by combining the results obtained from their graphs. Students then solve practice problems using gas cycle processes to help make a connection between the law of thermodynamics and the ideal gas equations. Examples of gas cycle problems can be found in most textbooks.

The graphical representations and analyses of this simulation help students better understand and visualize the relationship between gas properties.

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Learning Objectives	Materials	Instructional Activities and Assessments
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]	Laws, Module 3, Activity 17.8.B **Supplies** Immersion heaters, Erlenmeyer flasks, one-hole rubber stoppers, plastic in-line couplers, Tygon tubing, beakers, temperature sensors, pressure sensors, computer data acquisition systems, data logger software	**Instructional Activity:** Students continue analyzing thermodynamic processes by observing how the pressure of a system changes as a function of changes in temperature. Students work in small groups to design a container that can accommodate temperature and gas pressure probes. When water is gradually heated to temperatures that do not allow too much water to evaporate, the probes will detect the changes in the system. By extrapolating the data to zero pressure, the absolute temperature can be determined.
		Formative Assessment: Students analyze the data from the previous instructional activity, making claims and forming conclusions that are supported by the data, and providing an explanation for the experimental design in a clear and logical manner. Then, working in small groups, students share their designs and defend their data analyses during a Socratic seminar session.

Extrapolating is an important skill in physics. Its significance should be emphasized to students during this activity.

I provide feedback on both the experimental design and data analysis directly to the students as they are sharing in their small groups.

Guiding Questions: How do we know thermal energy is transferred or exchanged? ▼ What is the role of temperature in the transference of thermal energy? ▼ How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases? ▼ How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
Create a plot of pressure versus volume for a thermodynamic process from given data. [LO 5.B.7.2, SP 1.1] 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] 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] 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] 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] 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]	Laws, Module 3, Activity 17.8.3 **Web** Baird, "2.06 Advanced Heat": Jobs 4 and 5 Duffy, "Adiabatic Process" and "Thermodynamic Processes: Isobaric, Isochoric, and Isothermal" (in the "Thermodynamics" section)	**Instructional Activity:** Students use the simulations created by Andrew Duffy to visualize the shape of the curves of pressure versus volume for the different thermodynamics processes. Students then complete a worksheet where they draw curves showing each process and explain qualitatively the changes present in each process. In each case the amount of work will be determined (area under the curve). Next, students work through Dean Baird's set of handouts on these topics.
	Teacher-produced quiz	**Formative Assessment:** Students take a multiple-choice quiz to demonstrate understanding of thermodynamic processes. The questions are designed to provide insight on students' depth of understanding in regard to the changes of gas properties during an isobaric, isothermal, isochoric, or adiabatic process.

Students may have some difficulties analyzing P–V diagrams. Simulations are helpful for visualizing thermodynamic changes.

I provide written feedback directly to students. If a large number of students demonstrate a lack of understanding, some additional reteaching of these concepts may be necessary.

Guiding Questions: How do we know thermal energy is transferred or exchanged? ▼ What is the role of temperature in the transference of thermal energy? ▼ How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases? ▼ How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?

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** Decks of cards ordered by number, suit, and color	**Instructional Activity:** Students address the second law of thermodynamics by performing an activity in which the idea of randomness is emphasized. Beginning with an ordered deck of cards, students work in small groups to develop an appropriate scientific experiment in which they formulate their hypothesis to measure the degree of order or disorder after shuffling the cards. They continue to shuffle the deck and look for the disorder. Students repeat this multiple times, recording their data in an appropriate table. Students then analyze the data and generalize about the degree of randomness after each shuffle.
All learning objectives in this unit are assessed in the summative assessment.	Teacher-produced unit assessment	**Summative Assessment:** This assessment consists of 15 multiple-choice questions, three short-answer items, and two long free-response questions. It is designed to assess the acquisition and application of knowledge related to thermodynamics concepts. For students who have not achieved mastery of the learning objectives, additional instruction will be provided, and individual students will be given the opportunity to retest on the learning objectives that they have not mastered.

This assessment addresses the following guiding questions:

- *How do we know thermal energy is transferred or exchanged?*
- *How is the ideal gas law modeled to demonstrate the relationships among temperature, pressure, and volume of gases?*
- *How is the law of conservation of energy applied to the understanding of the laws of thermodynamics?*

Unit 2: Static and Dynamic Fluids

Laboratory Investigations:

- Determining the Density of a Fluid Using Archimedes' Principle
- Water Fountain: Determining the Volume Rate
- Determining the Landing Spot of a Stream of Water as it Exits
- Fluid Relationships

Estimated Time:

4 weeks

Guiding Questions: ▼ How does Archimedes' principle help us to understand why certain objects float in fluids? ▼ How do various factors affect fluid flow rates? ▼ How is the law of conservation of energy applied to understanding the fluidity of substances?

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]	Knight, Jones, and Field, Chapter 13: "Fluids" (applies to the entire unit) **Supplies** Springs, objects of various mass, containers, water, various liquids	**Instructional Activity:** Students model the forces acting on a floating object. They build on their prior knowledge of free-body diagram analysis as they apply the appropriate representations to their floating objects. Next, students work in small groups to design an experiment to determine the density of a fluid using a spring. Based on their free-body diagrams, students make predictions about the changing density of the object prior to the investigation. Typically, students choose to attach an object to a spring and submerge it in a fluid with an unknown density value. After determining the buoyant force, the students can then calculate the density of the fluid. This activity includes both guided- and open-inquiry components.
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]	**Web** Baird, "2.12 Fluids": Jobs 2, 3, and 4 "Physics – Beyond Mechanics"	**Formative Assessment:** Students solve problems (activities from Baird's handouts and end-of-chapter exercises from the textbook) to continue applying models related to Archimedes' principle (investigated in the last activity). Most problem-solving sessions will be conducted in groups, following the modeling approach. Students present their results using the whiteboard-modeling technique designed by Dave Hestenes at Arizona State University. In the modeling approach, students work in small groups and record their solutions on a large whiteboard. The groups then present their solutions, enhancing the level of discussion.

Fluids are an important application of Newtonian mechanics to deformable media. However, due to the abstract nature of density, pressure, and buoyancy, these concepts typically present challenges for students. The activities mentioned in this unit plan can help to make these concepts clearer and more tangible.

This formative assessment allows students to focus on identifying some of their previously held misconceptions related to fluids. For example, many students think that buoyant force depends on mass. I provide verbal feedback directly to individual students as they present their results. If some students still demonstrate misconceptions, I may reteach the topic to those students and assign a few extra practice problems to ensure mastery.

Guiding Questions: ▼ How does Archimedes' principle help us to understand why certain objects float in fluids? ▼ How do various factors affect fluid flow rates? ▼ How is the law of conservation of energy applied to understanding the fluidity of substances?

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] 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] Construct an explanation of Bernoulli's equation in terms of the conservation of energy. [LO 5.B.10.4, SP 6.2]	**Supplies** Metersticks or rulers, protractors	**Instructional Activity:** Students work in pairs to determine parameters such as volume rate, gauge pressure, and speed of water as it exits a water fountain spout. Once the stream of water flowing from the spout is steady, students measure the stream's maximum height and angle to determine the speed at which the water leaves the fountain. With the area of the fountain's exit hole, the volume rate can be determined. Knowing the diameter of the feeder pipe, parameters such as pressure and speed of the water in the feeder can be calculated using the continuity equation and Bernoulli's equation. Based on the results, which are discussed in the post-lab session, students develop ideas to explain the high flow achieved by nozzles employed by fire departments.
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]	**Supplies** 2-liter bottles, cups **Web** "Fluid Pressure and Flow"	**Instructional Activity:** Students make a connection between the law of conservation of energy and Bernoulli's equation in this guided-inquiry activity. Working in pairs, they develop a model to estimate the first landing spot of a stream of water. Students place a 2-liter bottle filled to a certain height with water on the lab table. A hole is punched in the side of the bottle near the bottom and the water is allowed to flow out of the hole. A cup is placed at the estimated landing spot to test the model designed by the students. Students compare the ideas implemented in this activity to those developed during the study of conservation laws.
	Knight, Jones, and Field, Chapter 13: "Fluids" Student clickers	**Formative Assessment:** During the last 5–10 minutes of class, students use response clickers to answer multiple-choice questions related to concepts involved in the study of fluids. I use a bank of questions from the textbook.

Students typically don't recognize the distinctions between the hydrostatic pressure in a liquid and the thermal pressure in a gas, and therefore attempts to use $p = p_0 + \rho g d$ *for the pressure in a container of gas are not uncommon. You should emphasize the relationship between force and pressure in moving fluids.*

The hole in the bottle can be made numerous ways, such as using a nail or heating one end of an unfolded paper clip to punch through the plastic.

Students often confuse the terms vacuum, atmospheric pressure, and barometric pressure. Emphasizing the differences among the various terms and concepts will help students differentiate between "kinds" of pressure. They may also utilize the PhET simulation on fluid pressure and flow for further reinforcement.

I provide verbal feedback to students during the activity as they solve problems. I also provide further instruction on concepts as needed, based on how the class responds to individual questions.

Guiding Questions: ▼ How does Archimedes' principle help us to understand why certain objects float in fluids? ▼ How do various factors affect fluid flow rates? ▼ How is the law of conservation of energy applied to understanding the fluidity of substances?

Learning Objectives	Materials	Instructional Activities and Assessments
All learning objectives in this unit are assessed in the summative assessment.	**Supplies** Supplies will vary based on students' experimental designs	**Summative Assessment:** Working in small groups, students design an experiment to investigate relationships between diameter of a tube, volume rate of a fluid, speed of the fluid, pressure, and range of a fluid stream. Students choose two parameters and perform an activity to determine if a relationship exists between those parameters. Their final report must include their selection of system(s), bar charts, mathematical representations, data analysis, and an explanation of uncertainties in their measurements. This activity includes both guided- and open-inquiry components.

This assessment addresses all of the guiding questions in this unit.

Electric Force, Electric Field, and Electric Potential

Laboratory Investigations:

- Electrons and Transparent Tape
- Equipotential Lines and Electric Fields

Estimated Time:

4 weeks

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims about natural phenomena based on conservation of electric charge. [LO 1.B.1.1, SP 6.4] Make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. [LO 1.B.1.2, SP 6.4, SP 7.2] Construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. [LO 1.B.2.1, SP 6.2] 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] 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] 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]	Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces" (applies to the entire unit) Chabay and Sherwood, Chapter 15: "Electric Fields and Matter" (applies to the entire unit) **Supplies** Rolls of transparent tape	**Instructional Activity:** Working in small groups, students place a length of transparent tape (approximately 20 cm) on top of another piece of tape of equal length. After separating the now attracting tapes, students create a model to explain such attraction. A more complex question for the students to answer next is how the top and the bottom tapes are attracted to one's finger. Students explore the interaction between the top piece of tape and the bottom piece of tape. Understanding transfer of charges and charge conservation is the desired outcome of this activity.

Chabay and Sherwood provide a good explanation of the phenomena in this activity in Chapter 15 of their textbook. Emphasis on the transfer of electrons is important in this section. Often students have the misconception that objects are positively charged because of the transfer of protons.

Electric Force, Electric Field, and Electric Potential

(continued)

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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] 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]	**Web** "Balloons and Static Electricity" "Charges and Fields"	**Instructional Activity:** Students use the PhET simulations to better understand conservation and transfer of charges. Students are provided with questions to answer as they move through the simulations. They may also design their own questions. Students present and describe their models for static electricity concepts such as transfer of charge, induction, attraction, repulsion, and grounding. Students generate their reports and present them to the class where their assumptions, predictions, and models are critiqued.

Many students misunderstand the difference between a charged object and motion of charges. During this activity, I emphasize that even though insulators do not allow the movement of charges, they can be charged via polarization.

Electric Force, Electric Field, and Electric Potential

(continued)

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

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] 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] Qualitatively and semiquantitatively 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] 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] 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] ***(learning objectives continue)***	**Web** "Electric Field Hockey" **Supplies** Van de Graaff generator, aluminum pie pan, packing peanuts	**Instructional Activity:** I start with a demonstration using the Van de Graaff generator and an aluminum container with packing peanuts. By placing the container on top of the generator, the peanuts will become charged and fly apart, following the direction of the electric field lines. Students sketch the paths of the peanuts and volunteer possible explanations. Next, students use the PhET simulation as a good illustration of the effect of electric fields on test charges. Students should look carefully at the path of the test charge as more charges are put in the field.

Students should understand that the electric field depends only on the nature of the charge and the distance from that charge. The lines are only to indicate the direction of the electric field. Sometimes students mistakenly believe that there is no electric field between the lines.

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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] 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] Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. [LO 3.C.2.1, SP 2.2, SP 6.4] Connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. [LO 3.C.2.2, SP 7.2] Use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry). [LO 3.C.2.3, SP 2.2] 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] 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 semiquantitative 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] ***(learning objectives continue)***		

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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]		
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]		**Formative Assessment:** Students draw electric field lines from different charge magnitudes and rank them according to their strengths. Some ranking problems can also be utilized as stimuli to elicit a class discussion to reach a consensus about the rankings.
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]	Christian and Belloni, Activities 22.1 and 22.2	**Instructional Activity:** Students explore two Physlet activities to help them better visualize the magnitude of the electric field and forces of charged particles. In these simulations, the strength of the electromagnetic interaction between the charges is measured with respect to the relative location of the charges.
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] 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]	**Supplies** Rolls of transparent tape	**Instructional Activity:** Following the Physlet simulations, students design an investigation to estimate the number of excess electrons present in one of the pieces of transparent tape (introduced in a previous activity). In this context, the two repelling pieces of tape are considered to have the same charge. Students review vector addition in order to estimate the magnitude of the repulsive electromagnetic force. I then lead a class discussion about ways to estimate the number of excess electrons, based on the electric field needed to ionize air (3×10^6 N/C). Students compare their results to the estimated value from the group discussion.

I examine students' rankings for each problem and provide them direct feedback. This assessment helps me determine if any reteaching is necessary.

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	Teacher-produced problem set Baird, "2.07 Advanced Electricity": Jobs 1 and 3	**Instructional Activity:** Students solve problems about electric fields using mathematical approaches. Vector analysis is usually problematic for students; modeling forces and electric fields is an excellent opportunity for students to practice this. The Baird handouts on electrical forces and electrical fields are used to support the understanding of these concepts.
	Van Heuvelen and Etkina, Activities 14.3–14.10	**Formative Assessment:** Students answer conceptual and mathematical questions from Van Heuvelen and Etkina's book.
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] 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] 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] ***(learning objectives continue)***	**Web** "Charges and Fields" **Supplies** Rectangular baking pans, water, metallic plates, long nails, geometrical metallic objects including hollow cylinders, grid paper, 9V batteries, wires, multimeters	**Instructional Activity:** Using a rectangular pan filled with a small amount of water (about 1 cm in depth), students design and implement a procedure for finding the equipotential lines generated by two electrically charged plates of equal magnitude and opposite signs. If two metal plates are charged with a battery, equipotential lines can be mapped by using the potential values at certain distances from one of the plates. Students then use the mapping of the equipotential lines to generate graphs indicating the direction of the electric field lines. Students also test the model using different geometrical metallic objects. Using cylinders is instructive, as the potential inside the cylinder should be the same in all points.

I provide written feedback to the students' answers. If students have trouble with particular questions, I reteach the relevant concepts and then provide similar practice problems to reinforce understanding.

Students may have the misconception that the absence of an electrical field indicates an absence of electric potential. If students struggle with this, I incorporate an additional demonstration or investigation to calculate the value of electric potentials inside a conductor.

For this investigation, it is helpful to have students write formal lab reports to discuss, based on evidence, the relationship between equipotential lines and electric field lines.

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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 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] 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] Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [LO 3.A.2.1, SP 1.1] Challenge a claim that an object can exert a force on itself. [LO 3.A.3.2, SP 6.1] Describe a force as an interaction between two objects and identify both objects for any force. [LO 3.A.3.3, SP 1.4] 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] ***(learning objectives continue)***		

Electric Force, Electric Field, and Electric Potential

(continued)

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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]		
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]	**Supplies** Battery-operated radio, metal cage, plastic cage	**Instructional Activity:** Students explore the difference between the effects of charges in conductors and insulators. By using a battery-operated radio, a metallic cage, and a plastic cage, students determine whether there is an electric field inside a charged conductor (no radio signal) and a nonconductor. After the activity, students continue to develop mathematical models to calculate electric potential for test charges and uniform-distributed charged objects.
Make predictions about the redistribution of charge during charging by friction, conduction, and induction. [LO 4.E.3.1, 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] 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]	**Supplies** Multimeters, charge sensors, hollow metallic cylinders, hollow plastic cylinders, metallic spheres, plastic spheres	**Instructional Activity:** Students test a series of insulators and conductors to see if any can be charged. They apply skills learned during previous activities to develop a model of the distribution of charges in conductors and insulators. After the activity, I lead a discussion to reach consensus on the matter.

Electric Force, Electric Field, and Electric Potential

(continued)

Guiding Questions: ▼ How does a charge affect other charged particles? ▼ How are charges transferred? ▼ How does the change of electric potential determine the movement of charges?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	Teacher-produced quiz	**Formative Assessment:** Students answer several conceptual questions emphasizing the understanding of transference of charges in conductors and insulators by contact and induction. Following the assessment, I lead a whole-class discussion to address any potential student misconceptions.
All learning objectives in this unit are assessed in the summative assessment.	Teacher-produced unit assessment	**Summative Assessment:** Students take a unit exam encompassing forces, electric fields, and electric potential. Students respond to conceptual and short-essay questions and perform calculations. If necessary, students can retest after additional instruction in order to better demonstrate their understanding.

I provide direct feedback to students on their responses and use this to guide the whole-group discussion, which serves as a review prior to the summative assessment.

This assessment addresses all of the guiding questions in this unit.

Unit 4: DC Circuits and RC Circuits (Steady-State Only)

Laboratory Investigations:

- The Relationship Between an Object's Length, Cross-Sectional Area, and Resistance
- The Behavior of Capacitors in Circuits
- The Validity of Kirchhoff's Rule
- RC Circuits

Estimated Time:

4 weeks

Guiding Questions: ▼ How is it possible to create and maintain a non-zero electric field inside a wire? ▼ How does the current divide between parallel resistors? ▼ What produces resistance and why are there resistors and conductors? ▼ What is the role of a capacitor in an electric circuit?

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] 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] 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] 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]	Knight, Jones, and Field, Chapter 22: "Current and Resistance" Chabay and Sherwood, Chapter 20: "Circuit Elements" **Web** "Resistance in a Wire" **Supplies** Conductive paper, multimeters, wires, scissors	**Instructional Activity:** In a guided-inquiry activity, students explore the relationship between the resistance of conductive paper and its length, as the area remains constant, and then they explore how the resistance changes as a function of the area for a determined length. Students use a strip of conductive paper and change the separation of the test leads to investigate the resistance–length dependency. The cross-sectional variable can be changed by stacking strips of conductive paper. This activity allows students to establish a model for resistivity. Students further inform their model by manipulating the resistance in a wire in the PhET simulation.
		Formative Assessment: Students construct a model that relates the resistance, length, and cross-sectional area of a given material using the prior activity's data. Students then present their models to the class.
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] 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]	**Web** "Circuit Construction Kit (DC Only)"	**Instructional Activity:** Students use the PhET simulation on DC circuits and compare the results with the previous investigation on resistivity. I lead a class discussion to help students reach consensus regarding the role of each element in the circuit.

Students may have misconceptions regarding the motion of charges when capacitors are present in a circuit, so it is helpful to emphasize the role of electric fields in the wires.

During their presentations, I provide direct feedback regarding students' understanding of resistance based on their models and descriptions.

Although simple circuit analysis was introduced in AP Physics 1, this activity helps to reintroduce students to the concept of a complete loop.

Guiding Questions: ▼ How is it possible to create and maintain a non-zero electric field inside a wire? ▼ How does the current divide between parallel resistors? ▼ What produces resistance and why are there resistors and conductors? ▼ What is the role of a capacitor in an electric circuit?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	**Supplies** 1-F capacitors (5V), batteries, thick-filament mini-bulbs, thin-filament mini-bulbs, compasses	**Instructional Activity:** Working in small groups, students use 1-F capacitors (5V) to investigate the behavior of capacitors in circuits. The first exploration is to connect a battery, a thick-filament mini-bulb, and a capacitor in series. After making pertinent observations, students repeat the investigation using a thin-filament mini-bulb. Students then provide explanations for their observations. The experiment will be repeated with two capacitors in the circuit, first connected in parallel and then in series. If available, a compass can be used to observe the direction of the current. Students individually write a formal lab report describing the models that explain their observations.
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] 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] 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]	Knight, Jones, and Field, Chapter 23: "Circuits" Chabay and Sherwood, Chapter 20: "Circuit Elements" Christian and Belloni, Activities in Chapter 30 **Supplies** Small light bulbs, capacitors, resistors, batteries, switches, multimeters	**Formative Assessment:** Students use small light bulbs, capacitors, resistors, batteries, and switches to test their predictions of the effect of changing some of the circuit elements. Using multimeters, they also test their numerical predictions. Students complete a series of ranking-task exercises at the end of class and submit their answers as "exit slips." These tasks address the relationships among values of circuit components.

I provide written feedback to students regarding their ranking tasks. If students demonstrate a lack of understanding, reteaching of these concepts may be necessary.

DC Circuits and RC Circuits (Steady-State Only)

(continued)

Guiding Questions: ▼ How is it possible to create and maintain a non-zero electric field inside a wire? ▼ How does the current divide between parallel resistors? ▼ What produces resistance and why are there resistors and conductors? ▼ What is the role of a capacitor in an electric circuit?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Teacher-produced assessment	**Formative Assessment:** Students respond to several multiple-choice questions and one free-response question to assess their understanding of circuit analysis.
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] 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] 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] 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]	Knight, Jones, and Field, Chapter 23: "Circuits" **Supplies** Resistors, 9V batteries, wires, multimeters	**Instructional Activity:** Students, working in small groups, construct a circuit with three resistors of different values connected to a 9V battery. Using a multimeter, they measure the potential differences of the elements to show that the sum of the potential differences in the loop is equal to zero. If a resistor is replaced, the potential differences will all change but the sum will still be zero. This activity clearly shows the validity of Kirchhoff's rule.

Students receive direct written feedback on both their multiple choice questions and the free-response question. The students' performances on this assessment provide insight into whether or not they need further instruction on these concepts.

Unusual circuit arrangements can cause confusion for students, so you must emphasize the current divider model to make the analysis of circuits easier to process and understand.

Jesus E. Hernandez

DC Circuits and RC Circuits (Steady-State Only)

(continued)

Guiding Questions: ▼ How is it possible to create and maintain a non-zero electric field inside a wire? ▼ How does the current divide between parallel resistors? ▼ What produces resistance and why are there resistors and conductors? ▼ What is the role of a capacitor in an electric circuit?

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]	O'Kuma, Maloney, and Hieggelke, "DC Circuit Ranking Tasks"	**Formative Assessment:** Students complete several ranking-task exercises in which they make predictions about the electric potential drop across various circuit elements.
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] 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]	Knight, Jones, and Field, Chapter 23: "Circuits"	**Instructional Activity:** Students test the law of conservation of charge by measuring values for current in different branches of complex circuits. Students also make predictions and compare them with experimental values.
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] 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]	**Supplies** 1F capacitors, mini-bulbs, batteries, electric and electric-potential probes (optional), multimeters (optional)	**Instructional Activity:** In this activity, which includes guided- and open-inquiry components, students use the equipment provided to design different RC circuits. If electric and electric-potential probes are available, graphs can be created to explain the behavior of different elements in RC circuits. Students can also use multimeters to monitor the change in value of current and electric potential in the RC circuit.

I provide verbal feedback to students as they complete the exercises and as they share their rankings with the class.

DC Circuits and RC Circuits (Steady-State Only)

(continued)

Guiding Questions: ▼ How is it possible to create and maintain a non-zero electric field inside a wire? ▼ How does the current divide between parallel resistors? ▼ What produces resistance and why are there resistors and conductors? ▼ What is the role of a capacitor in an electric circuit?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	Teacher-produced assessment	**Formative Assessment:** Students complete a series of ranking tasks and circuit schematics utilizing the concepts from the previous RC circuit investigation. For example, they might create a circuit to maximize charge in the capacitor or current through light bulbs.
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 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]	Christian and Belloni, Activities in Chapter 30 Chabay and Sherwood, Chapter 20: "Circuit Elements"	**Instructional Activity:** Students perform the numerical integration of an RC circuit as designed by Chabay and Sherwood. I then lead a class discussion to compare their findings with the observations they made in the lab activity about RC circuits.
All learning objectives in this unit are assessed in the summative assessment.	Teacher-produced unit assessment	**Summative Assessment:** Students take a comprehensive test consisting of 15 multiple-choice questions, three short-answer questions, and two long free-response questions. The test includes quantitative and conceptual questions.

I provide direct feedback to the students on their ranking of each task.

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

Magnetostatics and Electromagnetism

Laboratory Investigations:

- Behavior of Stacked Magnets
- Magnetic Force on a Current-Carrying Wire
- Faraday's Law

Estimated Time:

4–5 weeks

Guiding Questions: ▼ How can we describe a magnetic field? ▼ How does a motor work? ▼ How does a magnet influence the movement of charged particles? ▼ How does the presence of a magnetic field generate a current in a conductive material? ▼ How can a magnet induce current in a wire?

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 semiquantitative 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] 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]	Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces" **Supplies** Sets of four disk-shaped magnets, rod magnets, compasses	**Instructional Activity:** Students individually investigate magnetic dipoles by stacking four disk-shaped magnets and comparing their behavior with that of a rod magnet. Then they separate the four magnets and do the same comparison. A compass is used to determine directionality of the magnetic field. Students predict what would happen if one of the magnets is cut in half and whether it is possible to separate the poles.
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 semiquantitative 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]		**Formative Assessment:** Students construct models to explain their observations of the behavior of stacked magnets. They must provide evidence of directionality of the magnetic field generated by the magnets. Students share their models with the entire class. The class is encouraged to provide feedback on the proposed models.
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]	Christian and Belloni, Activity 27.2 and 27.3 **Supplies** Cathode ray tube or Crookes tube, permanent magnet	**Instructional Activity:** Students analyze the behavior of charged particles as they move through a magnetic field. I demonstrate how electron beams can be deflected, either through a cathode ray tube or Crookes tube, by placing a permanent magnet with the north pole directed at different angles with respect to the beam of electrons. Students compare the degree of deflection of the beam as the magnet is moved at different angles.
	O'Kuma, Maloney, and Hieggelke, "Magnetism and Electromagnetism Ranking Tasks"	**Formative Assessment:** Students rank the degree of deflection of the electron beam as a function of the strength of the magnetic field. This assessment gives students an opportunity to apply mathematical routines to determine the force exerted on a moving charge by a magnetic field.

Students receive feedback directly from me during their presentations. Peer critique of the models also provides students with feedback on their proposed models. This assessment helps me determine whether any reteaching is necessary.

If the electric beam is not available, a helpful virtual demonstration of the phenomenon was developed by Christian and Belloni.

Students receive direct feedback on their solutions to this ranking-task problem. Their ability to provide appropriate rankings provides insight into whether further instruction on these concepts is needed.

Guiding Questions: ▼ How can we describe a magnetic field? ▼ How does a motor work? ▼ How does a magnet influence the movement of charged particles? ▼ How does the presence of a magnetic field generate a current in a conductive material? ▼ How can a magnet induce current in a wire?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	Laws, Module 4, Activity 26.7 **Supplies** 1V batteries, wires, switches, neodymium magnets (or magnets of at least 7.5 kG)	**Instructional Activity:** Students use a compass to detect the presence of a magnetic field created by a current-carrying wire. If enough current passes through a wire, a compass will respond and students will be able to map the direction of the magnetic field. In Laws's activity book, there are many practical exercises that students can use to gain a better understanding of this phenomenon.
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]	**Supplies** Magnets, power supply, wires, switches	**Instructional Activity:** In this guided-inquiry activity, students design and implement a method to investigate the force on a current-carrying wire caused by the presence of a magnet. A quantitative activity can be performed by measuring the angle of deflection caused by the magnet on the wire when a different set of current values pass through the wire.
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]	Teacher-produced assessment	**Formative Assessment:** Students answer several multiple-choice questions related to the presence of a magnetic field created by a current-carrying wire.
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] 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]	Christian and Belloni, Activity 27.1 **Supplies** Magnets, compasses, magnetic field sensors	**Instructional Activity:** Students use a series of magnets to detect the direction of magnetic fields using a compass and a magnetic field sensor if one is available. They compare the strength of the magnetic field of Earth with the one generated by a permanent magnet. Simulations such as Christian and Belloni's Physlet exercises provide a good opportunity for students to visualize the behavior of ferromagnetic magnets.
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]		**Formative Assessment:** Students work in groups and use whiteboards to create models explaining the behavior of permanent magnets and addressing the question of why ferromagnetic magnets stick to refrigerators. They present their models to the class.

It's a good idea to locate a compass near a permanent magnet before using it with the current-carrying wire so that students can draw comparisons between the different phenomena.

I lead a whole-class discussion on the appropriate answers to the questions, soliciting explanations from the students. This assessment helps me identify topics that may require reteaching.

Students receive feedback on their models from me and on their whiteboard presentations from their peers.

Guiding Questions: ▼ How can we describe a magnetic field? ▼ How does a motor work? ▼ How does a magnet influence the movement of charged particles? ▼ How does the presence of a magnetic field generate a current in a conductive material? ▼ How can a magnet induce current in a wire?

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] 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] 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]	Nguyen and Meltzer, "Visualization Tool for 3-D Relationships and the Right-Hand Rule"	**Instructional Activity:** Students apply Newton's laws to calculate forces on moving charges due to the presence of a magnetic field. Students should be helped to visualize the plane containing the vectors $\vec{v}$ and $\vec{B}$. The force vector is then perpendicular to that plane. Using the whiteboard-modeling technique, students solve assigned problems and present their solutions and analyses to the whole 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]	Teacher-produced assessment	**Formative Assessment:** Several multiple-choice questions and one short free-response question are used to check for student understanding of the effect of a magnet on a moving charge.
This summative assessment addresses all of the learning objectives covered in this unit up until this point.	Teacher-produced assessment	**Summative Assessment:** A comprehensive exam consisting of 15 multiple-choice, three short-response, and two open-response questions is used to address the learning objectives and the essential questions related to permanent magnets and the effect of a magnetic field on a moving charged particle. For students who don't demonstrate mastery, additional instruction is provided and opportunities for retesting are available.

Visualizing the situation in three dimensions and the use of the right-hand rule for the force on a moving charged particle is not a trivial exercise for many students. Creating models in 3-D is essential. The Nguyen and Meltzer visualization tool is helpful to understand the cross-product of two vectors.

I provide written feedback to address specific areas of concern that I find when looking at students' answers to the formative assessment questions.

This assessment addresses the following guiding questions:

- *How can we describe a magnetic field?*
- *How does a motor work?*
- *How does a magnet influence the movement of charged particles?*
- *How does the presence of a magnetic field generate a current in a conductive material?*

Magnetostatics and Electromagnetism

(continued)

Guiding Questions: ▼ How can we describe a magnetic field? ▼ How does a motor work? ▼ How does a magnet influence the movement of charged particles? ▼ How does the presence of a magnetic field generate a current in a conductive material? ▼ How can a magnet induce current in a wire?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Knight, Jones, and Field, Chapter 25: "Electromagnetic Induction and Electromagnetic Waves" **Supplies** Magnetic field sensors, wires, multimeters, batteries or power supply	**Instructional Activity:** In a guided-inquiry activity, students work in small groups to design investigations to test Faraday's law. Using a magnetic sensor, wire, and multimeter, they explore the relationship among current, number of wire loops, and diameter of the loops. Students change only one parameter at a time and then establish a relationship between each quantity and the magnetic field generated in the center of the loop. A good modification of the activity is to assign each group only one of the tasks, and then in a whole-class discussion, each group can explain their findings. If a magnetic sensor is not available, the degree of deflection on a compass needle is also an indication of the changing field.
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]	Teacher-produced ranking task exercise O'Kuma, Maloney, and Hieggelke, "Magnetism and Electromagnetism Ranking Tasks"	**Formative Assessment:** As an exit slip, a ranking-task exercise is given to the students. The intention is to reinforce the objectives of the lab.
	Web "Faraday's Law" **Supplies** Neodymium magnets, solenoids, wires, multimeters	**Instructional Activity:** Students use a magnet and a solenoid to generate current in a wire. When moving a magnet in and out of a solenoid, students can detect the presence of a current by using a multimeter. Students also use the PhET simulation on Faraday's law to gain a greater understanding of the phenomena involved.
All learning objectives in this unit are assessed in the summative assessment.		**Summative Assessment:** Students write a research paper about the applications of Faraday's law and its effects on our daily life. Each student focuses on a particular application and illustrates how Faraday's law applies to it. For instance, interesting topics could be DC motors, speakers, generators, electric guitars, etc.

Students should notice that the sensor is very sensitive and able to detect the Earth's magnetic field. It is important to account for that when reaching conclusions. Graphs will help to visualize the relationship of each parameter in the generated magnetic field.

Direct feedback is provided to students about their rankings on this exercise. Any areas of concern are addressed the next day in a whole-class discussion of the exercise.

It is important to do both the hands-on activity and the online simulation, as they reinforce the ideas that a current can be induced in a conductor in the presence of a changing magnetic field and that a current produces a magnetic field.

I use two summative assessments in this unit so that I can more deeply assess student understanding of induction, as it is a difficult concept for most students to master.

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

Unit 6:

Geometric Optics and Physical Optics

Laboratory Investigations:

- Generating Transverse and Longitudinal Waves
- Waves on a String: Standing Waves
- Measurement Using Diffraction Patterns
- The Index of Refraction
- Lenses and Mirrors and the Formation of Images

Estimated Time:

4–5 weeks

Guiding Questions: ▼ How can transverse and longitudinal waves manifest? ▼ How are standing waves produced? ▼How can the separation between items such as CD tracks or the thickness of a piece of hair be measured? ▼ How can the index of refraction be measured, and what is its importance in determining the purity of liquid substances?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe representations of transverse and longitudinal waves. [LO 6.A.1.2, SP 1.2] 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] 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]	Knight, Jones, and Field, Chapters 15 and 16: "Traveling Waves and Sound" and "Superposition and Standing Waves" **Web** "Wave Motion" **Supplies** Spring toys, timers, metersticks	**Instructional Activity:** Students generate waves using spring toys. By swinging the spring toys in a transverse way, they can determine properties such as wavelength, frequency, amplitude, and speed. Students produce transverse and longitudinal waves during this activity. They also model the motion of the two kinds of waves by becoming part of the wave. (A good description of the activity can be found in Chapter 15 of the textbook.) Students make a "wave" as they would at a sporting event: they act like the particles as the wave propagates. The wave will travel horizontally through the medium of the class, but the particles that carry the wave are moving along a different axis, corresponding to a different polarization.
	Teacher-produced assessment	**Formative Assessment:** Students complete a multiple-choice assessment to determine whether they understand the difference in the motion of longitudinal waves and transverse waves. The formative assessment is designed to reinforce the learning objectives covered during their prior laboratory investigations about mechanical waves.
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] 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]	**Supplies** Tuning forks, clamps, strings, masses, pulleys	**Instructional Activity:** In a guided-inquiry activity, students work in small groups to design a method to produce standing waves. Typically, a tuning fork is attached to a clamp. A string with a low-hanging mass attached to it passes over a pulley and then is connected to the tuning fork. If a wave is generated in the tuning fork, the wave will rebound from the pulley and cause standing waves. Students make a video of the activity in order to analyze properties of waves. If possible, beforehand, have students conduct a video analysis of the plucking of a string on a musical instrument as it will demonstrate the same behavior experienced by the string attached to the tuning fork.

It is important to emphasize that waves do not carry particles as they propagate. Visualizing longitudinal waves presents some difficulties. The first two activities model the difference between the two kinds of waves.

I provide written feedback to students about their understanding of wave motion. This also identifies common student misconceptions that may need to be addressed through additional instruction.

A variety of parameters can be identified in this activity. Different masses can be attached to change the tension in the string, and students can find the relationship between wavelength and tension; or the tuning fork can be changed, and students can find the relationship between nodes and frequency. By combining these relationships and the equation for the speed of a wave, a new relationship between speed and tension can be derived.

Guiding Questions: ▼ How can transverse and longitudinal waves manifest? ▼ How are standing waves produced? ▼How can the separation between items such as CD tracks or the thickness of a piece of hair be measured? ▼ How can the index of refraction be measured, and what is its importance in determining the purity of liquid substances?

Learning Objectives	Materials	Instructional Activities and Assessments
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]		**Formative Assessment:** Students write a formal lab report in which they detail the derivations of the relationships among mass, tension, period, and wavelength. They also use the video analysis taken during the previous activity to make a model of standing waves. This helps students understand the production of standing waves.
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]	**Supplies** Diode lasers, diffraction gratings, screens	**Instructional Activity:** Working in small groups, students observe the patterns created on a screen as a laser beam passes through a diffraction grating. Diode lasers of many different wavelengths can be used to observe the difference in the patterns generated. The same phenomenon can be observed if a water wave is generated in a ripple tank and the wave is constrained to pass through a small opening.
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]		**Formative Assessment:** In small groups, students use a white-boarding technique to articulate the models they developed to explain their observations of interference patterns in the previous activity. The evaluation is based on students' ability to explain and defend their models.
	Supplies CDs, DVDs, lasers, metersticks	**Instructional Activity:** In small groups, students measure the spacing between tracks (polymer layers) on a CD and DVD based on the diffraction patterns generated when a laser passes through the CD or DVD or reflects from the surface of those objects. Students also determine the thickness of a piece of hair as the distance between two consecutive orders in the diffraction pattern is measured. They conclude this activity by writing a formal lab report.

I provide direct feedback to students on their formal lab reports. This assessment helps me determine if any reteaching is required.

Students may have difficulty understanding this concept if too few visualizations are available for them to analyze.

I provide direct feedback to both individual students and groups as they explain their models.

Geometric Optics and Physical Optics

(continued)

Guiding Questions: ▼ How can transverse and longitudinal waves manifest? ▼ How are standing waves produced? ▼How can the separation between items such as CD tracks or the thickness of a piece of hair be measured? ▼ How can the index of refraction be measured, and what is its importance in determining the purity of liquid substances?

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]	**Supplies** Glass containers, light sensors, lasers, plane mirrors	**Instructional Activity:** In small groups, students use a light sensor to compare the intensity of a laser beam before passing through a glass of water and after passing through a glass of water. They also measure the intensity of laser light before and after it is reflected from a plane mirror. Students report their findings in a class discussion to gain a better understanding of transmission, reflection, and absorption of light.
		Formative Assessment: Based on the previous activity, students write an essay considering the advantage of fiber optics over traditional copper wiring in the communication industry. They must articulate a clear scientific argument for the benefits of fiber optics based on evidence from physics principles and prior investigations.
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] ***(learning objectives continue)***	Knight, Jones, and Field, Chapter 17: "Wave Optics" **Supplies** Lasers, plane mirrors, prisms	**Instructional Activity:** Students use lasers and plane mirrors to measure the angle of incidence and reflection. They also point the laser beam toward a prism and observe the direction of the beam after it has passed through the prism; then they measure the angles of incidence and refraction.
		Formative Assessment: In small groups, students create models to demonstrate light behaving as a particle. They are assessed as a group as they defend their own models before the class.

I provide written feedback to students on their essays.

Although students are assessed and receive feedback as a group, I also provide individual feedback to students as necessary. This may illuminate the need to provide extra practice for some students in order to help them master this concept.

Geometric Optics and Physical Optics

(continued)

Guiding Questions: ▼ How can transverse and longitudinal waves manifest? ▼ How are standing waves produced? ▼How can the separation between items such as CD tracks or the thickness of a piece of hair be measured? ▼ How can the index of refraction be measured, and what is its importance in determining the purity of liquid substances?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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] 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] 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]		

Geometric Optics and Physical Optics

(continued)

Guiding Questions: ▼ How can transverse and longitudinal waves manifest? ▼ How are standing waves produced? ▼How can the separation between items such as CD tracks or the thickness of a piece of hair be measured? ▼ How can the index of refraction be measured, and what is its importance in determining the purity of liquid substances?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] Make qualitative comparisons of the wavelengths of types of electromagnetic radiation. [LO 6.F.1.1, 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]	Knight, Jones, and Field, Chapter 18: "Ray Optics" **Web** "Geometric Optics"	**Instructional Activity:** The HippoCampus website contains a series of videos under the Geometric Optics heading that can be used to start a conversation about lenses and mirrors and their respective image formations. The format of this lesson is in the "flipped classroom" style, whereby students watch the videos prior to coming to class so that the instruction focuses on class discussions about misconceptions and questions that students may have.
		Formative Assessment: Students answer the following question about the nature of virtual and real images: *What is the meaning of a virtual image?* Then they formulate their own questions to prove the existence of virtual images. Students draw diagrams to show the formation of virtual images. A class discussion facilitates deeper understanding and helps me assess student knowledge.
	Supplies Flat/plane mirrors, candles, lenses, rulers	**Instructional Activity:** Students develop procedures to determine the position of virtual images generated by plane mirrors. Students also use candles, lenses, and rulers to perform their investigations.
All learning objectives in this unit are assessed in the summative assessment.	Teacher-produced unit assessment	**Summative Assessment:** Students take a unit test consisting of 15 multiple-choice questions, three short-answer questions, and two long free-response questions to assess the level of understanding in waves and optics. Students who demonstrate a lack of understanding on the assessment may retake the summative assessment after receiving teacher feedback and additional instruction.

In addition to providing feedback on the students' diagrams, I provide feedback on individual comments and questions during the whole-class discussion.

Students may have difficulty understanding the formation of images. They need to recognize that one sees something when a bundle of rays enters the pupil and is then focused by the eye to form the image.

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

Unit 7:

Quantum, Atomic, and Nuclear Physics

Laboratory Investigations:

- Blackbody Radiation (Virtual)
- Photoelectric Effect
- Davisson–Germer Experiment (Virtual)

Estimated Time:

4 weeks

Guiding Questions: ▼ What unsolved problems in classical physics led to the development of quantum mechanics? ▼ What behavior is exhibited by particles on the atomic scale? ▼ How do LEDs work? ▼ Why are only certain transitions between energy states of the atom allowed?

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] 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] Identify the strong force as the force that is responsible for holding the nucleus together. [LO 3.G.3.1, SP 7.2] 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]	Knight, Jones, and Field, Chapters 28, 29, and 30: "Quantum Physics," "Atoms and Molecules," and "Nuclear Physics" **Web** "Bohr Model of the Atom for Chemistry"	**Instructional Activity:** Working in small groups, students use the model of the hydrogen atom in the PhET simulation to do the following: understand Bohr's energy-level atomic model, calculate the energy or wavelength of emitted/absorbed photons, explain the origin of spectra of gases, calculate the energy or wavelength for a single-step transition given that information for a two-step transition between the same levels, and diagram the energy levels of an atom given an expression for those levels and determine the lines in that atom's spectrum. In their small groups, students report their findings using the modeling-physics method.
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]	**Web** Duffy, "Blackbody Radiation"	**Instructional Activity:** Working in pairs in a guided-inquiry activity, students utilize the applet to explore the relationship between temperature and the emitted frequencies of radiation. This is an introduction to the idea of the ideal blackbody radiation given off by any object above absolute zero. Students graph the change of particular frequencies as a function of temperature. The activity helps to explain blackbody radiation, the ultraviolet catastrophe, and the mathematical error that Planck made that led to the solution.

I emphasize that all models are approximations, but most of them are useful to explain certain phenomena.

Guiding Questions: ▼ What unsolved problems in classical physics led to the development of quantum mechanics? ▼ What behavior is exhibited by particles on the atomic scale? ▼ How do LEDs work? ▼ Why are only certain transitions between energy states of the atom allowed?

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] 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] 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] 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 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] 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] 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]	**Web** Duffy, "Energy Levels for Hydrogen"	**Instructional Activity:** Students working in pairs use the simulation to visualize emission and absorption spectra for the hydrogen atom. Students gather data from the simulation and explain the association of a color with a certain frequency.

During the simulation, it is important to point out to students that energy appears in discrete quanta rather than in a continuum.

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Learning Objectives	Materials	Instructional Activities and Assessments
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]	Teacher-produced ranking-task exercise	**Formative Assessment:** Students complete a series of ranking tasks to match transitions with frequency and associated energy.
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] 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] 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]	**Web** "Alpha Decay" "Beta Decay" "Nuclear Fission"	**Instructional Activity:** Working in pairs, students explore the PhET simulations that show the differences between alpha decay and beta decay. Students make observations for the different decays simulated and write a report emphasizing differences between the processes.
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] 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] 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] ***(learning objectives continue)***	Atom Building Game	**Instructional Activity:** In small groups, students design game activities to model nuclear reactions and nuclear processes. The activity is based on the Cambridge Physics Outlet's Atom Building Game.
	Teacher-produced assessment	**Formative Assessment:** Students complete a multiple-choice assessment regarding the difference between the nuclear processes.

I provide direct feedback to students' rankings. Their rankings provide insight into whether further instruction on this concept is necessary.

In this formative assessment, I am looking for mastery of differentiating between nuclear processes. I provide feedback to students based on their answers to the multiple-choice questions, and I also identify specific concepts that may need further explanation or reteaching.

Guiding Questions: ▼ What unsolved problems in classical physics led to the development of quantum mechanics? ▼ What behavior is exhibited by particles on the atomic scale? ▼ How do LEDs work? ▼ Why are only certain transitions between energy states of the atom allowed?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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] 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]		
Support the photon model of radiant energy with evidence provided by the photoelectric effect. [LO 6.F.3.1, SP 6.4] 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]	**Web** "Photoelectric Effect" **Supplies** LEDs (five different colors), multimeters, wires, potentiometers, 9V batteries	**Instructional Activity:** Working in small groups in a guided-inquiry activity, students estimate the value of Planck's constant by using LEDs of different colors, potentiometers, and a multimeter to graph the minimum voltage needed to illuminate LEDs versus the LEDs' frequencies. The slope of the graph will be proportional to Planck's constant. If this equipment is not available, you can also use the simulation of this activity found on the PhET website.

It is good at this point to compare Einstein's solution and Planck's mathematical trick for blackbody radiation. Students may have difficulties understanding the roles of V (stopping potential), hf, *and the work function* W *in the photoelectric effect experiment. Emphasizing the role of stopping voltage is fundamental to understanding the experiment.*

Guiding Questions: ▼ What unsolved problems in classical physics led to the development of quantum mechanics? ▼ What behavior is exhibited by particles on the atomic scale? ▼ How do LEDs work? ▼ Why are only certain transitions between energy states of the atom allowed?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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]	**Web** "Davisson-Germer: Electron Diffraction"	**Instructional Activity:** In pairs, students use the Davisson–Germer online lab to visualize electrons diffracted off a crystal of atoms at certain angles due to wave interference, thus confirming the wave-model nature of electrons. After completing the activity, students discuss the results of the photoelectric effect experiment and the Davisson–Germer experiment as a way to address the dual behavior of light.
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] 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]	**Online video** "The Challenge of Quantum Reality"	**Instructional Activity:** I introduce the formula for the de Broglie wavelength. Working in small groups, students compute the wavelength of an electron moving at a typical speed and that of a baseball or other macroscopic object in order to understand why we don't see the wave nature of matter at ordinary scales. Different groups can compare different objects. This is also a good time to introduce the idea of the wave function that we use to represent particles. Students watch the video from the Perimeter Institute and answer questions associated with quantum phenomena; the questions come with the video package.

Extrapolating is an important tool in physics. This activity further emphasizes the importance of this practice.

Guiding Questions: ▼ What unsolved problems in classical physics led to the development of quantum mechanics? ▼ What behavior is exhibited by particles on the atomic scale? ▼ How do LEDs work? ▼ Why are only certain transitions between energy states of the atom allowed?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Knight, Jones, and Field, Chapters 28, 29, and 30: "Quantum Physics," "Atoms and Molecules," and "Nuclear Physics"	**Formative Assessment:** I pose a series of questions to the class to address the following two guiding questions: • What unsolved problems in classical physics led to the development of quantum mechanics? • Why are only certain transitions between energy states of the atom allowed? I use an electronic-response system to collect and display students' answers. In small groups, students explain to me the solutions to the tasks. Questions for this activity can be drawn from the Knight, Jones, and Field textbook as well as the textbook's website.
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] 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]	**Web** Duffy, "Radioactive Decay"	**Instructional Activity:** Students form pairs to predict the radioactive decay of some nuclei, based on mathematical models. They also collect data from the online activity and graph it to determine the half-life of particles.
	Teacher-produced ranking-task exercise	**Formative Assessment:** Students work in small, collaborative groups to solve a series of ranking tasks to classify the decay rate for different nuclei. Students are evaluated on their justifications for their choices. Student groups then explain to me the solutions to the tasks.
All learning objectives in this unit are assessed in the summative assessment.	Teacher-produced unit assessment	**Summative Assessment:** A unit test (1 hour) consisting of 15 multiple-choice questions, three short-answer questions, and two long free-response questions is given to assess the acquisition and application of knowledge related to modern physics concepts. Following additional instruction, a retest is given to students who did not display mastery of the material.

I provide verbal feedback to students' responses. If students need to learn more about the subject, I arrange meetings with small groups.

If students need to learn more about the subject, I arrange meetings with individual students in order to address their concerns.

This assessment addresses all of the guiding questions in this unit.

Resources

General Resources

Baird, Dean. "The Book of Phyz." Accessed June 30, 2013. http://marge.ragesw.com/~phyzorg/phyz/BOP/.

Chabay, Ruth W., and Bruce A. Sherwood. *Matter and Interactions*. 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2010.

Christian, Wolfgang, and Mario Belloni. *Physlet® Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics.* Boston: Addison-Wesley Publishing, 2004.

Edmodo. Accessed August 29, 2013. https://www.edmodo.com/.

Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach*. 2nd ed. AP® ed. Boston: Addison-Wesley Publishing, 2009.

Laws, Priscilla. *Workshop Physics Activity Guide. Modules 3 and 4*. 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc., 2004.

"Modeling Instruction." American Modeling Teachers Association. David Hestenes. Accessed June 30, 2013. http://modelinginstruction.org/.

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

Van Heuvelen, Alan, and Eugenia Etkina. *The Physics Active Learning Guide*. Boston: Addison-Wesley, 2006.

Unit 1 (Thermodynamics) Resources

Duffy, Andrew. "Adiabatic Process" in the "Thermodynamics" section. Boston University: Physics. Accessed August 1, 2013. http://physics.bu.edu/~duffy/semester1/semester1.html.

Duffy, Andrew. "Thermodynamic Processes: Isobaric, Isochoric, and Isothermal" in the "Thermodynamics" section. Boston University: Physics. Accessed August 1, 2013. http://physics.bu.edu/~duffy/semester1/semester1.html.

"Gas Properties." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/gas-properties.

"PGP – Thermodynamics." Pretty Good Physics. Accessed August 1, 2013. http://prettygoodphysics.wikispaces.com/PGP-Thermodynamics.

Unit 2 (Static and Dynamic Fluids) Resources

"Fluid Pressure and Flow." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/fluid-pressure-and-flow.

"Physics – Beyond Mechanics." American Modeling Teachers Association. Accessed August 1, 2013. http://modelinginstruction.org/teachers/resources/physics-beyond-mechanics/.

Supplementary Resource

"PGP – Fluids." Pretty Good Physics. Accessed August 1, 2013. http://prettygoodphysics.wikispaces.com/PGP-Fluids.

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.

Unit 3 (Electric Force, Electric Field, and Electric Potential) Resources

"Balloons and Static Electricity." PhET. University of Colorado at Boulder. Accessed August 27, 2013. http://phet.colorado.edu/en/simulation/balloons.

"Charges and Fields." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/charges-and-fields.

"Electric Field Hockey." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/electric-hockey.

Supplementary Resource

"3D Lecture-Demo Programs for E&M." Matter & Interactions. Accessed August 29, 2013. http://matterandinteractions.org/Content/Materials/programs2.html.

Unit 4 (DC Circuits and RC Circuits [Steady-State Only]) Resources

"Circuit Construction Kit (DC Only)." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc.

"Resistance in a Wire." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/resistance-in-a-wire.

Supplementary Resource

"3D Lecture-Demo Programs for E&M." Matter & Interactions. Accessed August 29, 2013. http://matterandinteractions.org/Content/Materials/programs2.html.

Unit 5 (Magnetostatics and Electromagnetism) Resources

"Faraday's Law." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/faradays-law.

Nguyen, Ngoc-Loan, and David E. Meltzer. "Visualization Tool for 3-D Relationships and the Right-Hand Rule." *The Physics Teacher* 43, no. 3 (2009): 155–157.

Unit 6 (Geometric Optics and Physical Optics) Resources

"Geometric Optics" on the Physics B page. HippoCampus. Accessed June 1, 2013. http://www.hippocampus.org/HippoCampus/Physics;jsessionid=555C87B682262C821623C937DED2E55B.

"Wave Motion." HippoCampus. Accessed August 1, 2013. http://www.hippocampus.org/HippoCampus/Physics?loadLeftClass=CourseCombination&loadLeftId=15&loadTopicId=2154.

Unit 7 (Quantum, Atomic, and Nuclear Physics) Resources

"Alpha Decay." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/alpha-decay.

"Beta Decay." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/beta-decay.

"Bohr Model of the Atom for Chemistry." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/contributions/view/3070.

"The Challenge of Quantum Reality." Perimeter Institute for Theoretical Physics. Acccessed August 1, 2013. http://www.perimeterinstitute.ca/outreach/teachers/class-kits/challenge-quantum-reality.

"Davisson-Germer: Electron Diffraction." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/davisson-germer.

Duffy, Andrew. "Blackbody Radiation" in the "Modern Physics" section on the Physlets in the Second Semester page. Boston University: Physics. Accessed August 1, 2013. http://physics.bu.edu/~duffy/classroom.html.

Duffy, Andrew. "Energy Levels for Hydrogen" in the "Modern Physics" section on the Physlets in the Second Semester page. Boston University: Physics. Accessed August 6, 2013. http://physics.bu.edu/~duffy/classroom.html.

Resources

(continued)

Duffy, Andrew. "Radioactive Decay" in the "Modern Physics" section on the Physlets in the Second Semester page. Boston University: Physics. Accessed June 1, 2013. http://physics.bu.edu/~duffy/classroom.html.

"Nuclear Fission." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/nuclear-fission.

"Photoelectric Effect." PhET. University of Colorado at Boulder. Accessed August 1, 2013. http://phet.colorado.edu/en/simulation/photoelectric.

Supplementary Resources

"B-2: Nuclear Reactions Game." Cambridge Physics Outlet. Accessed on August 27, 2013. http://www.cpo.com/pdf/SC_ABTEACH.pdf.

"Schrödinger's Cat." Minute Physics. Video, 1:49. Accessed August 1, 2013. http://www.youtube.com/watch?v=IOYyCHGWJq4.