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

Parish Episcopal School
Dallas, Texas

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

Overview of the Course

Students in AP Physics 2 are required to have completed a full first year of physics — either AP Physics 1 or an equivalent course. Therefore, the level of sophistication at which I expect students in AP Physics 2 to question, predict, analyze, and draw conclusions is much higher than in the Physics 1 course.

As in my AP Physics 1 course, I use inquiry-based instructional strategies that focus on experimentation to develop students' conceptual understanding of physics principles. The students begin studying a topic by making observations and discovering patterns of natural phenomena. Next, they develop, test, and apply models. Physics 2 students build on their existing understandings about using multiple representations of physical processes, solving multistep problems, and designing investigations.

In my Physics 2 course, I maintain the focus on engaging in scientific argumentation that I established in Physics 1. By now, students should have greater confidence in making and revising claims based on evidence, as well as in challenging other student's claims. Students will further develop their ability to pose meaningful questions that clarify and probe assumptions, implications, and consequences.

Laboratory Investigations

Laboratory investigations, which account for at least 25 percent of instructional time, are designed by the students. Some labs focus on investigating a physical phenomenon without having an expectation of the outcome. In other experiments, students have an expectation of the outcome based on concepts constructed from prior experiences. AP Physics 2 students are expected to transfer and build upon the foundational concepts and experiences from their previous physics coursework by applying them in new, more challenging contexts. In application experiments, students use acquired physics principles to address practical problems.

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

Problem-Solving Strategy

The students continue to master an explicit problem-solving strategy that involves three primary steps:

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

Graphing

Students are expected to be proficient in basic graphing skills, including correct labeling of a graph, scale, and axes. They will continue to master more advanced graphing skills that include the derivation of relationships from a graph and the physical interpretation of graphs through the analysis of slopes, areas under the curve, and intercepts, as well as through the linearization of functions.

Homework Assignments

I design homework assignments to provide a careful balance between qualitative and quantitative elements. I develop some assignments based on the feedback I get about student understanding from the formative assessments.

Homework assignments are chosen from textbook problems, Physlets, TIPERS (Tasks Inspired by Physics Education Research), and interactive simulation resources. The guide includes the specific Physlet and simulation exercises assigned to the students.

Formative and Summative Assessments

I incorporate formative assessment into every class by using tools and methods such as a classroom-response system (Socrative), whiteboards, and class discussion. This allows for immediate feedback for both me and my students. Throughout this guide, I describe a variety of specific formative assessment strategies and activities.

The students also complete a self-assessment at the end of each unit of instruction. As this is the second full year of physics, I expect students to have a greater ability to reflect on their own depth of knowledge. Student feedback is especially useful to me when I am making decisions about next instructional steps.

Summative assessments in my AP Physics 2 course include unit tests, consisting of conceptual questions and application problems, and lab practicums. Specific details about summative assessments can be found within each unit of this guide.

Technology

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

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

Unit 1: Electrostatics

Laboratory Investigations:

- Electrostatics Investigations
- Electroscope Investigation
- Coulomb's Law Investigation
- Equipotential Mapping Investigation

Estimated Time:

6 Weeks

Guiding Questions: ▼ How can the charge model be used to explain electric phenomena? ▼ How can electric charge interactions be explained with an electric field model? ▼ How can physical quantities such as electric field and electric potential be defined operationally? ▼ How can the structure of isolines be predicted?

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 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] Make predictions about the redistribution of charge during charging by friction, conduction, and induction. [LO 4.E.3.1, SP 6.4] 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] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces" **Web** "Electric Forces: Straws and Pens" "Electric Charges: Charges and Sticky Tape" "An Electrostatics Puzzler" **Supplies** Sticky tape, straws, pens, assorted cloth (wool, silk, fur), PVC rod, metal can, commercial electrostatics kit (optional)	**Instructional Activity: Electrostatics Investigations** In this guided-inquiry lab, students work with a partner to complete the following three activities: 1. Electric Forces: Straws and Pens 2. Electric Charges: Charges and Sticky Tape 3. An Electrostatics Puzzler The goal of these activities is to investigate the behavior of electric charges, charging processes, and the distribution of charge on a conducting object. Students answer all the questions in the activities and then partner with another team to compare their answers. The teams discuss any discrepancies and modify their conclusions. To conclude, I ask for volunteers to share the highlights of their investigations and their answers with the class.

These activities provide an opportunity to explore the interactions between charged and uncharged objects. Students often have difficulty understanding how they can test whether an object is charged. I help them discover that testing for charge can be done by checking for the attraction that occurs between a charged object and a neutral object.

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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 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, LO 7.2] Challenge the claim that an electric charge smaller than the elementary charge has been isolated. [LO 1.B.3.1, SP 1.5, SP 6.1, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 14: “Electric Charge, Force, and Energy” Knight, Jones, and Field, Chapter 20: “Electric Fields and Forces” **Supplies** Van de Graff generator, packing peanuts, polystyrene cup, string, paper towel, soap bubbles, aluminum foil, fluorescent tube	**Instructional Activity: Van de Graff Generator Demonstrations** I conduct a series of demonstrations using the Van de Graff generator. Prior to the demonstrations, students predict the outcomes and discuss their predictions with their peers, offering explanations for their predictions. Students revise their explanations (if necessary) as they observe the demonstrations and share their revised explanations in a wrap-up discussion.
Make claims about natural phenomena based on conservation of electric charge. [LO 1.B.1.1, SP 6.4] Make predictions about the redistribution of charge during charging by friction, conduction, and induction. [LO 4.E.3.1, SP 6.4] Make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects. [LO 4.E.3.2, SP 6.4, SP 7.2] Plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure. [LO 4.E.3.5, SP 3.2, SP 4.1, SP 4.2, SP 5.1, SP 5.3]	Etkina, Gentile, and Van Heuvelen, Chapter 14: “Electric Charge, Force, and Energy” Knight, Jones, and Field, Chapter 20: “Electric Fields and Forces” **Supplies** Electroscope, electrophorus, strips of transparent acetate, strips of opaque vinyl, light-colored silk or cotton, dark-colored wool, PVC tube, metal tube	**Instructional Activity: Electroscope Investigation** In this open-inquiry lab, students working in teams of three or four plan and conduct an investigation to make qualitative observations of the behavior of an electroscope when it is charged by conduction and by induction. They use an electroscope and a set of electrostatic materials in their investigation. Students record their observations in their lab journals.

The wrap-up discussion helps students confirm their understanding of the charge model based on empirical evidence about the properties of charges, charging processes, conduction and induction, and the electric properties of materials.

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Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]		**Formative Assessment: Creating Qualitative-Prediction Questions** Working in teams of three, students create two qualitative-prediction questions that include representations of the distribution of fixed and mobile charge in insulators and conductors in processes involving induction or conduction. Each question should include an annotated rubric. The teams hand in a first draft, and I review the questions and provide feedback. When they submit their final versions, I compile the questions and assign them to the class as a formative assessment. The groups grade the responses to the questions they created, using the rubrics that they wrote.
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] 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] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces" **Supplies** Small balloons, string, analytical balance, meterstick	**Instructional Activity: Coulomb's Law Investigation** In this guided-inquiry lab, students work in pairs to design and conduct a procedure to estimate the net charge on a balloon by measuring the deflection between two charged balloons. The lab report, which students write independently, should include a detailed free-body diagram of the forces acting on each of the balloons. Students show the sum of the forces and the derivation of the equation that allows them to estimate the charge on the balloons. Students also compare the magnitudes of the electric and gravitational forces exerted on the charged balloons. Students are not able to determine a percent error for this lab because they have no way of confirming the actual charge on the balloons; however, I do require them to address possible sources of error in the experiment.

This activity takes place over four class periods. It is important for students to receive feedback about how to write a good question and to learn the process of creating and applying a rubric. This activity allows students to assess their own knowledge based on their ability to write complex questions. Additionally, the quality of the questions the students create provides me with insight into any concepts that may need further instruction or reteaching.

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Learning Objectives	Materials	Instructional Activities and Assessments
(continued) Make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge. [LO 3.A.3.4, SP 6.1, SP 6.4] Use 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] 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] 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]		

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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] 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] 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] 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] Use mathematics to describe the electric force that results from the interaction of several separated point charges. [LO 3.C.2.3, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces"	**Formative Assessment: Solving Electric Force Problems** Students work individually on sets of problems involving two or three charges in a variety of configurations. All problems require multiple representations of the physical situations: a sketch, annotated free-body diagrams, the net force equation, and the complete mathematical solution. One of the problems yields a comparison between the magnitudes of the electric force and the gravitational force. I circulate among students as they are working and provide feedback if I see evidence of misunderstanding. When the students have completed the assignment, I divide the whiteboard into sections and have individual students write their complete (correct) solutions for the class to view. Students then go on a gallery walk, checking their answers against the solutions posted and making any appropriate corrections on their own work.

For electric force problems, I have students write the absolute value of the charges so that the force yields a positive value of its magnitude. Students use the sign of each charge only to determine whether the charges will be attracted or repelled. Students should recognize that Coulomb's law describes an action–reaction pair between interacting charges.

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Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 15: "The Electric Field" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces" **Web** "Charges and Fields" "Electric Field Hockey"	**Instructional Activity: Electric Field Simulations** This activity is divided into two parts that involve online simulations. First, working with a partner, students use the "Charges and Fields" simulation to help them visualize the electric field. Then, students form teams of four and play hockey using the "Electric Field Hockey" simulation. The challenge is to use no more than 12 electric charges.
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]	**Web** Reif, "Modern-Day Faradays: Teaching Students to Visualize Electric Fields"	**Instructional Activity: Electric Field Mapping** I guide students as they learn how to represent electric fields using the steps described in Reif's article. The students are assigned a variety of charge arrangements as homework exercises, and we review their answers in a class discussion the next day. This activity helps students recognize that the electric field due to a charge exists at all points in space, and that a test charge measures an electric field but does not cause it. I remind students that the signs of charges should not be included in electric field equations; they are only used to determine the direction of the electric field.

The field concept is abstract and students typically have difficulty understanding it. It is important to explain that while a gravitational field is created by an object with mass, an electric field is created by an object with charge.

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Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" and Chapter 15: "The Electric Field" Knight, Jones, and Field, Chapter 20: "Electric Fields and Forces"	**Formative Assessment: Electric Field Between Parallel Plates** Students work individually on a set of exercises involving a charged particle accelerated through a potential difference. The completed solutions should include labeled diagrams showing the motion of the particle. These problems require the application of the concepts of electric field, electric force, and electric potential — along with the concepts of the work–energy theorem and/or Newton's second law — to solve for the unknown quantities. After students have completed the exercises, they share their solutions with a partner and discuss any discrepancies. I then ask each pair to share its solution for one particular exercise with the class; by the end of the activity, we have had a whole-class discussion about each of the solutions.
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]	**Web** Wells, "Electric Potential and Potential Energy"	**Instructional Activity: Electric Potential** To teach electric potential energy and electric-potential concepts, I follow the approach described in Connie Wells' article. Wells provides a set of classroom activities that help students visualize these abstract concepts. I review the suggested example problems with the class.

As students are sharing solutions with their partners, I walk around and listen to the conversations, and I provide immediate feedback to correct any misconceptions. I also identify and address any misconceptions that emerge during the whole-class discussion — reteaching or providing further examples of the concepts as needed.

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Learning Objectives	Materials	Instructional Activities and Assessments
Construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential. [LO 2.E.1.1, SP 1.4, SP 6.4, SP 7.2] 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] 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]	Christian and Belloni, Explorations 25.1 and 25.2 and Illustrations 25.2 and 25.3	**Instructional Activity: Analyzing Equipotential Lines** Working in groups of three, students use whiteboards to explore four Physlet exercises requiring a qualitative analysis of electric potential and equipotential lines. The groups then take turns presenting their whiteboards, briefly explaining their rationale for each solution. I encourage the students to challenge each other's claims and to support their answers with evidence.
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]	Etkina, Gentile, and Van Heuvelen, Chapter 14: "Electric Charge, Force, and Energy" and Chapter 15: "The Electric Field" Knight, Jones, and Field, Chapter 21: "Electrical Potential" **Supplies** DC power supply (6V output), digital multimeter, conductive ink, conductive paper, graph paper	**Instructional Activity: Equipotential Mapping Investigation** This lab involves both guided-inquiry and open-inquiry components. I first guide the students by demonstrating the mapping of a dipole arrangement. The students then work in pairs to map equipotential isolines around charged conducting electrodes (painted on conductive paper with conductive ink) and to construct electric field lines. The students investigate the relationship between electric potential and electric fields. After completing this investigation, it should be clear to the students that the electric field is always perpendicular to equipotential surfaces.

This activity gives students the opportunity to first understand the concepts before they learn the numerical computations. This approach is important in developing students' reasoning skills.

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Learning Objectives	Materials	Instructional Activities and Assessments
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 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]		**Instructional Activity: Point Charges** Students work individually on two problem sets using specific problem-solving strategies, as described below. • Set 1 (Electric field due to two or more point charges): First, draw an accurate, labeled diagram locating the position of each charge. Then, determine the magnitude and direction of the electric field due to each charge at the point in question. Use the vector component method to solve for the resultant electric field. • Set 2 (Electric potential due to two or more point charges): Solve for the potential due to each charge. The potential due to a negative charge is negative and for a positive charge the potential is positive. You can check your calculations as the total potential equals the arithmetic sum of the potentials due to the individual point charges.
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]	**Web** Bertrand, "Conceptual Links in Electrostatics: Using a Visual Mnemonic for Electrostatic Relationships"	**Instructional Activity: Concept Maps** The goal of this activity is for the students to construct a concept map similar to the one presented in Peggy Bertrand's lesson. Students work with a partner to create an electrostatics concept map (showing electric force, field, and potential) to be used as a review for the summative assessment. A concept map is a diagram of nodes, each containing concept labels; the nodes are linked together with directional lines, also labeled. The nodes are arranged in hierarchical levels that move from general to specific concepts. Concept maps are a useful instructional strategy, as they assess how well students see the big picture of a particular topic. Students' concept maps should include mathematical representations for each of the concepts.

Students often confuse the fact that the electric field is a vector quantity and the electric potential is a scalar quantity. The specific problem-solving strategies outlined in this activity help students easily differentiate between these quantities.

Guiding Questions: ▼ How can the charge model be used to explain electric phenomena? ▼ How can electric charge interactions be explained with an electric field model? ▼ How can physical quantities such as electric field and electric potential be defined operationally? ▼ How can the structure of isolines be predicted?

Learning Objectives	Materials	Instructional Activities and Assessments
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] Use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. [LO 3.C.2.1, SP 2.2, SP 6.4] Use mathematics to describe the electric force that results from the interaction of several separated point charges. [LO 3.C.2.3, SP 2.2] 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] 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] 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]		**Summative Assessment: Unit Test** The unit test includes a set of 12 multiple-choice questions and three free-response questions on the concepts of electric force, electric field, and electric potential.

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

Unit 2: **Electric Circuits**

Laboratory Investigations:

- Resistance and Resistivity Investigation
- DC Circuits and Brightness Investigation
- DC Circuits and Resistors Investigation
- RC Circuit Investigation

Estimated Time: *5 Weeks*

Guiding Questions: ▼ How can the concepts of resistance and resistivity be used in predicting currents in circuits? ▼ How can phenomena occurring in electric circuits be described in terms of physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits? ▼ How is the behavior of an electric circuit determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors?

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] Analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. [LO 4.E.4.3, SP 5.1] Make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships. [LO 4.E.4.1, SP 2.2, SP 6.4] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" **Supplies** Play-Doh, variable power supply, ammeter, wire with alligator clips, meterstick, colored pencils, dice, small ruler, copper BBs in a clear CD case **Web** "The Nature of Resistance"	**Instructional Activity: Resistance and Resistivity Investigation** The goal of this guided-inquiry investigation is to explore the microscopic and macroscopic factors that influence the electrical resistance of conducting materials. Students work in groups of two or three to investigate the ways that geometry affects the resistance of an ionic conductor — in this case, Play-Doh. In these student-directed activities, students confirm that resistivity is dependent on length and cross-sectional area. The investigation also involves thermal considerations of resistance and the effect of material defects on resistivity and electron drift.
Analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors. [LO 4.E.4.3, SP 5.1] Make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships. [LO 4.E.4.1, SP 2.2, SP 6.4] 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]	Knight, Jones, and Field, Chapter 23: "Circuits" **Web** "Capacitor Lab"	**Instructional Activity: Capacitor Lab** Working in pairs, students use the online PhET simulation to conduct a virtual lab. The objectives of the virtual lab are as follows: • Determine the relationship between charge and voltage for a capacitor. • Determine the energy stored in a capacitor or a set of capacitors in a circuit. Students report the collected data, data analysis, and a conclusion in their lab journals. This simulation activity helps students realize that each capacitor plate is at the same potential as the battery terminal to which it is connected.

Exposure to air and current dries out the Play-Doh. I instruct students to minimize the time the Play-Doh is out of the container and take as little time as possible between measurements. Students should immediately disconnect the circuit when they have finished recording data.

This is an extension to an activity performed in my Physics 1 course. It is assumed that students have knowledge of atomic bonding, Ohm's law, and conceptual definitions of current, resistance, and voltage.

Guiding Questions: ▼ How can the concepts of resistance and resistivity be used in predicting currents in circuits? ▼ How can phenomena occurring in electric circuits be described in terms of physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits? ▼ How is the behavior of an electric circuit determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors?

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]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" **Supplies** Small light bulbs, light bulb sockets, wires, batteries	**Instructional Activity: DC Circuits and Brightness Investigation** In small groups, students engage in guided-inquiry investigations that explore the concepts of electric circuits and series and parallel connections. This student-directed activity includes an investigation of parallel circuits containing more than one branch, which are not addressed in Physics 1. The tasks require students to make predictions about the brightness of light bulbs in a circuit when one or two of the light bulbs are removed. Students start with qualitative observations of the brightness of light bulbs connected in series and in parallel. They also draw schematic diagrams of the circuits during their investigations. Students mark each junction with a large dot to better visualize the different paths, making it easier to identify whether elements are connected in series or in parallel arrangements.
	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" Christian and Belloni, Problems 30.1 a–e and 30.3 **Web** "Circuit Construction Kit (DC Only)"	**Formative Assessment: DC Circuits Simulation** Working with a partner, students use the "Circuit Construction Kit (DC Only)" simulation to construct and collect data on a variety of series and parallel circuits. This simulation is recommended prior to the next physical investigation of DC circuits as it allows the students to manipulate the equipment in a virtual setting and to determine the correct placement of the ammeter and voltmeter. Students collect measurements including resistance, current, and potential differences. Students share their data in a Google Doc using a template that I have created. We then review and discuss the overall results as a class.

I review the students' Google Docs and provide written feedback. During the class discussion, I address any conceptual misunderstandings regarding how current and potential difference work in series and parallel circuits, based on what I saw when looking at students' data.

Guiding Questions: ▼ How can the concepts of resistance and resistivity be used in predicting currents in circuits? ▼ How can phenomena occurring in electric circuits be described in terms of physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits? ▼ How is the behavior of an electric circuit determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 22: "Current and Resistance" and Chapter 23: "Circuits" **Supplies** Assorted resistors, wires, batteries, digital multimeter or analog voltmeter and ammeter	**Instructional Activity: DC Circuits and Resistors Investigation** In this open-inquiry lab, students work in groups of three or four to design and conduct an experiment to investigate the behavior of resistors in series, parallel, and series–parallel circuits. The lab should include measurements of potential differences and currents. The final report should include explicit application of Kirchhoff's loop and junction rules.

Understanding Kirchhoff's rules is essential, and students should apply these rules when solving DC circuit problems. The analogies of conservation of energy for Kirchhoff's loop rule and conservation of charge for Kirchhoff's junction rule are effective for building appropriate student understanding.

Guiding Questions: ▼ How can the concepts of resistance and resistivity be used in predicting currents in circuits? ▼ How can phenomena occurring in electric circuits be described in terms of physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits? ▼ How is the behavior of an electric circuit determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 16: "DC Circuits" Knight, Jones, and Field, Chapter 23: "Circuits" **Web** Castro, "Kirchhoff's Gambit" **Supplies** Assorted resistors or a variable resistor, batteries or DC power supply, wires, digital or analog voltmeter and ammeter	**Instructional Activity: Kirchhoff's Loop and Junction Rules** I conduct an interactive lecture on Kirchhoff's loop and junction rules that combines presentation of material, a demonstration, and a couple of sample problems. I conduct the demonstration with an electric circuit, using an ammeter to verify the junction rule and a voltmeter to verify the loop rule. Students sketch a graph of the potential versus the distance around the loop to make the connection between a graphical representation and the reading of the voltmeter in the circuit. Students work through a variety of exercises on the application of Kirchhoff's loop and junction rules. As a homework assignment, they complete the exercise in David Castro's article, and we discuss the solution the following day. Depending on the students' responses, I review the exercise as needed.
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] 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" Christian and Belloni, Illustrations 30.6 and 30.7 and Problem 30.7 **Supplies** Assorted resistors, capacitor, wires, batteries, digital multimeter or analog voltmeter and ammeter	**Instructional Activity: RC Circuit Investigation** Students work in groups of three or four in this two-part lab investigation. The first part of the lab is guided inquiry and consists of an observational experiment in which the students make qualitative descriptions of the charging and discharging of a capacitor. Even though the treatment of this subject is qualitative, students discuss the current-versus-time and charge-versus-time graphs, which demonstrate exponential functions. The second part of this lab is open inquiry. Students design and conduct an experiment to investigate the behavior of resistors in a series–parallel combination with a capacitor in series. Measurements of currents and potential differences are required.

The charge-versus-time graph in the first part of the lab shows exponential growth, while the current-versus-time graph shows exponential decay. Students will learn about exponential decay later in the year.

Electric Circuits

(continued)

Guiding Questions: ▼ How can the concepts of resistance and resistivity be used in predicting currents in circuits? ▼ How can phenomena occurring in electric circuits be described in terms of physical quantities such as potential difference (voltage), electric current, electric resistance, and electric power? ▼ How do conservation laws apply to electric circuits? ▼ How is the behavior of an electric circuit determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]		**Summative Assessment: Unit Test** Students complete a unit test with 10 multiple-choice questions and 3 free-response questions. The free-response questions address topics including electric current, multiloop electric circuits with resistors, and combination circuits with resistors and capacitors. One of the free-response questions is a lab-based question in which students analyze multiple representations of DC circuits including graphs and schematic diagrams.

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

Unit 3: Magnetism and Electromagnetic Induction

Laboratory Investigations:

- Earth's Magnetic Field Investigation
- Magnetic Force on a Current-Carrying Wire Investigation
- Electromagnetic Induction Investigation

Estimated Time:

5 Weeks

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 17: "Magnetism" Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces" Christian and Belloni, Illustrations 27.1 and 27.5	**Instructional Activity: Visualizing Magnetism** Students work individually on the Physlet illustrations in order to better visualize and understand how magnetism can be explained from an atomic basis. Using these illustrations, students also explore how the dipole model of magnetism explains basic magnetic phenomena such as the following: • Magnets and compass needles • Permanent magnets and ferromagnetism Students note their observations in their lab journals. I then conduct a guided discussion to help students recognize that even though magnetic poles are not the same as electric charges, the dipole model is analogous to the charge model of electricity.
Describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. [LO 2.D.3.1, SP 1.2] Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 17: "Magnetism" Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces" Christian and Belloni, Illustration 27.2 and Problem 27.8 **Web** "Magnet and Compass"	**Formative Assessment: Magnet and Compass Simulation** Working in pairs, students use the "Magnet and Compass" simulation to complete three tasks: 1. Predict the direction of the magnetic field for different locations around a bar magnet. 2. Quantitatively and qualitatively relate magnetic field strength to distance. 3. Describe how Earth's magnetic field is similar to that of a bar magnet.

I observe the students as they are working and make notes about any items that appear to be challenging. After completion of the activity, I conduct a brief wrap-up to answer questions and clarify any misunderstandings I noted.

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. [LO 2.D.3.1, SP 1.2] Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or 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]	Etkina, Gentile, and Van Heuvelen, Chapter 17: "Magnetism" Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces" Stewart, "Measuring Earth's Magnetic Field Simply" **Supplies** Solenoid, batteries, magnetic compass (or a commercial magnaprobe) **Web** "Estimated Values of Magnetic Field"	**Instructional Activity: Earth's Magnetic Field Investigation** In this guided-inquiry investigation, students working in pairs design and conduct an experiment using a solenoid and a compass to measure the horizontal component of Earth's magnetic field. Students then compare their experimental value to the accepted value of the horizontal component of Earth's magnetic field, as provided by the National Geophysical Data Center.

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

Learning Objectives	Materials	Instructional Activities and Assessments
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]	Etkina, Gentile, and Van Heuvelen, Chapter 17: "Magnetism" Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces" **Web** "Magnetic Force on a Current-Carrying Wire" **Supplies** DC power supply, triple-beam balance, 12-inch dowels (with clips that are conducting and nonmagnetic), ring stand with three clamps and crossbar, three insulated wires and two alligator clips, magnetic compass, straight bare (uninsulated) wire, 0.5-ohm resistor (10 W), three horseshoe magnets clamped together (poles aligned)	**Instructional Activity: Magnetic Force on a Current-Carrying Wire Investigation** In this guided-inquiry investigation, students working in teams of three or four design and conduct an experiment to determine the magnitude and direction of the magnetic force exerted on a current-carrying wire. I encourage students to make qualitative observations of the magnetic field on a current-carrying wire before starting with quantitative measurements. After the lab, we discuss the parameters that affect the magnetic force on the current-carrying wire.

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 17: "Magnetism" Knight, Jones, and Field, Chapter 24: "Magnetic Fields and Forces"	**Formative Assessment: Magnetic Fields** Teams of three students work on qualitative and quantitative exercises that involve a charged particle traveling through a magnetic field. These exercises, drawn from the textbooks, reinforce the concept that in order to apply the right-hand rule correctly, one must first determine whether the particle is positively or negatively charged. I typically include a problem about a mass spectrometer where the charged particle is being deflected into circular motion. Students should recognize that the magnetic force produces a centripetal acceleration. If the speed of the particle as it enters the magnetic field is given or can be calculated, students determine the radius of the circle in which the particle travels.

I pair teams and have them compare their solutions. I provide feedback directly to the groups that solved the problems incorrectly.

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

Learning Objectives	Materials	Instructional Activities and Assessments
Construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area. [LO 4.E.2.1, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 18: "Electromagnetic Induction" Knight, Jones, and Field, Chapter 25: "Electromagnetic Induction and Electromagnetic Waves" Christian and Belloni, Problem 29.3 **Web** "Faraday's Electromagnetic Lab"	**Instructional Activity: Magnetic Flux** To illustrate the concept of magnetic flux, I rotate an embroidery hoop in front of a fan and ask how much air flows through the hoop. Students discuss the problem with their peers until they arrive at the conclusion that the parameters that determine the answer are the rate of the flow of air, the size of the hoop, and the angle between the hoop and the airflow. Next, working in pairs, students use the "Faraday's Electromagnetic Lab" simulation to predict the direction of the magnetic field at various locations around five different objects: bar magnet, coil of wire, electromagnet, transformer, and generator. Students gather measurements of the magnitude and direction of the magnetic field and record their observations and measurements in their lab journals.
	Etkina, Gentile, and Van Heuvelen, Chapter 18: "Electromagnetic Induction" Knight, Jones, and Field, Chapter 25: "Electromagnetic Induction and Electromagnetic Waves" **Supplies** Bar magnet, solenoid, galvanometer	**Laboratory Investigation: Electromagnetic Induction Investigation** This qualitative guided-inquiry investigation offers students a hands-on opportunity to see how Lenz's law works. In this lab, students in groups of three or four move a bar magnet in and out of a solenoid and observe the deflection of the galvanometer. Using this process, they examine the effects of a changing magnetic field by observing currents induced in a solenoid. Students determine whether their observations agree with Faraday's law and Lenz's law, and they create labeled diagrams to support their observations. As a follow-up activity, students complete a set of three quantitative problems on electromagnetic induction drawn from their textbooks.

A commonly held misconception about this topic is that the induced magnetic field opposes the flux that creates it rather than the change in flux. Also, students may believe that a magnetic field directed to the right implies that an induced magnetic field will always be to the left, as they tend to ignore whether the magnetic flux is increasing or decreasing.

Magnetism and Electromagnetic Induction

(continued)

Guiding Questions: ▼ How is the magnetic field model a mechanism of action-at-a-distance? ▼ How does a magnetic field exert a force on moving charges and on electric currents? ▼ How is a current induced by a magnetic field, and how is Lenz's law applied to determine the direction of the induced current? ▼ How is the law of electromagnetic induction (Faraday's law) applied?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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 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]		**Summative Assessment: Unit Test** Students complete a unit test consisting of conceptual questions as well as problems on a variety of applications of magnetism and electromagnetic induction, such as mass spectrometry and generation of electricity. One problem features a scenario involving a satellite tethered to a spacecraft.

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

Thermodynamics

Laboratory Investigations:

- Gas Laws Investigation
- Thermal Conductivity Investigation
- Heat Engine Investigation

Estimated Time:

4 Weeks

Guiding Questions: ▼ How are the pressure, volume, and temperature of an ideal gas related and graphically represented? ▼ How is energy transferred and transformed? ▼ How is the first law of thermodynamics applied to processes undergone by a system? ▼ What are the implications of the second law of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and refine a scientific question concerning a proposed incorrect relationship between the variables. [LO 7.A.3.2, SP 3.2, SP 4.2] Analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$. [LO 7.A.3.3, SP 5.1] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 12: "First Law of Thermodynamics" Knight, Jones, and Field, Chapter 12: "Thermal Properties of Matter" Christian and Belloni, Explorations 20.1 and 20.3 and Illustration 20.1 **Web** "Gas Properties" **Supplies** Commercial Boyle's law units, metal spheres, 1500 mL beakers, hot plates, thermometers, ice	**Instructional Activity: Gas Laws Investigation** This activity involves both guided-inquiry and open-inquiry components. Prior to conducting a hands-on investigation, students working in pairs use the "Gas Properties" simulation to predict how changing a variable (pressure, volume, or temperature) influences other gas properties. After completing the simulation activity, each pair of students designs and conducts an experiment to verify the relationships between pressure, temperature, and volume of a gas (air). Students record their observations, prepare a table of the data gathered, and create and analyze graphs of temperature versus volume and pressure versus volume.

Guiding Questions: ▼ How are the pressure, volume, and temperature of an ideal gas related and graphically represented? ▼ How is energy transferred and transformed? ▼ How is the first law of thermodynamics applied to processes undergone by a system? ▼ What are the implications of the second law of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 12: "First Law of Thermodynamics" Knight, Jones, and Field, Chapter 12: "Thermal Properties of Matter" **Web** "States of Matter"	**Instructional Activity: Kinetic Theory of Matter** Students are introduced to the kinetic theory of matter by working with a partner on the "Phase Changes" section of the "States of Matter" simulation. By changing the temperature or volume of a container, the students can see how a pressure–temperature diagram responds in real time. As a follow-up activity, the students work on a set of textbook problems involving calculations of force, pressure, and area.
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 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]	Knight, Jones, and Field, Chapter 12: "Thermal Properties of Matter" **Supplies** Shot plates, Vernier calipers, ice, plates of various materials (e.g., Masonite, aluminum, plexiglass, plywood, or Teflon)	**Instructional Activity: Thermal Conductivity Investigation** In this open-inquiry investigation, the students work in small groups to design and conduct an experiment to determine the thermal conductivity of a material by comparing the difference in temperature across that material to the difference in temperature across a second material of known thermal conductivity. In their lab journals, students record their procedure, diagram of setup, data, and analysis of data, including a comparison of the experimental value of the calculated thermal conductivity of a material to the known value for that material.

I find it worthwhile for students to derive the equation for the average translational kinetic energy of the molecules. This provides an opportunity for students to apply concepts they learned in AP Physics 1 (or another prior physics course) about pressure, elastic collisions, conservation of momentum, and energy.

Guiding Questions: ▼ How are the pressure, volume, and temperature of an ideal gas related and graphically represented? ▼ How is energy transferred and transformed? ▼ How is the first law of thermodynamics applied to processes undergone by a system? ▼ What are the implications of the second law of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 12: "First Law of Thermodynamics" Knight, Jones, and Field, Chapter 11: "Using Energy" **Web** Mooney, "The First Law of Thermodynamics and P–V Diagrams"	**Instructional Activity: Introduction to P–V Diagrams** Students read about the first law of thermodynamics in their textbooks prior to class. At the beginning of class, I ask the students a few questions to activate their knowledge of the content. I then use Jim Mooney's article to guide my presentation about the first law of thermodynamics and P–V diagrams. In pairs, students work through the article's examples before I present the full solutions.
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] 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] Create a plot of pressure versus volume for a thermodynamic process from given data. [LO 5.B.7.2, SP 1.1] Use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). [LO 5.B.7.3, SP 1.1, SP 1.4, SP 2.2]	**Supplies** 10 cc low-friction glass syringe with ring stand support, flasks (test tube) with one-hole rubber stoppers, pressure sensors, temperature sensors, two insulated (e.g., polystyrene) containers, two 400 mL glass beakers, several lengths of Tygon tubing, paper towels, rulers, 50 g masses, hot water, ice water	**Instructional Activity: Heat Engine Investigation** This lab investigation presents an opportunity for students to understand the principles that led to the development of heat engines during the 19th-century Industrial Revolution. In an open-inquiry investigation, students work in teams of three or four to design and implement a data-collection strategy to explore how the work done by an engine, which raises a small mass during each of its cycles, is related to the area enclosed by its P–V graph. After completing this lab, students should recognize and appreciate how the physics of the expansion and compression of gases has helped engineers to design more efficient engines.

The signs of the processes are often a source of difficulty for students. I explain to them that positive work is work done on the system and positive heat is heat added to the system.

Guiding Questions: ▼ How are the pressure, volume, and temperature of an ideal gas related and graphically represented? ▼ How is energy transferred and transformed? ▼ How is the first law of thermodynamics applied to processes undergone by a system? ▼ What are the implications of the second law of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 13: "Second Law of Thermodynamics" Knight, Jones, and Field, Chapter 11: "Using Energy" Christian and Belloni, Exploration 21.3	**Formative Assessment: Introduction to the Second Law of Thermodynamics** I post the following qualitative statements involving the second law of thermodynamics on chart paper in different parts of the classroom: • Heat cannot be transferred spontaneously from a cold object to a hot object. • Any system that is free of external influences becomes more disordered with time. This disorder can be expressed in terms of the quantity called *entropy*. • You cannot create a heat engine that extracts heat and converts it all into useful work. In teams of three, students circulate through the classroom, elaborating on the statements via written comments and reflecting on the written comments of other groups. After the teams have completed this gallery walk, each team offers a final summary on all three of the concepts explored.

I listen to the students' summary statements and provide direct feedback about any incorrect statements to help address misconceptions about the second law of thermodynamics.

Guiding Questions: ▼ How are the pressure, volume, and temperature of an ideal gas related and graphically represented? ▼ How is energy transferred and transformed? ▼ How is the first law of thermodynamics applied to processes undergone by a system? ▼ What are the implications of the second law of thermodynamics?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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] 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]	**Software/Web** Jing or Screencast-O-Matic	**Summative Assessment: Unit Test** The students receive an individual assessment consisting of three multiple-choice questions and one free-response problem in a Google Doc. Each assessment is different, although some of the questions may be in a similar format but with different data. Each student completes the assessment by creating a video using a free screencasting tool. They post their videos to our class YouTube account.

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

Unit 5: Fluids

Laboratory Investigations:

- Archimedes' Principle Investigation
- Torricelli's Theorem Investigation
- Water Fountain Investigation

Estimated Time:

3 Weeks

Guiding Questions: ▼ How are pressure and depth related? ▼ How is the buoyant force related to Archimedes' principle? ▼ What are the simplifications used in describing ideal fluid flow? ▼ How is energy transformed within a system and between a system and the environment?

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] Predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction. [LO 1.E.1.1, SP 4.2, SP 6.4] Select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects. [LO 1.E.1.2, SP 4.1, SP 6.4] Make claims about various contact forces between objects based on the microscopic cause of those forces. [LO 3.C.4.1, SP 6.1] Explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. [LO 3.C.4.2, SP 6.2]	Etkina, Gentile, and Van Heuvelen, Chapter 10: "Static Fluids" Knight, Jones, and Field, Chapter 13: "Fluids" **Supplies** Triple-beam balance, beakers, graduated cylinders, two objects of different densities, liquid of unknown density, string, overflow cans	**Instructional Activity: Archimedes' Principle Investigation** In this open-inquiry lab, students work in pairs to design and implement a data-collection strategy to determine the unknown densities of a liquid and two objects using Archimedes' principle. In their lab journals, students document the different stages of their experiment and include a free-body diagram of the forces exerted on the objects. A clear articulation of the nature of the buoyant force is an expected goal of this activity.
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]	Etkina, Gentile, and Van Heuvelen, Chapter 11: "Fluids in Motion" Knight, Jones, and Field, Chapter 13: "Fluids" **Web** "Balloons & Buoyancy"	**Instructional Activity: Research Presentation** As a class, we list real-world questions that students have relating to buoyancy and density. I then assign student pairs one question for research. They have two class periods to post their research on a Google Doc. Each pair makes a brief oral presentation to the class. The following are some typical questions students are assigned: • How do metal ships float? • Will a ship full of oil float differently than an empty ship? • If an oil tanker develops a leak, why does it sink? • How will a ship float differently in fresh water as opposed to salt water? • How and why do hot air balloons ascend and descend? • Would hydrogen balloons float longer than hot air balloons?

As an extension activity, students may investigate an application of buoyant forces in a biological system: the swim bladder of a fish. Students learn how fish maintain their position in water (descend or ascend) by controlling their buoyancy.

Guiding Questions: ▼ How are pressure and depth related? ▼ How is the buoyant force related to Archimedes' principle? ▼ What are the simplifications used in describing ideal fluid flow? ▼ How is energy transformed within a system and between a system and the environment?

Learning Objectives	Materials	Instructional Activities and Assessments
Make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). [LO 5.F.1.1, SP 2.1, SP 2.2, SP 7.2] Use Bernoulli's equation 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]	Etkina, Gentile, and Van Heuvelen, Chapter 11: "Fluids in Motion" Knight, Jones, and Field, Chapter 13: "Fluids" **Supplies** Clear 2 L plastic bottle, water, ruler, stopwatch, compass or other sharp object (for creating a small opening in the bottle)	**Instructional Activity: Torricelli's Theorem Investigation** Students design and conduct an experiment using a clear 2 L plastic bottle to determine the exit velocity of a liquid and predict the range attained with holes at varying heights. Students work in groups of three or four in this open-inquiry lab.
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]	Christian and Belloni, Problem 15.7 Etkina, Gentile, and Van Heuvelen, Chapter 11: "Fluids in Motion" Knight, Jones, and Field, Chapter 13: "Fluids"	**Formative Assessment: Ideal Fluid Flow** In this Physlet exercise, the students must decide what quantities they should measure in order to identify the animation that shows a possible physical situation for ideal fluid flow. I use the think-pair-share strategy in this exercise. Students first work individually and write down their answers. Then they form pairs and discuss any discrepancies in their answers. At the end of the exercise, I ask a couple of teams to share their answers with the class. This deceptively simple simulation requires the students to determine the evidence necessary in order to validate the claim of an ideal fluid-flow depiction. Both the continuity equation and Bernoulli's principle must hold true.
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 the continuity equation to make calculations related to a moving fluid. [LO 5.B.10.3, SP 2.2]	Etkina, Gentile, and Van Heuvelen, Chapter 11: "Fluids in Motion" Knight, Jones, and Field, Chapter 13: "Fluids" **Supplies** Water fountain, beakers, stopwatch, ruler	**Instructional Activity: Water Fountain Investigation** Working in pairs in this guided-inquiry activity, students design and conduct an investigation of a water fountain to determine the following: • Exit angle and exit speed of the water • Maximum height of water • Radius of the fountain's exit hole • Flow volume rate

In this investigation, students will be able to apply their prior knowledge of projectile motion from AP Physics 1 or an introductory course.

I provide feedback to students as they choose their initial quantities and again as they share their answers at the end of the exercise.

Guiding Questions: ▼ How are pressure and depth related? ▼ How is the buoyant force related to Archimedes' principle? ▼ What are the simplifications used in describing ideal fluid flow? ▼ How is energy transformed within a system and between a system and the environment?

Learning Objectives	Materials	Instructional Activities and Assessments
Select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects. [LO 1.E.1.2, SP 4.1, SP 6.4] Make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). [LO 5.F.1.1, SP 2.1, SP 2.2, SP 7.2] Use Bernoulli's equation and/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]		**Summative Assessment: Unit Test** Students complete a unit test that consists of two ranking tasks and three free-response questions.

The summative assessment addresses the following guiding questions:

- *What are the simplifications used in describing ideal fluid flow?*
- *How is energy transformed within a system and between a system and the environment?*

Geometric and Physical Optics

Laboratory Investigations:

- Mirrors Investigation
- Concave Mirror Investigation
- Index of Refraction Investigation
- Thin Lenses Investigation
- Double-Slit Interference and Diffraction Investigations
- Human Eye Investigation (Lab Practicum)

Estimated Time:

5 Weeks

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How can wave boundary behavior be used to explain absorption, reflection, and transmission of light? ▼ How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses? ▼ How does light interference demonstrate the wave nature of light?

Learning Objectives	Materials	Instructional Activities and Assessments
Describe representations of transverse and longitudinal waves. [LO 6.A.1.2, SP 1.2] 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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 20: "Mechanical Waves" and Chapter 24: "Electromagnetic Waves" Knight, Jones, and Field, Chapter 15: "Traveling Waves and Sound" and Chapter 25: "Electromagnetic Induction and Electromagnetic Waves" **Web** "Wave Interference"	**Instructional Activity: Wave Interference** The students work through the "Wave Interference" simulation with a partner to investigate interference and superposition. In their lab journals, students write a summary of constructive and destructive wave interference and how to apply the principle of superposition.
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]	**Web** "Polarised Wave"	**Instructional Activity: Polarization Simulation** I project the simulation for the class and use it to guide a discussion about how polarization occurs.
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] 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]		**Instructional Activity: Real-World Use of Electromagnetic Radiation** As a homework assignment, students work in groups of four to post a Google Doc responding to the following: • What are the characteristics of the seven types of electromagnetic radiation? • Describe how each of the seven types of radiation is used in our everyday lives and/or in certain industries. In the next class we project the students' documents and compare and contrast the results of their research.

This activity provides a review of the concepts of interference and superposition, which were covered in AP Physics 1.

Students are familiar with applications of polarization, such as glare-reducing sunglasses and 3D movies, but they often do not quite understand this phenomenon. Using the simulation helps the students visualize the transverse nature of electromagnetic waves.

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How can wave boundary behavior be used to explain absorption, reflection, and transmission of light? ▼ How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses? ▼ How does light interference demonstrate the wave nature of light?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface. [LO 6.E.2.1, SP 6.4, SP 7.2]	Etkina, Gentile, and Van Heuvelen, Chapter 21: "Reflection and Refraction" and Chapter 22: "Mirrors and Lenses" Knight, Jones, and Field, Chapter 18: "Ray Optics" Christian and Belloni, Problems 33.4, 34.4, and 35.4 **Supplies** Plane mirrors, concave and convex mirrors, pins, rulers, protractors, light source	**Instructional Activity: Mirrors Investigation** In this guided-inquiry lab, students working in pairs design and conduct an investigation to answer the following question: *Are there any patterns in the way plane mirrors and curved mirrors reflect light?*
Plan data collection strategies, and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors. [LO 6.E.4.1, SP 3.2, SP 4.1, SP 5.1, SP 5.2, SP 5.3] Use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces. [LO 6.E.4.2, SP 1.4, SP 2.2]	**Supplies** Concave mirrors, screens, lit candles or other light sources, metersticks or commercial optic benches	**Instructional Activity: Concave Mirror Investigation** Prior to this lab, students use geometry, algebra, and simple ray construction to develop the mirror equation relating the object distance, image distance, and focal length. Students then work in teams of three or four to design and conduct a two-part guided-inquiry investigation to achieve the following: 1. Determine the focal length of a concave mirror. 2. Determine two locations where a magnified image can be formed using a concave mirror. The lab report should include the procedure, annotated sketch of the setup, data collected, ray-tracing images, and calculations that validate the results.

Geometric and Physical Optics

(continued)

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How can wave boundary behavior be used to explain absorption, reflection, and transmission of light? ▼ How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses? ▼ How does light interference demonstrate the wave nature of light?

Learning Objectives	Materials	Instructional Activities and Assessments
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] 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] 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]	**Supplies** Acrylic blocks, commercial ray tables or printed protractors, light sources	**Instructional Activity: Index of Refraction Investigation** Working with a partner in this guided-inquiry lab, students design and conduct an investigation to determine the index of refraction of an acrylic block. The investigation must involve an analysis of the data plotted on an appropriate graph.
Use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses. [LO 6.E.5.1, SP 1.4, SP 2.2] Plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses. [LO 6.E.5.2, SP 3.2, SP 4.1, SP 5.1, SP 5.2, SP 5.3]	**Supplies** Converging lenses, diverging lenses, screens, light sources, metersticks or commercial optic benches	**Instructional Activity: Thin Lenses Investigation** In a guided-inquiry investigation, students design and implement two separate data-collection strategies to determine the focal length of a converging lens directly and the focal length of a diverging lens by combining it with a converging lens. Students conduct this lab in pairs or groups of three. The lab report for this investigation should include neat, labeled ray diagrams depicting the measurements taken from the position of the images.

Most students are inclined to use pairs of data and apply Snell's Law directly. We have a discussion about how finding the slope of the plotted data is a better way to take into account the whole range of data collected.

While finding the focal length of a converging lens is a relatively standard optics lab, finding the focal length of a diverging lens is a bit more challenging, as diverging lenses do not produce a real image. Students must understand that combining a converging lens of known focal length with the diverging lens may result in a real image that can be projected on a screen.

Geometric and Physical Optics

(continued)

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How can wave boundary behavior be used to explain absorption, reflection, and transmission of light? ▼ How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses? ▼ How does light interference demonstrate the wave nature of light?

Learning Objectives	Materials	Instructional Activities and Assessments
Use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the 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]	Knight, Jones, and Field, Chapter 18: "Ray Optics"	**Formative Assessment: Conflicting Contentions** Students are given a set of four problems involving the formation of images by converging and diverging mirrors and lenses. Each problem shows a couple of representations, such as a ray diagram, a mathematical representation, a sketch of a setup, and/or a graph of image distance versus object distance. Each problem has conflicting statements about the nature of the images (real or virtual). Students must decide which contention they agree with and explain why. Students work the problems on a whiteboard with a partner. This task is useful for contrasting statements of students' alternate conceptions with physically accepted statements.

I walk around the room answering any questions the students might have. When they have finished working, we address any incorrect solutions in a whole-class discussion in which students help guide their peers to the correct solution.

Guiding Questions: ▼ How are waves energy transport phenomena? ▼ How can wave boundary behavior be used to explain absorption, reflection, and transmission of light? ▼ How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses? ▼ How does light interference demonstrate the wave nature of light?

Learning Objectives	Materials	Instructional Activities and Assessments
Make claims and predictions about the net disturbance that occurs when two waves overlap.[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] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 23: "Wave Optics" Knight, Jones, and Field, Chapter 17: "Wave Optics" Christian and Belloni, Problems 17.4 and 17.10 **Supplies** Green lasers, red lasers, double slits, diffraction gratings, metersticks	**Instructional Activity: Double-Slit Interference and Diffraction Investigations** The students work in groups of three or four to design their own investigations in a guided-inquiry format to achieve the following: 1. Use a double slit to determine the wavelength of a green laser. 2. Apply the results of the double-slit experiment to predict the location of bright and dark fringes when a red laser is used. 3. Determine the spacing in a diffraction grating.
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] 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]	**Supplies** Converging lenses, diverging lenses, commercial eye model, rulers	**Summative Assessment: Human Eye Investigation (Lab Practicum)** This activity combines research with an open-inquiry investigation. To begin, students research how the human eye works. Then, in teams of three, they design and conduct an experiment to determine which types of lenses are appropriate to correct visual eye defects such as myopia and hyperopia. Students complete the final report individually during class time.

The summative assessment addresses the following guiding question: How do the basic optic phenomena of reflection and refraction explain the formation of images by mirrors and lenses?

Laboratory Investigations:
- Spectroscopy Investigation
- Photoelectric Effect Investigation
- Radioactive Decay Investigation

Estimated Time: *5 Weeks*

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

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]	Etkina, Gentile, and Van Heuvelen, Chapter 27: "Atomic Physics" Knight, Jones, and Field, Chapter 29: "Atoms and Molecules" Christian and Belloni, Illustration 2.1 and Problem 2.1 **Web** "Isotopes and Atomic Mass" "Build an Atom"	**Instructional Activities: Atomic Structure Review** Students work individually with the "Isotopes and Atomic Mass" and "Build an Atom" simulations to review basic concepts about atomic number, mass number, and isotopes. In a class discussion, students share their findings and answer the following questions: 1. In an atom, how will the addition or subtraction of a proton, neutron, or electron change the element, the charge, and the mass? 2. How can the number of protons, neutrons, and electrons in an atom help one draw a model of the atom, identify the element, and determine the mass and charge? 3. Is the chance of finding one isotope of an element the same for all isotopes of that element?
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] 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** "Models of the Hydrogen Atom"	**Formative Assessment: Models of the Hydrogen Atom** In a jigsaw activity, students use the PhET simulation to investigate the following questions: 1. What experimental predictions are made by each model? 2. What are some of the strengths of each model, and why was each historical model inadequate? 3. What is the relationship between the physical representation of an electron's orbit (shown in some models) and the corresponding energy-level diagram of the electron? Students form six teams, with two teams working on each question. When all the teams have their results, I assign students to new groups — scattering members from the original teams to form the new groups. Students share their findings on the three questions with their group and assemble the pieces to form the full picture of the models of hydrogen. We follow this with a whole-class discussion.

Students are expected to know basic concepts about atomic structure from their chemistry courses, so I assign the simulations as an open-ended homework activity and devote about half of the next class period to reviewing students' findings.

I provide direct feedback on students' ideas and claims about the models throughout the assessment. This activity provides me with insight into what areas I may need to reteach before moving on. This activity also provides students the opportunity to test ideas from classical and quantum physics while exploring conceptual models, before we go on to develop more detailed quantitative models.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

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] 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]	**Supplies** Commercial diffraction gratings, spectroscopes, commercial spectrum tubes (argon, chlorine, iodine, hydrogen), spectrum tube power supply **Web** "A CD Spectrometer"	**Instructional Activity: Spectroscopy Investigation** In this guided-inquiry activity, students work in teams of three or four to use a quantitative analysis spectroscope to analyze spectrum tubes. They report their results from this student-directed activity in their lab journals.
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]	**Web** Gende, "Graphing Analysis in Modern Physics"	**Formative Assessment: Modern Physics — Graphing Analysis** Students work on the five exercises found in the "Graphing Analysis in Modern Physics" article. The first exercise asks the students to apply linearizing techniques to derive an equation in terms of the energy and the quantum numbers for the hydrogen atom. The other exercises involve the construction and/or analysis of energy-level diagrams involving emission and absorption. Students check their results with the provided solutions.
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]	**Web** "Lasers"	**Summative Assessment: Laser Research Project** Students work with a partner to investigate how a laser works using the "Lasers" simulation; this PhET simulation helps students understand how absorption and spontaneous and stimulated emission work. After recording their observations, students conduct online research to investigate the applications of lasers in modern medicine; common applications include vision correction (LASIK surgery), tattoo removal, and varicose vein treatments, among others. Students work individually to write a paper based on their research, demonstrating their ability to read and summarize scientific literature.

If spectroscopes are not available for a lab investigation, students can build an inexpensive spectrometer with a CD and perform qualitative observations of a variety of light sources. The web resource "A CD Spectrometer" has step-by-step instructions.

When students have completed the exercises, I ask them probing questions to assess their comprehension and provide direct feedback as needed.

Students should be able to explain how the following factors influence the laser in the simulation: the intensity and wavelength of the lamp, the mirror reflectivity, and the lifetimes of the excited states of the atom.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
Explain why classical mechanics cannot describe all properties of objects by articulating the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties. [LO 1.D.1.1, SP 6.3] 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]	Etkina, Gentile, and Van Heuvelen, Chapter 26: "Quantum Optics" Knight, Jones, and Field, Chapter 28: "Quantum Physics" **Web** "Photoelectric Effect"	**Instructional Activity: Photoelectric Effect Simulation** The goal of this activity is for students to gather evidence to describe how the results of photoelectric effect investigations led to the photon model of light. Working individually, students use the "Photoelectric Effect" simulation to complete a guided-inquiry activity in which they predict the results of a variety of experiments involving the photoelectric effect. These student-directed experiments include changing each of the following: the intensity of light, the wavelength of light, the voltage of light, and the material of the target. In each case, the students predict how the current and energy of electrons will be affected by each of the changes.
Support the photon model of radiant energy with evidence provided by the photoelectric effect. [LO 6.F.3.1, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 26: "Quantum Optics" Knight, Jones, and Field, Chapter 28: "Quantum Physics" **Supplies** LED color strip, ammeter, wires, variable power source, resistor (1 k ohm), digital camera (optional)	**Instructional Activity: Photoelectric Effect Investigation** Students work with a partner in a guided-inquiry activity in which they assemble a simple circuit with an LED color strip to measure the voltages across the LEDs until light is produced in the LEDs. In order to calculate an experimental value of Planck's constant, students must graph the voltage versus the inverse of the wavelength. Students individually write a formal lab report that includes their procedure, collected data, graphical analysis, and conclusions. Students should account for uncertainties in their measurements and how the uncertainties affect the reliability of their results.

The infrared LED is not visible with the naked eye. One way to get data for this point is to use a digital camera that will "convert" infrared light to visible light. The camera on most cell phones will work well.

Quantum, Atomic, and Nuclear Physics

(continued)

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
Articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal. [LO 6.G.2.1, SP 6.1] Predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. [LO 6.G.2.2, SP 6.4] Make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed. [LO 5.D.1.6, SP 6.4] Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. [LO 5.D.1.7, SP 2.1, SP 2.2] Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum as the appropriate solution method for an inelastic collision, recognize that there is a common final velocity for the colliding objects in the totally inelastic case, solve for missing variables, and calculate their values. [LO 5.D.2.5, SP 2.1, SP 2.2] Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. [LO 5.D.2.6, SP 6.4, SP 7.2] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 26: "Quantum Optics" Knight, Jones, and Field, Chapter 28: "Quantum Physics"	**Formative Assessment: Diffraction of Matter** I use a peer-instruction strategy in this activity on diffraction of matter. For homework, students read about the topic in their textbooks. During the next class, I post a multiple-choice question on the board; students consider the question individually and submit an answer using an online feedback tool such as Socrative. Students then discuss their responses with their neighbors and submit a new negotiated response. If 25 percent or more of the responses are incorrect, I have students offer interpretations of what the question is asking and what information is needed to provide an answer. When everyone agrees with the answer, we move on to a new question. The second part of the activity involves quantitative scenarios. Students have about 10 minutes to submit their responses.

As an alternative to using an online feedback tool, large colored cards with the lettered answer choices on them also work well to poll students and get a rapid count of their responses.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) Make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system. [LO 5.D.3.2, SP 6.4] Make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system. [LO 5.D.3.3, SP 6.4]		
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, Chapter 29: "Atoms and Molecules" **Web** "Quantum Tunneling and Wave Packets" "Quantum Bound States"	**Instructional Activity: Quantum Mechanics Simulations** I project the simulations and discuss them with the class. I use these simulations to help students visualize a wave-function-versus-position graph and recognize how the probabilities of reflection and transmission of a wave are related to the energy of the wave, the energy of the step or barrier, and the width of the barrier.
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]	Knight, Jones, and Field, Chapter 28: "Quantum Physics" and Chapter 29: "Atoms and Molecules" **Web** "Quantum Wave Interference"	**Instructional Activity: Quantum Wave Interference Simulation** This simulation includes a series of experimental trials in which students are confronted with the basic conflict between the wave model and the particle model. It helps students visualize the behavior of photons, electrons, and atoms as particles and as waves through a double slit. I conduct a class discussion, guiding the students to justify how the double-slit interference pattern is consistent with both the classical wave view and the photon wave view. By the end of the activity, students should be able to articulate how the wave view is related to the photon view.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
Articulate the reasons that classical mechanics must be replaced by special relativity to describe the experimental results and theoretical predictions that show that the properties of space and time are not absolute. [LO 1.D.3.1, SP 6.3, SP 7.1]	Etkina, Gentile, and Van Heuvelen, Chapter 25: "Special Relativity" Knight, Jones, and Field, Chapter 27: "Relativity" **Web** "Einstein Light"	**Instructional Activity: Relativity Research Paper and Presentation** Working individually, students write a research paper that answers the following questions: • What is the difference between inertial and non-inertial reference frames? • What are the two postulates of special relativity? • What is the premise of the general theory of relativity? Students also prepare a multimedia presentation based on their research and post it to the class wiki. Students critique their peers' presentations.
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] 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] 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] 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] ***(learning objectives continue)***	Etkina, Gentile, and Van Heuvelen, Chapter 28: "Nuclear Physics" Knight, Jones, and Field, Chapter 30: "Nuclear Physics" **Web** "Alpha Decay" "Beta Decay" "The Dating Game" **Supplies** Shoe box with lid; 80 pennies, dice, or sugar cubes; 80 paper clips; graph paper; marker	**Instructional Activity: Radioactive Decay Simulations and Investigation** To provide visual depictions of radioactive decay, I project the "Alpha Decay" and "Beta Decay" simulations and discuss them with the class. Additionally, the simulations show a graph of half-life that helps students grasp the concept of the randomness of half-life. After examining the simulations, students work in teams of five to complete "The Dating Game" activity, which serves as our "lab" for this topic. This activity uses readily available materials: pennies, dice, or sugar cubes in a shoe box. The exponential nature of decay should be evident after doing this activity.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
(continued) 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] Identify the strong force as the force that is responsible for holding the nucleus together. [LO 3.G.3.1, SP 7.2]		**Formative Assessment: Radioactive Decay Problem Set** Students work with a partner on several different types of problems involving radioactive decay, applying what they learned from the simulations in the previous activity.
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] 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] Apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay. [LO 5.G.1.1, SP 6.4] Predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay. [LO 7.C.3.1, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 28: "Nuclear Physics" Knight, Jones, and Field, Chapter 30: "Nuclear Physics"	**Instructional Activity: Radioactive Decay and Nuclear Reaction Problems** Students work individually on a set of problems drawn from their textbooks involving radioactive decay and nuclear reactions. I post the solutions to the class website, and after the activity students check their solutions.

I review students' work on the practice problems and provide written feedback. If I see that there are concepts that are not clear to students, I will reteach those concepts during the following class period.

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

Learning Objectives	Materials	Instructional Activities and Assessments
Apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay. [LO 5.G.1.1, SP 6.4]	Etkina, Gentile, and Van Heuvelen, Chapter 28: "Nuclear Physics" Knight, Jones, and Field, Chapter 30: "Nuclear Physics"	**Instructional Activity: Research and Debate on Nuclear Energy** Students work in pairs to investigate a socio-scientific issue: the pros and cons of the use of nuclear energy. The research should focus on the process of nuclear fission, the basic operation of a nuclear reactor, how a chain reaction works, and how magnetic and inertial confinements can provide thermonuclear power. Students must address cost-effectiveness as well as safety and environmental issues, such as the impact on wildlife and human health. In addition to understanding the relevant physics concepts, students must perform an evaluation of ethical concerns to decide whether nuclear energy is beneficial. The culminating activity is a debate moderated by the students themselves.
Describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed. [LO 5.B.8.1, SP 1.2, SP 7.2] Construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [LO 7.C.4.1, SP 1.1, SP 1.2] Support the photon model of radiant energy with evidence provided by the photoelectric effect. [LO 6.F.3.1, SP 6.4] Predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. [LO 6.G.2.2, SP 6.4] Make predictions 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)***		**Summative Assessment: Unit Test** This assessment consists of a set of five problems on the following concepts: • Emission spectra: solving for the wavelength of the light emitted when an electron transition occurs between two energy levels. • Photoelectric effect: finding the work function of the metal and the maximum kinetic energy of the electrons. • Binding energy: determination of the difference between the mass of the nucleus and the mass of the constituent particles and using Einstein's energy–mass equation to determine the binding energy. • Compton scattering: analysis of an elastic collision between a photon and an electron. • Alpha decay: calculation of the disintegration energy of an alpha decay scenario. Students apply conservation of momentum and conservation of energy.

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

Guiding Questions: ▼ How do emission and absorption spectra occur? ▼ How does the photoelectric effect exemplify the particle nature of light, and how does the de Broglie hypothesis suggest the wavelike nature of particles? ▼ How are the concepts of momentum and energy in collisions applied to the scattering of photons by electrons? ▼ How are mass–energy equivalence and charge and nucleon conservation laws applied to nuclear reactions?

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] 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] Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. [LO 5.D.2.6, SP 6.4, SP 7.2] 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] 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] Predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay. [LO 7.C.3.1, SP 6.4] Apply conservation of 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]		

Resources

General Resources

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

Etkina, Eugenia, Michael Gentile, and Alan Van Heuvelen. *College Physics.* San Francisco: Pearson, 2014. *Also see the AP edition.*

Hieggelke, Curtis J., David P. Maloney, Stephen E. Kanim, and Thomas O'Kuma. *E&M TIPERs: Electricity and Magnetism Tasks*. Upper Saddle River, NJ: Pearson, 2006.

Knight, Randall D., Brian Jones, and Stuart Field. *College Physics: A Strategic Approach*. 2nd ed., AP® ed. Boston: Pearson, 2012.

O'Kuma, Thomas L., David P. Maloney, and Curtis J. Hieggelke. *Ranking Task Exercises in Physics*. Upper Saddle River, NJ: Pearson, 2004.

Supplementary Resources

Socrative. Classroom feedback system. Accessed August 1, 2013. http://www.socrative.com.

Unit 1 (Electrostatics) Resources

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

"Charges and Fields." PhET. University of Colorado at Boulder. Accessed January 2, 2013. http://phet.colorado.edu/sims/charges-and-fields/charges-and-fields_en.html.

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

"Electric Field Hockey." PhET. University of Colorado at Boulder. Accessed January 2, 2013. http://phet.colorado.edu/en/simulation/electric-hockey.

"Electric Forces: Straws and Pens." Physics education server at Buffalo State College. Accessed October 27, 2012. http://physicsed.buffalostate.edu/SeatExpts/EandM/straws/index.htm.

"An Electrostatics Puzzler." Peter Bohacek. comPADRE: Physics and Astronomy Education Communities. Accessed January 2, 2013. http://serc.carleton.edu/sp/compadre/demonstrations/examples/48756.html.

Reif, Marc Price. "Modern-Day Faradays: Teaching Students to Visualize Electric Fields." In *Special Focus: Electrostatics,* 16–29. AP Physics, 2007–2008 Professional Development Workshop Materials. New York: The College Board, 2007. Accessed March 12, 2013. http://apcentral.collegeboard.com/apc/public/repository/physics-special-focus-electrostatics.pdf.

Wells, Connie. "Electric Potential and Potential Energy." In *Special Focus: Electrostatics,* 30–49. AP Physics, 2007–2008 Professional Development Workshop Materials. New York: The College Board, 2007. Accessed March 12, 2013. http://apcentral.collegeboard.com/apc/public/repository/physics-special-focus-electrostatics.pdf.

Supplementary Resources

Morse, Robert. "Electrostatics Activities for Students." American Association of Physics Teachers. Accessed January 2, 2013. http://www.as.wvu.edu/phys/rotter/phys201/6_Electricity/Electrostatics.htm.

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 2 (Electric Circuits) Resources

"Capacitor Lab." PhET. University of Colorado at Boulder. Accessed January 2, 2013. http://phet.colorado.edu/en/simulation/capacitor-lab.

Castro, David. "Kirchhoff's Gambit." The College Board. Accessed January 2, 2013. http://apcentral.collegeboard.com/apc/members/courses/teachers_corner/44593.html.

"Circuit Construction Kit (DC Only)." PhET. University of Colorado at Boulder. Accessed July 26, 2013. http://phet.colorado.edu/en/simulation/circuit-construction-kit-dc.

"The Nature of Resistance." CNS Institute for Physics Teachers. Accessed August 25, 2013. http://www.cns.cornell.edu/cipt/labs/labPDFs/Current%20labs%20on%20web/4.09_Nature%20of%20Resistance%20with%20worksheet_complete.pdf.

Unit 3 (Magnetism and Electromagnetic Induction) Resources

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