CollegeBoard AP

INCLUDES
- Course framework
- Instructional section
- Sample exam questions

AP® Physics 2

COURSE AND EXAM DESCRIPTION

Effective
Fall 2020

AP® CollegeBoard

AP® Physics 2: Algebra-Based

COURSE AND EXAM DESCRIPTION

Effective
Fall 2020

AP COURSE AND EXAM DESCRIPTIONS ARE UPDATED PERIODICALLY

Please visit AP Central (apcentral.collegeboard.org) to determine whether a more recent course and exam description is available.

About College Board

College Board is a mission-driven, not-for-profit organization that connects students to college success and opportunity. Founded in 1900, College Board was created to expand access to higher education. Today, the membership association is made up of over 6,000 of the world's leading educational institutions and is dedicated to promoting excellence and equity in education. Each year, College Board helps more than seven million students prepare for a successful transition to college through programs and services in college readiness and college success—including the SAT® and the Advanced Placement® Program. The organization also serves the education community through research and advocacy on behalf of students, educators, and schools.

For further information, visit **collegeboard.org**.

AP Equity and Access Policy

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. College Board also believes that all students should have access to academically challenging coursework 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.

Designers: Sonny Mui and Bill Tully

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About AP

College Board's Advanced Placement® Program (AP®) enables willing and academically prepared students to pursue college-level studies—with the opportunity to earn college credit, advanced placement, or both—while still in high school. Through AP courses in 38 subjects, each culminating in a challenging exam, students learn to think critically, construct solid arguments, and see many sides of an issue—skills that prepare them for college and beyond. Taking AP courses demonstrates to college admission officers that students have sought the most challenging curriculum available to them, and research indicates that students who score a 3 or higher on an AP Exam typically experience greater academic success in college and are more likely to earn a college degree than non-AP students. Each AP teacher's syllabus is evaluated and approved by faculty from some of the nation's leading colleges and universities, and AP Exams are developed and scored by college faculty and experienced AP teachers. Most four-year colleges and universities in the United States grant credit, advanced placement, or both on the basis of successful AP Exam scores; more than 3,300 institutions worldwide annually receive AP scores.

AP Course Development

In an ongoing effort to maintain alignment with best practices in college-level learning, AP courses and exams emphasize challenging, research-based curricula aligned with higher education expectations.

Individual teachers are responsible for designing their own curriculum for AP courses, selecting appropriate college-level readings, assignments, and resources. This course and exam description presents the content and science practices that are the focus of the corresponding college course and that appear on the AP Exam. It also organizes the content and science practices into a series of units that represent a sequence found in widely adopted college textbooks and that many AP teachers have told us they follow in order to focus their instruction. The intention of this publication is to respect teachers' time and expertise by providing a roadmap that they can modify and adapt to their local priorities and preferences. Moreover, by organizing the AP course content and science practices into units, the AP Program is able to provide teachers and students with free formative assessments—Personal Progress Checks—that teachers can assign throughout the year to measure student progress as they acquire content knowledge and develop science practices.

Enrolling Students: Equity and Access

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. College Board also believes that all students should have access to academically challenging coursework 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.

Offering AP Courses: The AP Course Audit

The AP Program unequivocally supports the principle that each school implements its own curriculum that will enable students to develop the content understandings and science practices described in the course framework.

While the unit sequence represented in this publication is optional, the AP Program does have a short list of curricular and resource requirements that must be fulfilled before a school can label a course "Advanced Placement" or "AP." Schools wishing to offer AP courses must participate in the AP Course Audit, a process through which AP teachers' course materials are reviewed by college faculty. The AP Course Audit was created to provide teachers and administrators with clear guidelines on curricular and resource requirements for AP courses and to help colleges and universities validate courses marked "AP" on students' transcripts. This process ensures that AP teachers' courses meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses.

The AP Course Audit form is submitted by the AP teacher and the school principal (or designated administrator) to confirm awareness and understanding of the curricular and resource requirements. A syllabus or course outline, detailing how course requirements are met, is submitted by the AP teacher for review by college faculty.

Please visit **collegeboard.org/apcourseaudit** for more information to support the preparation and submission of materials for the AP Course Audit.

How the AP Program Is Developed

The scope of content for an AP course and exam is derived from an analysis of hundreds of syllabi and course offerings of colleges and universities. Using this research and data, a committee of college faculty and expert AP teachers work within the scope of the corresponding college course to articulate what students should know and be able to do upon the completion of the AP course. The resulting course framework is the heart of this course and exam description and serves as a blueprint of the content and science practices that can appear on an AP Exam.

The AP Test Development Committees are responsible for developing each AP Exam, ensuring the exam questions are aligned to the course framework. The AP Exam development process is a multiyear endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are accurate, fair, and valid and that there is an appropriate spread of difficulty across the questions.

Committee members are selected to represent a variety of perspectives and institutions (public and private, small and large schools and colleges) and a range of gender, racial/ethnic, and regional groups. A list of each subject's current AP Test Development Committee members is available on **apcentral.collegeboard.org**.

Throughout AP course and exam development, College Board gathers feedback from various stakeholders in both secondary schools and higher education institutions. This feedback is carefully considered to ensure that AP courses and exams are able to provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement or college credit.

How AP Exams Are Scored

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions and through-course performance assessments, as applicable, are scored by thousands of college faculty and expert AP teachers. Most are scored at the annual AP Reading, while a small portion is scored online. All AP Readers are thoroughly trained, and their work is monitored throughout the Reading for fairness and consistency. In each subject, a highly respected college faculty member serves as Chief Faculty Consultant and, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions and performance assessments are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is converted into a composite AP score on a 1–5 scale.

AP Exams are **not** norm-referenced or graded on a curve. Instead, they are criterion-referenced, which means that every student who meets the criteria for an AP score of 2, 3, 4, or 5 will receive that score, no matter how many students that is. The criteria for the number of points students must earn on the AP Exam to receive scores of 3, 4, or 5—the scores that research consistently validates for credit and placement purposes—include:

- The number of points successful college students earn when their professors administer AP Exam questions to them.
- The number of points researchers have found to be predictive that an AP student will succeed when placed into a subsequent, higher-level college course.
- Achievement-level descriptions formulated by college faculty who review each AP Exam question.

Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. Frequent and regular research studies establish the validity of AP scores as follows:

AP Score	Credit Recommendation	College Grade Equivalent
5	Extremely well qualified	A
4	Well qualified	A-, B+, B
3	Qualified	B-, C+, C
2	Possibly qualified	n/a
1	No recommendation	n/a

While colleges and universities are responsible for setting their own credit and placement policies, most private colleges and universities award credit and/or advanced placement for AP scores of 3 or higher. Additionally, most states in the U.S. have adopted statewide credit policies that ensure college credit for scores of 3 or higher at public colleges and universities. To confirm a specific college's AP credit/placement policy, a search engine is available at **apstudent.org/creditpolicies**

BECOMING AN AP READER

Each June, thousands of AP teachers and college faculty members from around the world gather for seven days in multiple locations to evaluate and score the free-response sections of the AP Exams. Ninety-eight percent of surveyed educators who took part in the AP Reading say it was a positive experience.

There are many reasons to consider becoming an AP Reader, including opportunities to:

- **Bring positive changes to the classroom:** Surveys show that the vast majority of returning AP Readers—both high school and college educators—make improvements to the way they teach or score because of their experience at the AP Reading.
- **Gain in-depth understanding of AP Exam and AP scoring standards:** AP Readers gain exposure to the quality and depth of the responses from the entire pool of AP Exam takers and thus are better able to assess their students' work in the classroom.
- **Receive compensation:** AP Readers are compensated for their work during the Reading. Expenses, lodging, and meals are covered for readers who travel.
- **Score from home:** AP Readers have online distributed scoring opportunities for certain subjects. Check **collegeboard.org/apreading** for details.
- **Earn Continuing Education Units (CEUs):** AP Readers earn professional development hours and CEUs that can be applied to PD requirements by states, districts, and schools.

How to Apply

Visit **collegeboard.org/apreading** for eligibility requirements and to start the application process.

AP Resources and Supports

By completing a simple activation process at the start of the school year, teachers and students receive access to a robust set of classroom resources.

AP Classroom

AP Classroom is a dedicated online platform designed to support teachers and students throughout their AP experience. The platform provides a variety of powerful resources and tools to provide yearlong support to teachers and enable students to receive meaningful feedback on their progress.

UNIT GUIDES

Appearing in this publication and on AP Classroom, these planning guides outline all required course content and science practices, organized into commonly taught units. Each unit guide suggests sequence and pacing of content, scaffolds science practice instruction across units, organizes content into topics, and provides tips on taking the AP Exam.

PERSONAL PROGRESS CHECKS

Formative AP questions for every unit provide feedback to students on the areas where they need to focus. Available online, Personal Progress Checks measure knowledge and science practices through multiple-choice questions with rationales to explain correct and incorrect answers, as well as free-response questions with scoring information. Because the Personal Progress Checks are formative, the results of these assessments cannot be used to evaluate teacher effectiveness or assign letter grades to students, and any such misuses are grounds for losing school authorization to offer AP courses.*

PROGRESS DASHBOARD

This dashboard allows teachers to review class and individual student progress throughout the year. Teachers can view class trends and see where students struggle with content and science practices that will be assessed on the AP Exam. Students can view their own progress over time to improve their performance before the AP Exam.

AP QUESTION BANK

This online library of real AP Exam questions provides teachers with secure questions to use in their classrooms. Teachers can find questions indexed by course topics and science practices, create customized tests, and assign them online or on paper. These tests enable students to practice and get feedback on each question.

*To report misuses, please call, 877-274-6474 (International: +1-212-632-1781).

Digital Activation

In order to teach an AP class and make sure students are registered to take the AP Exam, teachers must first complete the digital activation process. Digital activation gives students and teachers access to resources and gathers students' exam registration information online, eliminating most of the answer sheet bubbling that has added to testing time and fatigue.

AP teachers and students begin by signing in to **My AP** and completing a simple activation process at the start of the school year, which provides access to all AP resources, including AP Classroom.

To complete digital activation:

- Teachers and students sign in to, or create, their College Board accounts.
- Teachers confirm that they have added the course they teach to their AP Course Audit account and have had it approved by their school's administrator.
- Teachers or AP coordinators, depending on who the school has decided is responsible, set up class sections so students can access AP resources and have exams ordered on their behalf.
- Students join class sections with a join code provided by their teacher or AP coordinator.
- Students will be asked for additional registration information upon joining their first class section, which eliminates the need for extensive answer sheet bubbling on exam day.

While the digital activation process takes a short time for teachers, students, and AP coordinators to complete, overall it helps save time and provides the following additional benefits:

- **Access to AP resources and supports:** Teachers have access to resources specifically designed to support instruction and provide feedback to students throughout the school year as soon as activation is complete.
- **Streamlined exam ordering:** AP coordinators can create exam orders from the same online class rosters that enable students to access resources. The coordinator reviews, updates, and submits this information as the school's exam order in the fall.
- **Student registration labels:** For each student included in an exam order, schools will receive a set of personalized AP ID registration labels, which replaces the AP student pack. The AP ID connects student's exam materials with the registration information they provided during digital activation, eliminating the need for pre-administration sessions and reducing time spent bubbling on exam day.
- **Targeted Instructional Planning Reports:** AP teachers will get Instructional Planning Reports (IPRs) that include data on each of their class sections automatically rather than relying on special codes optionally bubbled in on exam day.

Instructional Model

Integrating AP resources throughout the course can help students develop the course science practices and conceptual understandings. The instructional model outlined below shows possible ways to incorporate AP resources into the classroom.

Plan

Teachers may consider the following approaches as they plan their instruction before teaching each unit.

- Review the overview at the start of each **unit guide** to identify essential questions, conceptual understandings, and science practices for each unit.
- Use the **Unit at a Glance** table to identify related topics that build toward a common understanding, and then plan appropriate pacing for students.
- Identify useful strategies in the **Instructional Approaches** section to help teach the concepts and science practices.

Teach

When teaching, supporting resources can be used to build students' conceptual understanding and mastery of science practices.

- Use the topic pages in the **unit guides** to identify the required content.
- Integrate the content with a science practice, considering any appropriate scaffolding.
- Employ any of the instructional strategies previously identified.
- Use the available resources on the topic pages to bring a variety of assets into the classroom.

Assess

Teachers can measure student understanding of the content and science practices covered in the unit and provide actionable feedback to students.

- At the end of each unit, use **AP Classroom** to assign students the online **Personal Progress Checks** as homework or as an in-class task.
- Provide question-level feedback to students through answer rationales; provide unit- and science practice-level feedback using the progress dashboard.
- Create additional practice opportunities using the **AP Question Bank** and assign them through **AP Classroom**.

About the AP Physics 2 Course

AP Physics 2 is an algebra-based, introductory college-level physics course. Students cultivate their understanding of physics through inquiry-based investigations as they explore these topics: fluids; thermodynamics; electrical force, field, and potential; electric circuits; magnetism and electromagnetic induction; geometric and physical optics; and quantum, atomic, and nuclear physics.

College Course Equivalent

AP Physics 2 is a full-year course that is the equivalent of a second-semester introductory college course in algebra-based physics.

Prerequisites

Students should have completed AP Physics 1 or a comparable introductory physics course and should have taken or be concurrently taking pre-calculus or an equivalent course.

Laboratory Requirement

This course requires that twenty-five percent of instructional time will be spent in hands-on laboratory work, with an emphasis on inquiry-based investigations that provide students with opportunities to demonstrate foundational physics principles and apply the science practices.

Inquiry-based laboratory experiences support the AP Physics 2 course and AP Course Audit curricular requirements by providing opportunities for students to engage in the seven science practices as they design plans for experiments, make predictions, collect and analyze data, apply mathematical routines, develop explanations, and communicate about their work.

Colleges may require students to present their laboratory materials from AP science courses before granting college credit for laboratory work, so students should be encouraged to retain their laboratory notebooks, reports, and other materials.

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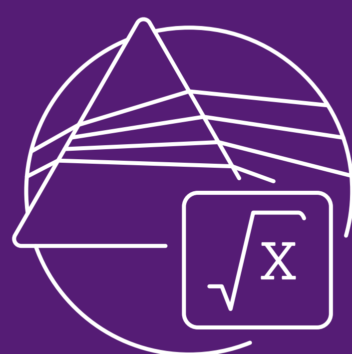
AP PHYSICS 2

Course Framework



Introduction

The AP Physics 2 course outlined in this framework reflects a commitment to what physics teachers, professors, and researchers have agreed is the main goal of a college-level physics survey course: to help students develop a deep understanding of the foundational principles that shape classical mechanics and modern physics. By confronting complex physical situations or scenarios, the course is designed to enable students to develop the ability to reason about physical phenomena using important science practices, such as explaining relationships, applying and justifying the use of mathematical routines, designing experiments, analyzing data, and making connections across multiple topics within the course.

To foster this deeper level of learning, the AP Physics 2 course defines concepts, skills, and understandings required by representative colleges and universities for granting college credit and placement. Students will practice reasoning skills used by physicists by discussing and debating, with peers, the physical phenomena investigated in class, as well as by designing and conducting inquiry-based laboratory investigations to solve problems through first-hand observations, data collection, analysis, and interpretation.

This document is not a complete curriculum. Teachers create their own local curriculum by selecting, for each concept, content that enables students to explore the course learning objectives and meets state or local requirements. The result is a course that prepares students for college credit and placement.

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Course Framework Components

Overview

This course framework provides a clear and detailed description of the course requirements necessary for student success. The framework specifies what students must know, be able to do, and understand to qualify for college credit or placement.

The course framework includes two essential components:

1 SCIENCE PRACTICES

The science practices are central to the study and practice of physics. Students should develop and apply the described practices on a regular basis over the span of the course.

2 COURSE CONTENT

The course content is organized into commonly taught units of study that provide a suggested sequence for the course and detail required content and conceptual understandings that colleges and universities typically expect students to master to qualify for college credit and/or placement. This content is grounded in big ideas, which are cross-cutting concepts that build conceptual understanding and spiral throughout the course.

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AP PHYSICS 2

Science Practices

The table that follows presents the science practices that students should develop during the AP Physics 2 course. These practices form the basis of many tasks on the AP Physics 2 Exam.

The unit guides that follow embed and spiral these practices throughout the course, providing teachers with one way to integrate the practices into the course content with sufficient repetition to prepare students to transfer those practices when taking the AP Physics 2 Exam.

More detailed information about teaching the science practices can be found in the Instructional Approaches section of this publication.

AP PHYSICS 2

Science Practices

Practice 1	Practice 2	Practice 3	Practice 4	Practice 5	Practice 6	Practice 7
Modeling 1 The student can use representations and models to communicate scientific phenomena and solve scientific problems.	***Mathematical Routines*** 2 The student can use mathematics appropriately.	***Scientific Questioning*** 3 The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course *(not assessed on the AP Exam).*	***Experimental Methods*** 4 The student can plan and implement data collection strategies in relation to a particular scientific question.	***Data Analysis*** 5 The student can perform data analysis and evaluation of evidence.	***Argumentation*** 6 The student can work with scientific explanations and theories.	***Making Connections*** 7 The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.
1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.	**2.1** The student can justify the selection of a mathematical routine to solve problems.	**3.1** The student can pose scientific questions.	**4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question.	**5.1** The student can analyze data to identify patterns or relationships.	**6.1** The student can justify claims with evidence.	**7.1** The student can connect phenomena and models across spatial and temporal scales.
1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain.	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena.	**3.2** The student can refine scientific questions.	**4.2** The student can design a plan for collecting data to answer a particular scientific question.	**5.2** The student can refine observations and measurements based on data analysis.	**6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices.	**7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
1.3 The student can refine representations and models of natural or man-made phenomena and systems in the domain.	**2.3** The student can estimate numerically quantities that describe natural phenomena.	**3.3** The student can evaluate scientific questions.	**4.3** The student can collect data to answer a particular scientific question.	**5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question.	**6.3** The student can articulate the reasons that scientific explanations and theories are refined or replaced.	
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.			**4.4** The student can evaluate sources of data to answer a particular scientific question.		**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	
1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.					**6.5** The student can evaluate alternative scientific explanations.	

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AP PHYSICS 2

Course Content

Based on the Understanding by Design® (Wiggins and McTighe) model, this course framework provides a clear and detailed description of the course requirements necessary for student success. The framework specifies what students must know, be able to do, and understand, with a focus on seven big ideas that encompass core principles, theories, and processes of the discipline. The framework also encourages instruction that prepares students to make connections across domains through a broader way of thinking about the physical world.

Big Ideas

The big ideas serve as the foundation of the course and allow students to create meaningful connections among concepts. They are often abstract concepts or themes that become threads that run throughout the course. Revisiting the big ideas and applying them in a variety of contexts allows students to develop deeper conceptual understanding. Below are the big ideas of the course and a brief description of each.

BIG IDEA 1: SYSTEMS (SYS)
Objects and systems have properties such as mass and charge. Systems may have internal structure.

BIG IDEA 2: FIELDS (FLD)
Fields existing in space can be used to explain interactions.

BIG IDEA 3: FORCE INTERACTIONS (INT)
The interactions of an object with other objects can be described by forces.

BIG IDEA 4: CHANGE (CHA)
Interactions between systems can result in changes in those systems.

BIG IDEA 5: CONSERVATION (CON)
Changes that occur as a result of interactions are constrained by conservation laws.

continued on next page

BIG IDEA 6: WAVES (WAV)
Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

BIG IDEA 7: PROBABILITY (PRO)
The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.

UNITS

The course content is organized into commonly taught units. The units have been arranged in a logical sequence frequently found in many college courses and textbooks.

The seven units in AP Physics 2, and their relevant weightings on the multiple-choice section of the AP Exam, are listed below.

Pacing recommendations at the unit level and on the Course at Glance provide suggestions for how teachers can teach the required course content and administer the Personal Progress Checks. The suggested class periods are based on a schedule in which the class meets five days a week for 45 minutes each day. While these recommendations have been made to aid in planning, teachers are free to adjust the pacing based on the needs of their students, alternate schedules (e.g., block scheduling), or their school's academic calendar.

TOPICS

Each unit is divided into teachable segments called *topics*. Visit the topic pages (starting on page 36) to see all required content contained in each topic.

Exam Weighting for the Multiple-Choice Section of the AP Exam

Units	Exam Weighting
Unit 1: *Fluids*	10–12%
Unit 2: *Thermodynamics*	12–18%
Unit 3: *Electric Force, Field, and Potential*	18–22%
Unit 4: *Electric Circuits*	10–14%
Unit 5: *Magnetism and Electromagnetic Induction*	10–12%
Unit 6: *Geometric and Physical Optics*	12–14%
Unit 7: *Quantum, Atomic, and Nuclear Physics*	10–12%

Spiraling the Big Ideas

The following table shows how the big ideas spiral across units:

Big Ideas	Unit 1 *Fluids*	Unit 2 *Thermodynamics*	Unit 3 *Electric Force, Field, and Potential*	Unit 4 *Electric Circuits*	Unit 5 *Magnetism and Electromagnetic Induction*	Unit 6 *Geometric and Physical Optics*	Unit 7 *Quantum, Atomic, and Nuclear Physics*
1-Systems **SYS**	✓	✓	✓	✓	✓		✓
2-Fields **FLD**			✓	✓	✓		
3-Force Interactions **INT**	✓	✓	✓		✓		✓
4-Change **CHA**		✓	✓	✓	✓		✓
5-Conservation **CON**	✓	✓	✓	✓			✓
6-Waves **WAV**						✓	✓
7-Probability **PRO**	✓						✓

Course at a Glance

Plan

The Course at a Glance provides a useful visual organization of the AP Physics 2 curricular components, including the following:

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

Teach

SCIENCE PRACTICES
Science practices spiral throughout the course.

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

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

BIG IDEAS
Big ideas spiral across topics and units.

- SYS 1-Systems
- FLD 2-Fields
- INT 3-Force Interactions
- CHA 4-Change
- CON 5-Conservation
- WAV 6-Waves
- PRO 7-Probability

Assess

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

UNIT 1 Fluids

~14–17 Class Periods | 10–12% AP Exam Weighting

Big Idea	Practices	Topic
SYS	1, 7	1.1 Fluid Systems
SYS	4, 6	1.2 Density
INT	+	1.3 Fluids: Pressure and Forces
INT	+	1.4 Fluids and Free-Body Diagrams
INT	6	1.5 Buoyancy
CON	2, 6	1.6 Conservation of Energy in Fluid Flow
CON	2, 7	1.7 Conservation of Mass Flow Rate in Fluids

Personal Progress Check 1

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

UNIT 2 Thermodynamics

~15–20 Class Periods | 12–18% AP Exam Weighting

Big Idea	Practices	Topic
SYS	1, 7	2.1 Thermodynamic Systems
PRO	+	2.2 Pressure, Thermal Equilibrium, and the Ideal Gas Law
INT	+	2.3 Thermodynamics and Forces
INT	+	2.4 Thermodynamics and Free-Body Diagrams
INT	6	2.5 Thermodynamics and Contact Forces
CHA	6	2.6 Heat and Energy Transfer
CON	+	2.7 Internal Energy and Energy Transfer
CON	+	2.8 Thermodynamics and Elastic Collisions: Conservation of Momentum
CON	+	2.9 Thermodynamics and Inelastic Collisions: Conservation of Momentum
SYS	4, 5	2.10 Thermal Conductivity
CON	6, 7	2.11 Probability, Thermal Equilibrium, and Entropy

Personal Progress Check 2

Multiple-choice: ~60 questions
Free-response: 2 questions
- Quantitative/Qualitative Translation
- Short Answer

UNIT 3 Electric Force, Field, and Potential

~23–25 Class Periods | 18–22% AP Exam Weighting

SYS 1 7	3.1	Electric Systems
SYS 6 7	3.2	Electric Charge
CON +	3.3	Conservation of Electric Charge
CHA +	3.4	Charge Distribution—Friction, Conduction, and Induction
SYS	3.5	Electric Permittivity
INT +	3.6	Introduction to Electric Forces
INT +	3.7	Electric Forces and Free-Body Diagrams
INT +	3.8	Describing Electric Force
INT 7	3.9	Gravitational and Electromagnetic Forces
FLD	3.10	Vector and Scalar Fields
FLD +	3.11	Electric Charges and Fields
FLD +	3.12	Isolines and Electric Fields
CON +	3.13	Conservation of Electric Energy

Personal Progress Check 3

Multiple-choice: ~75 questions
Free-response: 2 questions
- Experimental Design
- Paragraph Argument Short Answer

UNIT 4 Electric Circuits

~14–16 Class Periods | 10–14% AP Exam Weighting

SYS 6 7	4.1	Definition and Conservation of Electric Charge
SYS 4	4.2	Resistivity and Resistance
CHA +	4.3	Resistance and Capacitance
CON +	4.4	Kirchhoff's Loop Rule
CON +	4.5	Kirchhoff's Junction Rule and the Conservation of Electric Charge

Personal Progress Check 4

Multiple-choice: ~40 questions
Free-response: 2 questions
- Quantitative/Qualitative Translation
- Short Answer

UNIT 5 Magnetism and Electromagnetic Induction

~13–15 Class Periods | 10–12% AP Exam Weighting

SYS 1 7	5.1	Magnetic Systems
SYS	5.2	Magnetic Permeability and Magnetic Dipole Moment
FLD	5.3	Vector and Scalar Fields
FLD +	5.4	Monopole and Dipole Fields
FLD 1 2	5.5	Magnetic Fields and Forces
INT +	5.6	Magnetic Forces
INT +	5.7	Forces Review
CHA +	5.8	Magnetic Flux

Personal Progress Check 5

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

UNIT 6 Geometric and Physical Optics

~15–18 Class Periods | 12–14% AP Exam Weighting

WAV, +	6.1 Waves
WAV, +	6.2 Electromagnetic Waves
WAV, 1	6.3 Periodic Waves
WAV, +	6.4 Refraction, Reflection, and Absorption
WAV, +	6.5 Images from Lenses and Mirrors
WAV, +	6.6 Interference and Diffraction

Personal Progress Check 6

Multiple-choice: ~50 questions
Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT 7 Quantum, Atomic, and Nuclear Physics

~13–15 Class Periods | 10–12% AP Exam Weighting

SYS, INT, 1, 7	7.1 Systems and Fundamental Forces
CON, +	7.2 Radioactive Decay
CON, +	7.3 Energy in Modern Physics (Energy in Radioactive Decay and $E = mc^2$)
SYS, CHA, +	7.4 Mass–Energy Equivalence
SYS, WAV, +	7.5 Properties of Waves and Particles
WAV, 6, 7	7.6 Photoelectric Effect
PRO, 1, 6	7.7 Wave Functions and Probability

Personal Progress Check 7

Multiple-choice: ~55 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

AP PHYSICS 2

Unit Guides

Introduction

Designed with input from the community of AP Physics 2 educators, the unit guides offer teachers helpful guidance in building students' science practices and knowledge. The suggested sequence was identified through a thorough analysis of the syllabi of highly effective AP teachers and the organization of typical college textbooks.

This unit structure respects new AP teachers' time by providing one possible sequence they can adopt or modify rather than having to build from scratch. An additional benefit is that these units enable the AP Program to provide interested teachers with formative assessments—the Personal Progress Checks—that they can assign their students at the end of each unit to gauge progress toward success on the AP Exam. However, experienced AP teachers who are satisfied with their current course organization and exam results should feel no pressure to adopt these units, which comprise an optional sequence for this course.

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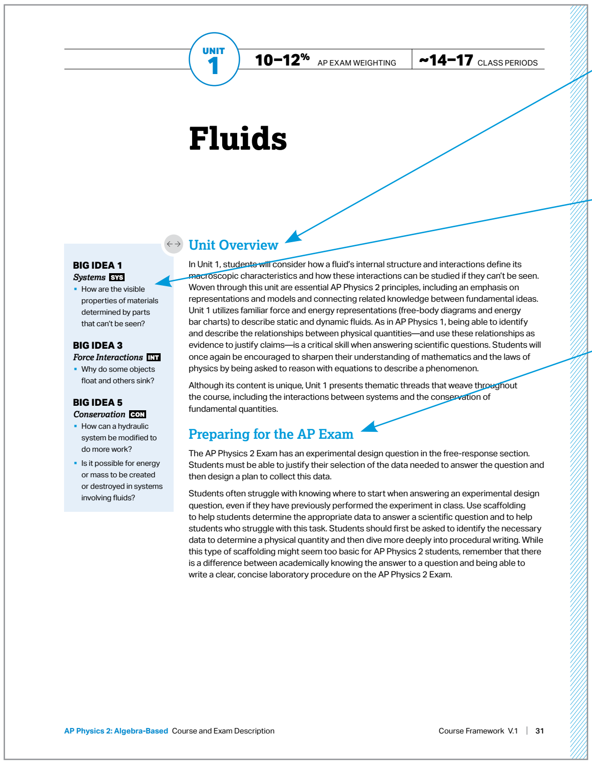
Using the Unit Guides



UNIT 1

10–12% AP EXAM WEIGHTING | ~14–17 CLASS PERIODS

Fluids

BIG IDEA 1
Systems SYS
- How are the visible properties of materials determined by parts that can't be seen?

BIG IDEA 3
Force Interactions INT
- Why do some objects float and others sink?

BIG IDEA 5
Conservation CON
- How can a hydraulic system be modified to do more work?
- Is it possible for energy or mass to be created or destroyed in systems involving fluids?

Unit Overview

In Unit 1, students will consider how a fluid's internal structure and interactions define its macroscopic characteristics and how these interactions can be studied if they can't be seen. Woven through this unit are essential AP Physics 2 principles, including an emphasis on representations and models and connecting related knowledge between fundamental ideas. Unit 1 utilizes familiar force and energy representations (free-body diagrams and energy bar charts) to describe static and dynamic fluids. As in AP Physics 1, being able to identify and describe the relationships between physical quantities—and use these relationships as evidence to justify claims—is a critical skill when answering scientific questions. Students will once again be encouraged to sharpen their understanding of mathematics and the laws of physics by being asked to reason with equations to describe a phenomenon.

Although its content is unique, Unit 1 presents thematic threads that weave throughout the course, including the interactions between systems and the conservation of fundamental quantities.

Preparing for the AP Exam

The AP Physics 2 Exam has an experimental design question in the free-response section. Students must be able to justify their selection of the data needed to answer the question and then design a plan to collect this data.

Students often struggle with knowing where to start when answering an experimental design question, even if they have previously performed the experiment in class. Use scaffolding to help students determine the appropriate data to answer a scientific question and to help students who struggle with this task. Students should first be asked to identify the necessary data to determine a physical quantity and then dive more deeply into procedural writing. While this type of scaffolding might seem too basic for AP Physics 2 students, remember that there is a difference between academically knowing the answer to a question and being able to write a clear, concise laboratory procedure on the AP Physics 2 Exam.

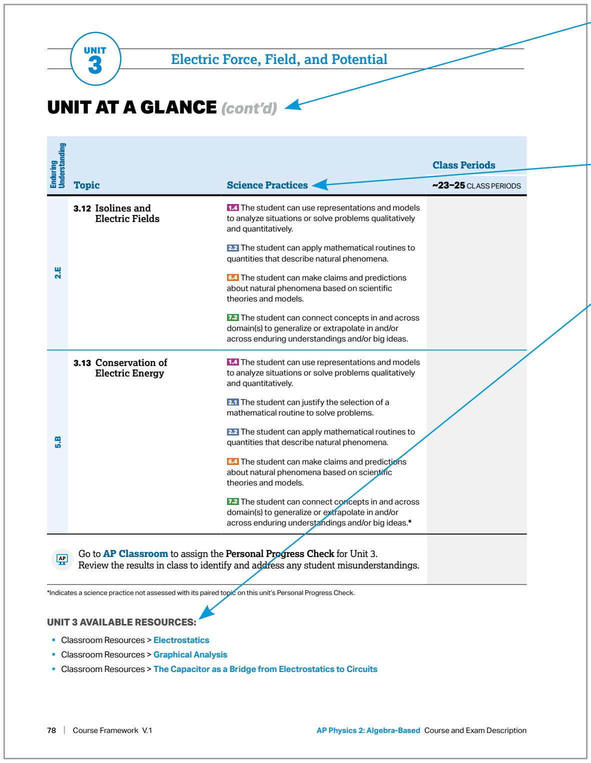
AP Physics 2: Algebra-Based Course and Exam Description   Course Framework V.1 | 31

UNIT OPENERS

Unit Overview contextualizes and situates the key content of the unit within the scope of the course. It also describes specific aspects of the science practices that are appropriate to focus on in that unit.

Big ideas serve as the foundation of the course and develop understanding as they spiral throughout the course. The **essential questions** are thought-provoking questions that motivate students and inspire inquiry.

Preparing for the AP Exam provides helpful tips and common student misunderstandings identified from prior exam data.



UNIT 3 — Electric Force, Field, and Potential

UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
2.E	3.12 Isolines and Electric Fields	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.B	3.13 Conservation of Electric Energy	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.1 The student can justify the selection of a mathematical routine to solve problems. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

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

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

UNIT 3 AVAILABLE RESOURCES:
- Classroom Resources > Electrostatics
- Classroom Resources > Graphical Analysis
- Classroom Resources > The Capacitor as a Bridge from Electrostatics to Circuits

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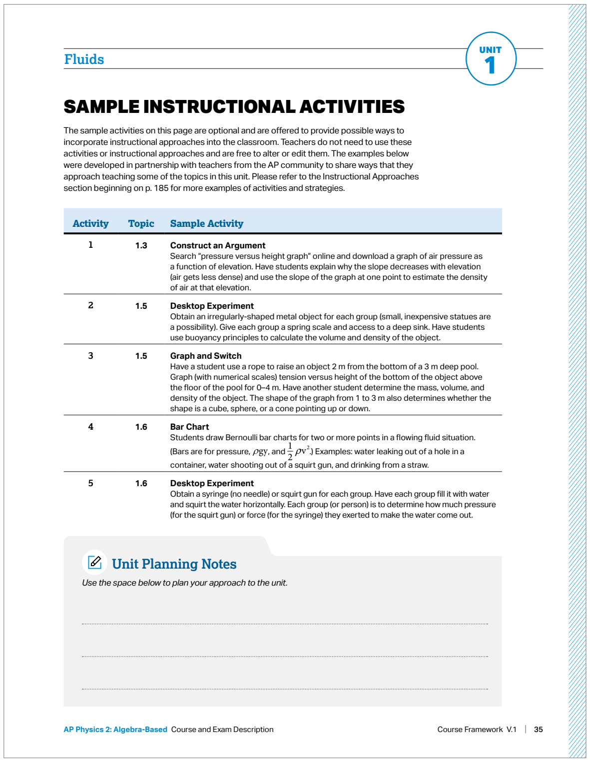
The **Unit at a Glance** table shows the topics, related enduring understandings, and science practices. The "class periods" column has been left blank so that teachers can customize the time they spend on each topic.

The **science practices** for each topic link content in that topic to specific AP Physics 2 science practices. The questions on the Personal Progress Checks are based on these links.

Available resources might help teachers address a particular topic in their classroom.

Using the Unit Guides

UNIT OPENERS


Fluids

UNIT 1

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

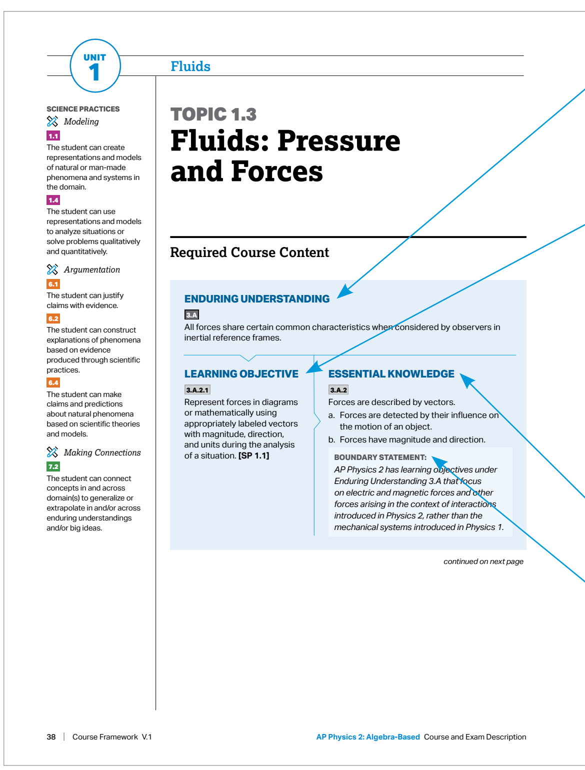
Activity	Topic	Sample Activity
1	1.3	**Construct an Argument** Search "pressure versus height graph" online and download a graph of air pressure as a function of elevation. Have students explain why the slope decreases with elevation (air gets less dense) and use the slope of the graph at one point to estimate the density of air at that elevation.
2	1.5	**Desktop Experiment** Obtain an irregularly-shaped metal object for each group (small, inexpensive statues are a possibility). Give each group a spring scale and access to a deep sink. Have students use buoyancy principles to calculate the volume and density of the object.
3	1.5	**Graph and Switch** Have a student use a rope to raise an object 2 m from the bottom of a 3 m deep pool. Graph (with numerical scales) tension versus height of the bottom of the object above the floor of the pool for 0–4 m. Have another student determine the mass, volume, and density of the object. The shape of the graph from 1 to 3 m also determines whether the shape is a cube, sphere, or a cone pointing up or down.
4	1.6	**Bar Chart** Students draw Bernoulli bar charts for two or more points in a flowing fluid situation. (Bars are for pressure, ρgy, and $\frac{1}{2}\rho v^2$.) Examples: water leaking out of a hole in a container, water shooting out of a squirt gun, and drinking from a straw.
5	1.6	**Desktop Experiment** Obtain a syringe (no needle) or squirt gun for each group. Have each group fill it with water and squirt the water horizontally. Each group (or person) is to determine how much pressure (for the squirt gun) or force (for the syringe) they exerted to make the water come out.

Unit Planning Notes

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

AP Physics 2: Algebra-Based Course and Exam Description Course Framework V.1 | 35

The **Sample Instructional Activities** page includes optional activities that can help tie together the content and science practices of a particular topic.


UNIT 1

Fluids

SCIENCE PRACTICES

Modeling

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

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

Argumentation

6.1 The student can justify claims with evidence.

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

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

Making Connections

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

TOPIC 1.3

Fluids: Pressure and Forces

Required Course Content

ENDURING UNDERSTANDING

3.A

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

LEARNING OBJECTIVE

3.A.2.1

Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

3.A.2

Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.

b. Forces have magnitude and direction.

BOUNDARY STATEMENT:

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

continued on next page

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TOPIC PAGES

Enduring understandings are the long-term takeaways related to the big ideas that leave a lasting impression on students. Students build and earn these understandings over time by exploring and applying course content throughout the year.

Learning objectives provide clear and detailed articulation of what students should know and be able to do in order to progress toward the enduring understandings. Each learning objective is designed to help teachers integrate science practices **[SP]** with specific content and to provide them with clear information on how students will be expected to demonstrate their knowledge and skills on the AP Physics 2 Exam. These learning objectives fully define what will be assessed on the exam. Questions that do not correspond to one or more learning objectives will not appear on the exam.

Essential knowledge statements describe the knowledge required to perform the learning objective.

Boundary statements provide guidance to teachers regarding the content boundaries of the AP Physics 1 and 2 courses. These statements help articulate the contextual differences of how the same big ideas and enduring understandings are applied in each course. Boundary statements appear at the end of essential knowledge statements where appropriate.

REQUIRED COURSE CONTENT LABELING SYSTEM

BIG IDEA 1	ENDURING UNDERSTANDING	ESSENTIAL KNOWLEDGE	LEARNING OBJECTIVE
Systems **SYS**	**1.E** Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	**1.E.1** Matter has a property called density. *Relevant Equation:* $\rho = \frac{m}{V}$	**1.E.1.1** Predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction. **[SP 4.2, 6.4]**

Note: Labels are used to distinguish each unique element of the required course content and are used throughout this course and exam description. Additionally, they are used in the AP Question Bank and other resources found in AP Classroom. Big ideas are labeled by number, with "1" referring to SYS, "2" referring to FLD, "3" referring to INT, "4" referring to CHA, "5" referring to CON, "6" referring to WAV, and "7" referring to PRO. Enduring understandings are labeled sequentially according to the big idea that they are related to. Essential knowledge statements are labeled to correspond with the enduring understanding they relate to. Finally, learning objectives are labeled to correspond with the essential knowledge statement they relate to.

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AP PHYSICS 2

UNIT 1

Fluids

10–12%
AP EXAM WEIGHTING

~14–17
CLASS PERIODS

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

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

Personal Progress Check 1

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

- Experimental Design
- Paragraph Argument Short Answer

UNIT 1

10–12% AP EXAM WEIGHTING

~14–17 CLASS PERIODS

Fluids

BIG IDEA 1
***Systems* SYS**
- How are the visible properties of materials determined by parts that can't be seen?

BIG IDEA 3
***Force Interactions* INT**
- Why do some objects float and others sink?

BIG IDEA 5
***Conservation* CON**
- How can a hydraulic system be modified to do more work?
- Is it possible for energy or mass to be created or destroyed in systems involving fluids?

Unit Overview

In Unit 1, students will consider how a fluid's internal structure and interactions define its macroscopic characteristics and how these interactions can be studied if they can't be seen. Woven through this unit are essential AP Physics 2 principles, including an emphasis on representations and models and connecting related knowledge between fundamental ideas. Unit 1 utilizes familiar force and energy representations (free-body diagrams and energy bar charts) to describe static and dynamic fluids. As in AP Physics 1, being able to identify and describe the relationships between physical quantities—and use these relationships as evidence to justify claims—is a critical skill when answering scientific questions. Students will once again be encouraged to sharpen their understanding of mathematics and the laws of physics by being asked to reason with equations to describe a phenomenon.

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Students often struggle with knowing where to start when answering an experimental design question, even if they have previously performed the experiment in class. Use scaffolding to help students determine the appropriate data to answer a scientific question and to help students who struggle with this task. Students should first be asked to identify the necessary data to determine a physical quantity and then dive more deeply into procedural writing. While this type of scaffolding might seem too basic for AP Physics 2 students, remember that there is a difference between academically knowing the answer to a question and being able to write a clear, concise laboratory procedure on the AP Physics 2 Exam.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~14–17 CLASS PERIODS
1.A	1.1 Fluid Systems	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.* 7.1 The student can connect phenomena and models across spatial and temporal scales.*	
1.E	1.2 Density	4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.	
3.A	1.3 Fluids: Pressure and Forces	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.1 The student can justify claims with evidence.* 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~14–17 CLASS PERIODS
3.B	**1.4 Fluids and Free-Body Diagrams**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.C	**1.5 Buoyancy**	6.1 The student can justify claims with evidence. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.	
5.B	**1.6 Conservation of Energy in Fluid Flow**	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.	
5.F	**1.7 Conservation of Mass Flow Rate in Fluids**	2.1 The student can justify the selection of a mathematical routine to solve problems. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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

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

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UNIT AT A GLANCE *(cont'd)*

UNIT 1 AVAILABLE RESOURCES:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **AP Physics Featured Question: Raft with Hanging Weights**
- Classroom Resources > **Conservation Concepts**
- Classroom Resources > **Critical Thinking Questions in Physics**
- Classroom Resources > **Inquiry Instruction in the AP Science Classroom: An Approach to Teaching and Learning**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	1.3	**Construct an Argument** Search "pressure versus height graph" online and download a graph of air pressure as a function of elevation. Have students explain why the slope decreases with elevation (air gets less dense) and use the slope of the graph at one point to estimate the density of air at that elevation.
2	1.5	**Desktop Experiment** Obtain an irregularly-shaped metal object for each group (small, inexpensive statues are a possibility). Give each group a spring scale and access to a deep sink. Have students use buoyancy principles to calculate the volume and density of the object.
3	1.5	**Graph and Switch** Have a student use a rope to raise an object 2 m from the bottom of a 3 m deep pool. Graph (with numerical scales) tension versus height of the bottom of the object above the floor of the pool for 0–4 m. Have another student determine the mass, volume, and density of the object. The shape of the graph from 1 to 3 m also determines whether the shape is a cube, sphere, or a cone pointing up or down.
4	1.6	**Bar Chart** Students draw Bernoulli bar charts for two or more points in a flowing fluid situation. (Bars are for pressure, ρgy, and $\frac{1}{2}\rho v^2$.) Examples: water leaking out of a hole in a container, water shooting out of a squirt gun, and drinking from a straw.
5	1.6	**Desktop Experiment** Obtain a syringe (no needle) or squirt gun for each group. Have each group fill it with water and squirt the water horizontally. Each group (or person) is to determine how much pressure (for the squirt gun) or force (for the syringe) they exerted to make the water come out.

Unit Planning Notes

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

SCIENCE PRACTICES

Modeling

1.1
The student can create representations and models of natural or man-made phenomena and systems in the domain.

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

Making Connections

7.1
The student can connect phenomena and models across spatial and temporal scales.

TOPIC 1.1
Fluid Systems

Required Course Content

ENDURING UNDERSTANDING

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

LEARNING OBJECTIVE

1.A.5.2
Construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.5
Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an *object*.

TOPIC 1.2
Density

Required Course Content

ENDURING UNDERSTANDING

1.E

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

LEARNING OBJECTIVE

1.E.1.1

Predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction. **[SP 4.2, 6.4]**

1.E.1.2

Select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects. **[SP 4.1, 6.4]**

ESSENTIAL KNOWLEDGE

1.E.1

Matter has a property called *density*.

Relevant Equation:

$$\rho = \frac{m}{V}$$

SCIENCE PRACTICES

Experimental Methods

4.1

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

4.2

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

Argumentation

6.4

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Argumentation

6.1

The student can justify claims with evidence.

6.2

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

6.4

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

Making Connections

7.2

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

TOPIC 1.3
Fluids: Pressure and Forces

Required Course Content

ENDURING UNDERSTANDING

3.A

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

LEARNING OBJECTIVE

3.A.2.1

Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

3.A.2

Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.

b. Forces have magnitude and direction.

BOUNDARY STATEMENT:

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

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.A.3.2 Construct an explanation for why an object cannot exert a force on itself. **[SP 6.1]** **3.A.3.3** Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]** **3.A.3.4** Make claims about the force on an object due to the presence of other objects with the same properties: mass, electric charge. **[SP 6.1, 6.4]**	**3.A.3** A force exerted on an object is always due to the interaction of that object with another object. a. An object cannot exert a force on itself. b. Even though an object is at rest, there may be forces exerted on that object by other objects. c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects. *Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$
3.A.4.1 Construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]** **3.A.4.2** Make claims and predictions about the action-reaction pairs of forces when two objects interact using Newton's third law. **[SP 6.4, 7.2]** **3.A.4.3** Analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**	**3.A.4** If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

1.5

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 1.4
Fluids and Free-Body Diagrams

Required Course Content

ENDURING UNDERSTANDING

3.B

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

LEARNING OBJECTIVE

3.B.1.3

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

3.B.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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Relevant Equation:

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

BOUNDARY STATEMENT:

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

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LEARNING OBJECTIVE

3.B.2.1

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

ESSENTIAL KNOWLEDGE

3.B.2

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

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

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

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

SCIENCE PRACTICES

Argumentation

6.1

The student can justify claims with evidence.

6.2

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

TOPIC 1.5
Buoyancy

Required Course Content

ENDURING UNDERSTANDING

3.C

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

LEARNING OBJECTIVE

3.C.4.1

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

3.C.4.2

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

ESSENTIAL KNOWLEDGE

3.C.4

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

Relevant Equations:

$$F_b = \rho V g$$

$$P = \frac{F}{A}$$

TOPIC 1.6

Conservation of Energy in Fluid Flow

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.10.1

Make calculations related to a moving fluid using Bernoulli's equation. **[SP 2.2]**

5.B.10.2

Make calculations related to a moving fluid using Bernoulli's equation and/or the relationship between force and pressure. **[SP 2.2]**

5.B.10.3

Make calculations related to a moving fluid using Bernoulli's equation and the continuity equation. **[SP 2.2]**

5.B.10.4

Construct an explanation of Bernoulli's equation in terms of the conservation of energy. **[SP 6.2]**

ESSENTIAL KNOWLEDGE

5.B.10

Bernoulli's equation describes the conservation of energy in fluid flow. The absolute pressure (*P*) equals atmospheric pressure (P_0) plus the gauge pressure (ρgh).

Relevant Equations:

$$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$$

$$P = \frac{F}{A}$$

$$A_1 v_1 = A_2 v_2$$

$$P = P_0 + \rho g h$$

SCIENCE PRACTICES

Mathematical Routines

2.2

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

Argumentation

6.2

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

SCIENCE PRACTICES

Mathematical Routines

2.1

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

2.2

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

Making Connections

7.2

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

TOPIC 1.7
Conservation of Mass Flow Rate in Fluids

Required Course Content

ENDURING UNDERSTANDING

5.F

Classically, the mass of a system is conserved.

LEARNING OBJECTIVE

5.F.1.1

Make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). **[SP 2.1, 2.2, 7.2]**

ESSENTIAL KNOWLEDGE

5.F.1

The continuity equation describes conservation of mass flow rate in fluids. Examples include volume rate of flow and mass flow rate.

Relevant Equation:

$A_1v_1 = A_2v_2$

AP PHYSICS 2

UNIT 2

Thermodynamics

12–18%
AP EXAM WEIGHTING

~15–20
CLASS PERIODS

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

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

Personal Progress Check 2

Multiple-choice: ~60 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Short Answer

UNIT 2

12–18% AP EXAM WEIGHTING | ~15–20 CLASS PERIODS

Thermodynamics

BIG IDEA 1
Systems **SYS**

- How is the temperature of a substance related to the energy and movement of its atoms and molecules?
- How can we best measure what we cannot see?

BIG IDEA 5
Conservation **CON**

- How does the direction in which a heat engine does work determine whether it is used as a refrigerator or a heat pump?
- How and why should we conserve energy?
- When is it beneficial to remove energy from a system?

BIG IDEA 7
Probability **PRO**

- How does probability help explain entropy?
- Can energy remain constant even in a closed system?

Unit Overview

In Unit 2, students will continue to investigate what they cannot see by examining heat, temperature, and thermal energy in practical contexts such as heat engines, heat pumps, and refrigerators. The focus of this unit is the study of relationships and change, so it's important that students can discuss—in addition to calculate—what happens when a physical scenario changes, such as the consequences of adding heat to, or removing heat from, a system. Throughout this unit, students will use representations and models (PV diagrams, energy bar charts, or free-body diagrams) to construct evidence-based explanations and help them make predictions and justify claims about new phenomena. These representations and models will also help students develop connections and transfer their learning across disciplinary boundaries so that they are able to link, synthesize, and apply ideas they have learned across the sciences and mathematics.

Unit 2 also acquaints students with the second law of thermodynamics, entropy, and how the behavior of complex systems can be modeled with the mathematics of probability. This will be explored further in Unit 7 to help support and explain the concepts of modern physics.

Preparing for the AP Exam

The AP Physics 2 Exam requires students to be able to re-express key elements of natural phenomena across multiple representations in the domain. This skill appears in the Quantitative/Qualitative Translation (QQT), a type of long, free-response question that requires students to use both words and mathematics to describe and analyze a situation. A QQT might ask students to work with multiple representations or evaluate another student's representations. Representations might include equations, narrative descriptions, graphs, diagrams, and data tables.

Students who have primarily been exposed to numerical problem solving often struggle with QQTs, because these questions require them to have a more conceptual understanding of both content and representations. Providing opportunities for students to translate between different representations (including equations, diagrams, graphs, and written descriptions) will help students perform better on a QQT.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~15–20 CLASS PERIODS
1.A	**2.1 Thermodynamic Systems**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.* 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.* 7.1 The student can connect phenomena and models across spatial and temporal scales.*	
7.A	**2.2 Pressure, Thermal Equilibrium, and the Ideal Gas Law**	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 3.2 The student can refine scientific questions. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.1 The student can connect phenomena and models across spatial and temporal scales.* 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~15–20 CLASS PERIODS
3.A	**2.3 Thermodynamics and Forces**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.* 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.1 The student can justify claims with evidence.* 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.* 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.B	**2.4 Thermodynamics and Free-Body Diagrams**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
3.C	**2.5 Thermodynamics and Contact Forces**	6.1 The student can justify claims with evidence.* 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.*	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~15–20 CLASS PERIODS
4.C	2.6 Heat and Energy Transfer	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.	
5.B	2.7 Internal Energy and Energy Transfer	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.1 The student can justify the selection of a mathematical routine to solve problems. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
5.D	2.8 Thermodynamics and Elastic Collisions: Conservation of Momentum	2.1 The student can justify the selection of a mathematical routine to solve problems.* 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~15–20 CLASS PERIODS
5.D	**2.9 Thermodynamics and Inelastic Collisions: Conservation of Momentum**	2.1 The student can justify the selection of a mathematical routine to solve problems.* 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
1.E	**2.10 Thermal Conductivity**	4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.* 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships.	
7.B	**2.11 Probability, Thermal Equilibrium, and Entropy**	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 7.1 The student can connect phenomena and models across spatial and temporal scales.	

AP

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

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

UNIT 2 AVAILABLE RESOURCES:

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

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	2.2	**Desktop Experiment** Give each group a 10 mL syringe with a Luer-Lok tip and a Luer-Lok cap. Instruct students to set the syringe to 10 mL, cap the end, turn the syringe vertical, and stack books on top. Students then calculate the absolute pressure of the books plus atmosphere, and make a pressure versus volume graph.
2	2.6	**Discussion Groups** Each group is to come up with a way to demonstrate each of the eight thermodynamic processes (isobaric, isochoric, isothermal, and adiabatic, each in both possible directions) using cheap-to-obtain/common school or household items. Example: For adiabatic compression, cap a syringe and push on the plunger really hard (see "fire syringe" for more on this example).
3	2.6	**Graph and Switch** Student A describes a three-step cyclical thermodynamic process (e.g., "isochoric heating, isothermal expansion, isobaric cooling") and Students B, C, and D make a PV, PT, and VT diagram (respectively) of the cycle.
4	2.7	**Construct an Argument/Concept-Oriented Demonstration** Look up "Contigo Autospout Addison Water Bottle" on Amazon and show it to students. Explain that a person takes this partially filled water bottle up to the top of a mountain, opens it, and gets sprayed in the face with water. Explain why and whether more water would spray out if there is more or less water in the bottle (answer: less). Discuss what would happen if the bottle is taken out of the refrigerator, opened, and the person gets sprayed.
5	2.11	**Changing Representations** Show students a single thermodynamic process on a PV/PT/VT diagram and a molecular-velocity distribution graph for the "initial" state. Have students draw the distribution for the "final" state or explain why it is the same graph (if it is).

Unit Planning Notes

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

TOPIC 2.1
Thermodynamic Systems

Required Course Content

ENDURING UNDERSTANDING

1.A

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

LEARNING OBJECTIVE

1.A.5.2

Construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.5

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Making Connections

7.1

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

SCIENCE PRACTICES

Modeling

1.4

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

Mathematical Routines

2.2

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

Scientific Questioning

3.2

The student can refine scientific questions.

Experimental Methods

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.4

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

TOPIC 2.2

Pressure, Thermal Equilibrium, and the Ideal Gas Law

Required Course Content

ENDURING UNDERSTANDING

7.A

The properties of an ideal gas can be explained in terms of a small number of macroscopic variables, including temperature and pressure.

LEARNING OBJECTIVE

7.A.1.1

Make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container and how changes in pressure affect the thermal equilibrium of the system. **[SP 6.4, 7.2]**

7.A.1.2

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. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

7.A.1

The pressure of a system determines the force that the system exerts on the walls of its container and is a measure of the average change in the momentum or impulse of the molecules colliding with the walls of the container. The pressure also exists inside the system itself, not just at the walls of the container.

Relevant Equations:

$$P = \frac{F}{A}$$

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

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LEARNING OBJECTIVE

7.A.2.1

Qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. **[SP 7.1]**

7.A.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. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

7.A.2

The temperature of a system characterizes the average kinetic energy of its molecules.

a. The average kinetic energy of the system is an average of the many different speeds of the molecules in the system that can be described by a distribution curve.

b. The root mean square speed corresponding to the average kinetic energy for a specific gas at a given temperature can be obtained from this distribution.

Relevant Equation:

$$K = \frac{3}{2}k_B T$$

LEARNING OBJECTIVE

7.A.3.1

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. **[SP 6.4, 7.2]**

7.A.3.2

Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and/or the amount of an ideal gas; and to refine a scientific question proposing an incorrect relationship between the variables. **[SP 3.2, 4.2]**

7.A.3.3

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 $PV = nRT$. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

7.A.3

In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V) are related by the ideal gas law $PV = nRT$.

Relevant Equation:

$$PV = nRT = Nk_B T$$

SCIENCE PRACTICES

Making Connections

7.1

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

7.2

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Argumentation

6.1

The student can justify claims with evidence.

6.2

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

6.4

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

Making Connections

7.2

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

TOPIC 2.3

Thermodynamics and Forces

Required Course Content

ENDURING UNDERSTANDING

3.A

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

LEARNING OBJECTIVE

3.A.2.1

Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

3.A.2

Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.

b. Forces have magnitude and direction.

BOUNDARY STATEMENT:

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

continued on next page

LEARNING OBJECTIVE

3.A.3.2

Construct an explanation for why an object cannot exert a force on itself. **[SP 6.1]**

3.A.3.3

Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**

3.A.3.4

Make claims about the force on an object due to the presence of other objects with the same properties: mass, electric charge. **[SP 6.1, 6.4]**

ESSENTIAL KNOWLEDGE

3.A.3

A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.

b. Even though an object is at rest, there may be forces exerted on that object by other objects.

c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

Relevant Equation:

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

LEARNING OBJECTIVE

3.A.4.1

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

3.A.4.2

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

3.A.4.3

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

ESSENTIAL KNOWLEDGE

3.A.4

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

1.5

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 2.4

Thermodynamics and Free-Body Diagrams

Required Course Content

ENDURING UNDERSTANDING

3.B

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

LEARNING OBJECTIVE

3.B.1.3

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

3.B.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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Relevant Equation:

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

BOUNDARY STATEMENT:

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

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LEARNING OBJECTIVE

3.B.2.1

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

ESSENTIAL KNOWLEDGE

3.B.2

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

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

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

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

SCIENCE PRACTICES

Argumentation

6.1
The student can justify claims with evidence.

6.2
The student can construct explanations of phenomena based on evidence produced through scientific practices.

TOPIC 2.5

Thermodynamics and Contact Forces

Required Course Content

ENDURING UNDERSTANDING

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

LEARNING OBJECTIVE

3.C.4.1
Make claims about various contact forces between objects based on the microscopic cause of those forces. **[SP 6.1]**

3.C.4.2
Explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. **[SP 6.2]**

ESSENTIAL KNOWLEDGE

3.C.4
Contact forces result from the interaction of one object touching another object, and they arise from interatomic electric forces. These forces include tension, friction, normal, spring (Physics 1), and buoyant (Physics 2).

Relevant Equations:

$$F_b = \rho V g$$

$$P = \frac{F}{A}$$

TOPIC 2.6

Heat and Energy Transfer

SCIENCE PRACTICES

Argumentation

6.4

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

Required Course Content

ENDURING UNDERSTANDING

4.C

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

LEARNING OBJECTIVE

4.C.3.1

Make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

4.C.3

Energy is transferred spontaneously from a higher-temperature system to a lower-temperature system. The process through which energy is transferred between systems at different temperatures is called *heat*.

a. Conduction, convection, and radiation are mechanisms for this energy transfer.

b. At a microscopic scale, the mechanism of conduction is the transfer of kinetic energy between particles.

c. During average collisions between molecules, kinetic energy is transferred from faster molecules to slower molecules.

SCIENCE PRACTICES

Modeling

1.1

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

1.2

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

1.4

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

Mathematical Routines

2.1

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

2.2

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

Experimental Methods

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

TOPIC 2.7
Internal Energy and Energy Transfer

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.2.1

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

ESSENTIAL KNOWLEDGE

5.B.2

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

Relevant Equation:

$\Delta U_E = q\Delta V$

BOUNDARY STATEMENT:

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

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LEARNING OBJECTIVE

5.B.4.1

Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**

5.B.4.2

Calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

5.B.4

The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.

a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy.

b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.

LEARNING OBJECTIVE

5.B.5.4

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

5.B.5.5

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

5.B.5.6

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. **[SP 4.2, 5.1]**

ESSENTIAL KNOWLEDGE

5.B.5

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

$$W = -P\Delta V$$

for constant pressure or an average pressure.

Relevant Equations:

$$\Delta E = W = Fd\cos\theta$$

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

continued on next page

SCIENCE PRACTICES

Argumentation

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE

5.B.6.1

Describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation. **[SP 1.2]**

ESSENTIAL KNOWLEDGE

5.B.6

Energy can be transferred by thermal processes involving differences in temperature; this process of transfer is called *heat*.

LEARNING OBJECTIVE

5.B.7.1

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. **[SP 6.4, 7.2]**

5.B.7.2

Create a plot of pressure versus volume for a thermodynamic process from given data. **[SP 1.1]**

5.B.7.3

Make calculations of internal energy changes, heat, or work, based on conservation of energy principles (i.e., the first law of thermodynamics), using a plot of pressure versus volume for a thermodynamic process. **[SP 1.1, 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

5.B.7

The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples include PV diagrams—isovolumetric processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of thermal energy or internal energy from temperature change are required; in this course, examples of these relationships are qualitative and/or semiquantitative.

Relevant Equations:

$$W = -P\Delta V$$

$$\Delta U = Q + W$$

TOPIC 2.8

Thermodynamics and Elastic Collisions: Conservation of Momentum

Required Course Content

ENDURING UNDERSTANDING

5.D

The linear momentum of a system is conserved.

LEARNING OBJECTIVE

5.D.1.6

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. **[SP 6.4]**

5.D.1.7

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

ESSENTIAL KNOWLEDGE

5.D.1

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

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

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

Relevant Equations:

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

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

continued on next page

SCIENCE PRACTICES

Mathematical Routines

2.1

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

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE

5.D.1.6

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. **[SP 6.4]**

5.D.1.7

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

ESSENTIAL KNOWLEDGE

BOUNDARY STATEMENT:

Physics 1 includes a quantitative and qualitative treatment of conservation of momentum in one dimension and a semiquantitative treatment of conservation of momentum in two dimensions. Test items involving solution of simultaneous equations are not included on either the Physics 1 or Physics 2 exams, but items testing whether students can set up the equations properly and can reason about how changing a given mass, speed, or angle would affect other quantities are included. Physics 1 includes only conceptual understanding of center-of-mass motion of a system without the need for calculation of center of mass. Physics 2 includes full qualitative and quantitative two-dimensional treatment of conservation of momentum and velocity of the center of mass of the system. Physics 1 addresses Enduring Understanding 5.D with topics in the context of mechanical systems. Physics 2 does so with content that involves interactions arising in the context of topics such as nuclear decay, other nuclear reactions, and interactions of subatomic particles with each other and with photons.

TOPIC 2.9

Thermodynamics and Inelastic Collisions: Conservation of Momentum

Required Course Content

ENDURING UNDERSTANDING

5.D

The linear momentum of a system is conserved.

LEARNING OBJECTIVE

5.D.2.5

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

5.D.2.6

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

ESSENTIAL KNOWLEDGE

5.D.2

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

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

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

Relevant Equations:

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

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

SCIENCE PRACTICES

Mathematical Routines

2.1

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

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

SCIENCE PRACTICES

Experimental Methods

4.1

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

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

TOPIC 2.10

Thermal Conductivity

Required Course Content

ENDURING UNDERSTANDING

1.E

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

LEARNING OBJECTIVE

1.E.3.1

Design an experiment, and analyze data from it to examine thermal conductivity. **[SP 4.1, 4.2, 5.1]**

ESSENTIAL KNOWLEDGE

1.E.3

Matter has a property called *thermal conductivity*. Thermal conductivity is the measure of a material's ability to transfer thermal energy.

Relevant Equation:

$$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$$

TOPIC 2.11

Probability, Thermal Equilibrium, and Entropy

Required Course Content

ENDURING UNDERSTANDING

7.B

The tendency of isolated systems to move toward states with higher disorder is described by probability.

LEARNING OBJECTIVE

7.B.1.1

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. **[SP 6.2]**

ESSENTIAL KNOWLEDGE

7.B.1

The approach to thermal equilibrium is a probability process.

a. The amount of thermal energy needed to change the temperature of an object depends both on the mass of the object and on the temperature change.

b. The details of the energy transfer depend on interactions at the molecular level.

c. Since higher-momentum particles will be involved in more collisions, energy is most likely to be transferred from higher to lower energy particles. The most likely state after many collisions is that both objects have the same temperature.

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SCIENCE PRACTICES

Argumentation

6.2

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

Making Connections

7.1

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

LEARNING OBJECTIVE

7.B.2.1

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. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

7.B.2

The second law of thermodynamics describes the change in entropy for reversible and irreversible processes. Only a qualitative treatment is considered in this course.

a. Entropy, like temperature, pressure, and internal energy, is a state function, the value of which depends only on the configuration of the system at a particular instant and not on how the system arrived at that configuration.
b. Entropy can be described as a measure of the disorder of a system, or of the unavailability of some system energy to do work.
c. The entropy of a closed system never decreases (i.e., it can stay the same or increase).
d. The total entropy of the universe is always increasing.

AP PHYSICS 2

UNIT 3

Electric Force, Field, and Potential

18–22%
AP EXAM WEIGHTING

~23–25
CLASS PERIODS

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

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

Personal Progress Check 3

Multiple-choice: ~75 questions
Free-response: 2 questions

- Experimental Design
- Paragraph Argument Short Answer

Electric Force, Field, and Potential

BIG IDEA 2
Fields **FLD**
- How are topographical maps connected to the ideas of electric field and potential?
- If our five senses cannot detect an electric field, how can we know it's there?
- Would you get lost in an electric field without a map? Why are some maps better than others?

BIG IDEA 3
Force Interactions **INT**
- How do electrical charges behave in an electric field?

BIG IDEA 5
Conservation **CON**
- Why do charges move?
- What parallels can be drawn between electric charge and energy?

Unit Overview

Unit 3 begins the study of electromagnetic phenomena at a fundamental level, introducing students to the concepts of electric charge, electric force, and electric field and potential. Despite the shift from examining fluids and gases to examining charged particles, the foundation of this unit continues to focus on relationships, change, and developing the science practice of making connections between scales, concepts, and representations. For instance, students will use the concept of equipotential lines to visualize the electric field and make connections between the isolines on topographic maps for gravitational fields and equipotential lines for the electric field. This unit will also help students better understand that interactions between systems result in changes within those systems—allowing students to further apply energy conservation principles in later units.

Students are encouraged to apply what they know when learning about fields (gravitational and electric), how fields interact, and the complex concepts of static and dynamic electricity. This will help students better understand energy conservation principles, as well as develop the science practice of data analysis. Data analysis is essential in identifying patterns and relationships between variables and helps students become better prepared to engage in and craft scientific arguments that describe a mechanism through which a phenomenon occurs.

Preparing for the AP Exam

During the exam, students will be asked to write a paragraph to demonstrate their ability to communicate their understanding of a physical situation in a reasoned, expository analysis. A student's analysis of the situation should be coherent, organized, and sequential. It should draw from evidence, cite physical principles, and clearly present the student's thinking. A paragraph-long response will earn points for correct physics principles. However, full credit may not be earned if the response contains any of the following: principles not presented in a logical order, lengthy digressions within an argument, or a lack of linking prose between equations or diagrams.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
1.A	3.1 Electric Systems	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.* 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.* 7.1 The student can connect phenomena and models across spatial and temporal scales.*	
1.B	3.2 Electric Charge	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.C	3.3 Conservation of Electric Charge	4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question. 4.2 The student can design a plan for collecting data to answer a particular scientific question.* 5.1 The student can analyze data to identify patterns or relationships. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
4.E	**3.4 Charge Distribution: Friction, Conduction, and Induction**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **3.2** The student can refine scientific questions. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
1.E	**3.5 Electric Permittivity**	N/A	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
3.A	**3.6 Introduction to Electric Forces**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **6.1** The student can justify claims with evidence.* **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.* **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
3.B	**3.7 Electric Forces and Free-Body Diagrams**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain.* **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.* **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
3.C	**3.8 Describing Electric Force**	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
3.G	**3.9 Gravitational and Electromagnetic Forces**	7.1 The student can connect phenomena and models across spatial and temporal scales.	
2.A	**3.10 Vector and Scalar Fields**	N/A	
2.C	**3.11 Electric Charges and Fields**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.1 The student can connect phenomena and models across spatial and temporal scales.* 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~23–25 CLASS PERIODS
2.E	**3.12** Isolines and Electric Fields	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.B	**3.13** Conservation of Electric Energy	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	

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

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

UNIT 3 AVAILABLE RESOURCES:

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

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	3.6	**Identify Subtasks** Students are shown three known charges at known positions on a line and asked to find the net force on each charge. Students describe in words what the subtasks are and come up with a procedure for finding the net force on each charge.
2	3.7	**Conflicting Contentions** Show a diagram with two charged spheres hanging from strings anchored to the same point in the ceiling, with the string for sphere A making a greater angle from the vertical. One student thinks this is because A has less charge so it is pushed on harder by B, but another student thinks it is because A has less mass and is pulled down less by gravity. Which student is right? Explain with free-body diagrams.
3	3.8	**Desktop Experiment** A spark occurs when the E-field between two conductors is 3×10^6 V/m. Obtain a Van de Graaf generator and find the distance from the ball that a grounded rod must be held to make a spark. Have students use $E = V/d$ to get the potential of the sphere, and use $V = kq/r^2$ with the radius of the sphere to get the charge of the sphere.
4	3.9	**Friends Without Pens** Have students consider a proton P and an alpha particle A released from rest near each other. Relate the electric and gravitational forces of P→A and A→P. Rank these four forces, and justify the ranking. How does the acceleration/momentum/kinetic energy of P compare to A (four times as much, same, four times)? How does the acceleration and velocity of P or A change as they move apart?
5	3.11 3.12	**Changing Representations** Given an arrangement of two or three charges (of various signs and either same or different magnitude), students sketch E-field vector diagrams and potential isolines for the arrangement. Students can use **PhET: Charges and Fields** to check their diagrams.

Unit Planning Notes

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Making Connections

7.1

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

TOPIC 3.1
Electric Systems

Required Course Content

ENDURING UNDERSTANDING

1.A

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

LEARNING OBJECTIVE

1.A.5.2

Construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[SP 1.1, 1.4, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.5

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

TOPIC 3.2

Electric Charge

Required Course Content

ENDURING UNDERSTANDING

1.B

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

LEARNING OBJECTIVE

1.B.1.1

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

1.B.1.2

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

ESSENTIAL KNOWLEDGE

1.B.1

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

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

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

Relevant Equation:

$$I = \frac{\Delta Q}{\Delta t}$$

BOUNDARY STATEMENT:

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

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SCIENCE PRACTICES

Argumentation

6.2

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

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
1.B.2.1 Construct an explanation of the two charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]** **1.B.2.2** Make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. **[SP 6.4, 7.2]** **1.B.2.3** Challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object. **[SP 6.1]**	**1.B.2** There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge. a. Like-charged objects and systems repel, and unlike-charged objects and systems attract. b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system.
1.B.3.1 Construct an explanation that challenges the claim that an electric charge smaller than the elementary charge has been isolated. **[SP 1.5, 6.1, 7.2]**	**1.B.3** The smallest observed unit of charge that can be isolated is the electron charge, also known as the *elementary charge*. a. The magnitude of the elementary charge is equal to 1.6×10^{-19} coulombs. b. Electrons have a negative elementary charge; protons have a positive elementary charge of equal magnitude, although the mass of a proton is much larger than the mass of an electron.

TOPIC 3.3

Conservation of Electric Charge

Required Course Content

ENDURING UNDERSTANDING

5.C

The electric charge of a system is conserved.

LEARNING OBJECTIVE

5.C.2.1

Predict electric charges on objects within a system by application of the principle of charge conservation within a system. **[SP 6.4]**

5.C.2.2

Design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data. **[SP 4.2, 5.1]**

5.C.2.3

Justify the selection of data relevant to an investigation of the electrical charging of objects and electric charge induction on neutral objects. **[SP 4.1]**

ESSENTIAL KNOWLEDGE

5.C.2

The exchange of electric charges among a set of objects in a system conserves electric charge.

a. Charging by conduction between objects in a system conserves the electric charge of the entire system.

b. Charge separation in a neutral system can be induced by an external charged object placed close to the neutral system.

c. Grounding involves the transfer of excess charge to another larger system (e.g., Earth).

SCIENCE PRACTICES

Experimental Methods

4.1

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

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.4

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Scientific Questioning

3.2

The student can refine scientific questions.

Experimental Methods

4.1

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

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.3

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

TOPIC 3.4

Charge Distribution: Friction, Conduction, and Induction

Required Course Content

ENDURING UNDERSTANDING

4.E

The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

LEARNING OBJECTIVE

4.E.3.1

Make predictions about the redistribution of charge during charging by friction, conduction, and induction. **[SP 6.4]**

4.E.3.2

Make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects. **[SP 6.4, 7.2]**

4.E.3.3

Construct a representation of the distribution of fixed and mobile charge in insulators and conductors. **[SP 1.1, 1.4, 6.4]**

4.E.3.4

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. **[SP 1.1, 1.4, 6.4]**

ESSENTIAL KNOWLEDGE

4.E.3

The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.

a. Charging can take place by friction or by contact.

b. An induced charge separation can cause a neutral object to become polarized.

c. Charging by induction can occur when a polarizing conducting object is touched by another.

d. In solid conductors, some electrons are mobile. When no current flows, mobile charges are in static equilibrium, excess charge resides at the surface, and the interior field is zero. In solid insulators, excess ("fixed") charge may reside in the interior as well as at the surface.

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LEARNING OBJECTIVE

4.E.3.5

Plan and/or analyze the results of experiments in which electric-charge rearrangement occurs by electrostatic induction, or be able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]**

ESSENTIAL KNOWLEDGE

4.E.3

The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.

a. Charging can take place by friction or by contact.

b. An induced charge separation can cause a neutral object to become polarized.

c. Charging by induction can occur when a polarizing conducting object is touched by another.

d. In solid conductors, some electrons are mobile. When no current flows, mobile charges are in static equilibrium, excess charge resides at the surface, and the interior field is zero. In solid insulators, excess ("fixed") charge may reside in the interior as well as at the surface.

SCIENCE PRACTICES

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 3.5
Electric Permittivity

Required Course Content

ENDURING UNDERSTANDING

1.E

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

LEARNING OBJECTIVE

[While there is no specific learning objective for it, EK 1.E.4 serves as a foundation for other learning objectives in the course.]

ESSENTIAL KNOWLEDGE

1.E.4

Matter has a property called *electric permittivity*.

a. Free space has a constant value of the permittivity that appears in physical relationships.
b. The permittivity of matter has a value different from that of free space.

TOPIC 3.6

Introduction to Electric Forces

Required Course Content

ENDURING UNDERSTANDING

3.A

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

LEARNING OBJECTIVE

3.A.2.1

Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

3.A.2

Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.

b. Forces have magnitude and direction.

BOUNDARY STATEMENT:

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

LEARNING OBJECTIVE

3.A.3.2

Construct an explanation for why an object cannot exert a force on itself. **[SP 6.1]**

3.A.3.3

Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

3.A.3

A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.

b. Even though an object is at rest, there may be forces exerted on that object by other objects.

c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

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SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Argumentation

6.1

The student can justify claims with evidence.

6.2

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

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
3.A.3.4 Make claims about the force on an object due to the presence of other objects with the same properties: mass, electric charge. **[SP 6.1, 6.4]**	*Relevant Equation:* $\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$
3.A.4.1 Construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]** **3.A.4.2** Make claims and predictions about the action-reaction pairs of forces when two objects interact using Newton's third law. **[SP 6.4, 7.2]** **3.A.4.3** Analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**	**3.A.4** If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

TOPIC 3.7

Electric Forces and Free-Body Diagrams

Required Course Content

ENDURING UNDERSTANDING

3.B

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

LEARNING OBJECTIVE

3.B.1.3

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

3.B.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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Relevant Equation:

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

BOUNDARY STATEMENT:

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

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SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

1.5

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE

3.B.2.1

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

ESSENTIAL KNOWLEDGE

3.B.2

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

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

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

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

TOPIC 3.8

Describing Electric Force

Required Course Content

ENDURING UNDERSTANDING

3.C

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

LEARNING OBJECTIVE

3.C.2.1

Make predictions about the interaction between two electric point charges, using Coulomb's law qualitatively and quantitatively.
[SP 2.2, 6.4]

3.C.2.2

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

3.C.2.3

Describe the electric force that results from the interaction of several separated point charges (generally two to four point charges, though more are permitted in situations of high symmetry) using appropriate mathematics. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

3.C.2

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

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

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

Relevant Equations:

$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\frac{\left|q_1 q_2\right|}{r^2}$$

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

SCIENCE PRACTICES

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

SCIENCE PRACTICE

Making Connections

7.1

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

TOPIC 3.9
Gravitational and Electromagnetic Forces

Required Course Content

ENDURING UNDERSTANDING

3.G

Certain types of forces are considered fundamental.

LEARNING OBJECTIVE

3.G.1.2

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 with other types of forces. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

3.G.1

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

Relevant Equation:

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

LEARNING OBJECTIVE

3.G.2.1

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. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

3.G.2

Electromagnetic forces are exerted at all scales and can dominate at the human scale.

Relevant Equation:

$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\frac{\left|q_1 q_2\right|}{r^2}$$

TOPIC 3.10

Vector and Scalar Fields

Required Course Content

ENDURING UNDERSTANDING

2.A

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

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

2.A.1

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

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

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

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Mathematical Routines

2.2

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

Argumentation

6.2

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

6.4

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

Making Connections

7.1

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

7.2

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

TOPIC 3.11
Electric Charges and Fields

Required Course Content

ENDURING UNDERSTANDING

2.C

An electric field is caused by an object with electric charge.

LEARNING OBJECTIVE

2.C.1.1

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. **[SP 6.4, 7.2]**

2.C.1.2

Calculate any one of the variables—electric force, electric charge, and electric field—at a point given the values and sign or direction of the other two quantities. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

2.C.1

The magnitude of the electric force F exerted on an object with electric charge q by an electric field E is

$$\vec{F} = q\vec{E}$$

The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

continued on next page

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
2.C.2.1 Qualitatively and semi quantitatively apply the vector relationship between the electric field and the net electric charge creating that field. **[SP 2.2, 6.4]**	**2.C.2** The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.
2.C.3.1 Explain the inverse square dependence of the electric field surrounding a spherically symmetric, electrically charged object. **[SP 6.2]**	**2.C.3** The electric field outside a spherically symmetric charged object is radial, and its magnitude varies as the inverse square of the radial distance from the center of that object. Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source. a. The inverse square relation known as Coulomb's law gives the magnitude of the electric field at a distance r from the center of a source object of electric charge q as $\lvert\vec{E}\rvert = \frac{1}{4\pi\varepsilon_0}\frac{\lvert q\rvert}{r^2}$. b. This relation is based on a model of the space surrounding a charged source object by considering the radial dependence of the area of the surface of a sphere centered on the source object.

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LEARNING OBJECTIVE

2.C.4.1

Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single-point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semiquantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. **[SP 2.2, 6.4, 7.2]**

2.C.4.2

Apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (two to four) 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. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

2.C.4

The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

a. When an object is small compared with the distances involved in the problem, or when a larger object is being modeled as a large number of very small constituent particles, these can be modeled as charged objects of negligible size, or "point charges."

b. The expression for the electric field due to a point charge can be used to determine the electric field, either qualitatively or quantitatively, around a simple, highly symmetric distribution of point charges.

Relevant Equation:

$$|\vec{E}| = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

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LEARNING OBJECTIVE

2.C.5.1

Create representations of the magnitude and direction of the electric field at various distances (small compared with plate size) from two electrically charged plates of equal magnitude and opposite signs, and be able to recognize that the assumption of uniform field is not appropriate near edges of plates. **[SP 1.1, 2.2]**

2.C.5.2

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. **[SP 2.2]**

2.C.5.3

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 Earth's gravitational field. **[SP 1.1, 2.2, 7.1]**

ESSENTIAL KNOWLEDGE

2.C.5

Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.

Relevant Equations:

$$E = \frac{Q}{\varepsilon_0 A}$$

$$\left|\vec{E}\right| = \left|\frac{\Delta V}{\Delta r}\right|$$

$$\Delta V = \frac{Q}{C}$$

$$U_C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$$

SCIENCE PRACTICES

Modeling

1.4

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 3.12
Isolines and Electric Fields

Required Course Content

ENDURING UNDERSTANDING

2.E

Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.

LEARNING OBJECTIVE

2.E.1.1

Construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential. **[SP 1.4, 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

2.E.1

Isolines on a topographic (elevation) map describe lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential). As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational and electrical potential and potential differences.]

Relevant Equation:

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

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LEARNING OBJECTIVE

2.E.2.1

Determine the structure of isolines of electric potential by constructing them in a given electric field.
[SP 6.4, 7.2]

2.E.2.2

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.
[SP 6.4, 7.2]

2.E.2.3

Construct isolines of electric potential in an electric field, and determine the effect of that field on electrically charged objects, qualitatively using the concept of isolines.
[SP 1.4]

ESSENTIAL KNOWLEDGE

2.E.2

Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as *equipotential lines*.

a. An isoline map of electric potential can be constructed from an electric field vector map, using the fact that the isolines are perpendicular to the electric field vectors.

b. Since the electric potential has the same value along an isoline, there can be no component of the electric field along the isoline.

Relevant Equation:

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

LEARNING OBJECTIVE

2.E.3.1

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.
[SP 2.2]

2.E.3.2

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.
[SP 1.4, 6.4]

ESSENTIAL KNOWLEDGE

2.E.3

The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

Relevant Equation:

$$\left|\vec{E}\right| = \left|\frac{\Delta V}{\Delta r}\right|$$

SCIENCE PRACTICES

Modeling

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

Mathematical Routines

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

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

Argumentation

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

Making Connections

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

TOPIC 3.13

Conservation of Electric Energy

Required Course Content

ENDURING UNDERSTANDING

5.B
The energy of a system is conserved.

LEARNING OBJECTIVE

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

ESSENTIAL KNOWLEDGE

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

Relevant Equation:

$$\Delta U_E = q\Delta V$$

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

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LEARNING OBJECTIVE

5.B.4.1

Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**

5.B.4.2

Calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

5.B.4

The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.

a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy.

b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.

BOUNDARY STATEMENT:

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

LEARNING OBJECTIVE

5.B.5.4

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

5.B.5.5

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

ESSENTIAL KNOWLEDGE

5.B.5

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

Relevant Equations:

$$\Delta E = W = Fd\cos\theta$$

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

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AP PHYSICS 2

UNIT 4

Electric Circuits

10–14%
AP EXAM WEIGHTING

~14–16
CLASS PERIODS

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

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

Personal Progress Check 4

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

- Quantitative/Qualitative Translation
- Short Answer

UNIT 4

10–14% AP EXAM WEIGHTING | **~14–16** CLASS PERIODS

Electric Circuits

BIG IDEA 1
Systems **SYS**

- How can what's inside affect what's outside?
- How can we measure something that has no weight, mass, or temperature?

BIG IDEA 4
Change **CHA**

- How can you change the value of something just by changing its shape?
- How does the resistance and capacitance of resistors and capacitors change in response to changes in the physical geometry of the circuit element?
- Why are holiday lights usually wired in series, while house lights are usually wired in parallel?

BIG IDEA 5
Conservation **CON**

- How can the electric company justify its claims that it sells "electricity"?
- What happens to the charge in a cell phone battery when it "dies"?

Unit Overview

Unit 4 revisits the behavior of charged particles, discussed in Unit 3, to deepen students' understanding of the law of conservation of energy and how it's applied to electric circuits. This unit will ask students to do more than calculate for the current, resistance, and voltage in a simple circuit; it will challenge them to draw connections between the interactions of systems and the changes that result from those interactions. For example, students will need to be able to articulate the impact of a light bulb being removed on a circuit consisting of several light bulbs. They will also need to design an experiment to test if a light bulb is ohmic or justify how changing the spacing of a capacitor will affect its capacitance. Using models and representations to analyze physical situations, as well as using mathematical relationships to justify claims, are critically important science practices in this unit. Unit 4 will also compel students to discover and understand the relationship between the conservation of total energy and the conservation of total electric charge in circuits. It will encourage them to use Kirchhoff's rules to describe both energy conservation and charge conservation.

Simultaneously, students will also have more opportunities in Unit 4 to expand their data collection and analysis abilities to include writing clear, concise procedural paragraphs in addition to revising their reasoning based on new data. In Unit 5, students will expand their investigations of the symmetry between electric and magnetic fields.

Preparing for the AP Exam

Students will be challenged to apply the science practices to the learning objectives in the course framework. These science practices and learning objectives can be addressed in many ways, including through inquiry-based labs. While inquiry experiments will take more time than simple verification/confirmation labs, they are important for student success. Students need to have firsthand experience in designing investigations and analyzing data instead of simply following a set of instructions given by the teacher.

Students are expected to provide a sequence of statements that is clear, concise, and orderly and that specifies the steps in the investigation needed to reasonably answer the question or investigate the phenomenon.

On the AP Physics 2 Exam, there is a 12-point experimental design question in the free-response question section. In addition, there will be 8 to 10 multiple-choice questions that ask students to think about experimental design.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~14–16 CLASS PERIODS
1.B	4.1 Definition and Conservation of Electric Charge	6.1 The student can justify claims with evidence.* 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.* 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.* 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
1.E	4.2 Resistivity and Resistance	4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.	
4.E	4.3 Resistance and Capacitance	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 6.1 The student can justify claims with evidence. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~14–16 CLASS PERIODS
5.B	**4.4 Kirchhoff's Loop Rule**	**1.5** The student can re-express key elements of natural phenomena across multiple representations in the domain. **2.1** The student can justify the selection of a mathematical routine to solve problems. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **4.2** The student can design a plan for collecting data to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	
5.C	**4.5 Kirchhoff's Junction Rule and the Conservation of Electric Charge**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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

UNIT 4 AVAILABLE RESOURCES:

- Classroom Resources > ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual***
- Classroom Resources > **Conservation Concepts**
- Classroom Resources > **The Capacitor as a Bridge from Electrostatics to Circuits**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	4.2	**Conflicting Contentions** Students A and B are trying to heat water by connecting mechanical pencil lead directly to a battery and immersing the lead in the water. To heat the water in less time, Student A says that 0.7 mm pencil lead should be used so that charges flow better, but Student B says that 0.5 mm pencil lead will have greater resistance. Resolve this conflict using equations and qualitative reasoning.
2	4.2	**Desktop Experiment** Connect a 1.5 volt battery to five light bulbs in parallel. Measure potential difference across and current through the battery, and then make a graph whose slope is the internal resistance of the battery.
3	4.3	**Desktop Experiment** Connect 0.5 mm or 0.7 mm mechanical pencil lead in series with a 1000 ohm resistor and a 1.5 volt battery. Measure the potential difference across and current through the lead, and then determine the resistivity of the graphite.
4	4.4 4.5	**Predict and Explain** Set up a mixed circuit with a battery and three or four light bulbs. Ask students to predict what happens to the brightness of each of the remaining bulbs if one is removed, and explain using Kirchhoff's principles. Alternately, ask what bulb must be removed to make another bulb brighter or dimmer.
5	4.4 4.5	**Working Backward/Graph and Switch** Students A and B each create a table of potential differences and currents for four or five ohmic resistors in a circuit. They switch tables and then draw the circuit diagram that corresponds to the other student's table, complete with resistance values and battery voltages.

Unit Planning Notes

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

TOPIC 4.1

Definition and Conservation of Electric Charge

Required Course Content

ENDURING UNDERSTANDING

1.B

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

LEARNING OBJECTIVE

1.B.1.1

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

1.B.1.2

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

ESSENTIAL KNOWLEDGE

1.B.1

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

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

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

Relevant Equation:

$$I = \frac{\Delta Q}{\Delta t}$$

BOUNDARY STATEMENT:

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

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SCIENCE PRACTICES

Argumentation

6.1

The student can justify claims with evidence.

6.2

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

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE

1.B.2.1

Construct an explanation of the two charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**

1.B.2.2

Make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. **[SP 6.4, 7.2]**

1.B.2.3

Challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object. **[SP 6.1]**

ESSENTIAL KNOWLEDGE

1.B.2

There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge.

a. Like-charged objects and systems repel, and unlike-charged objects and systems attract.

b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system.

TOPIC 4.2

Resistivity and Resistance

SCIENCE PRACTICE

Experimental Methods

4.1

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

Required Course Content

ENDURING UNDERSTANDING

1.E

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

LEARNING OBJECTIVE

1.E.2.1

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

ESSENTIAL KNOWLEDGE

1.E.2

Matter has a property called *resistivity*.

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

b. The resistivity depends on the temperature of the material.

Relevant Equation:

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

SCIENCE PRACTICES

Mathematical Routines

2.2

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

Experimental Methods

4.1

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

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

Argumentation

6.1

The student can justify claims with evidence.

6.4

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

TOPIC 4.3

Resistance and Capacitance

Required Course Content

ENDURING UNDERSTANDING

4.E

The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

LEARNING OBJECTIVE

4.E.4.1

Make predictions about the properties of resistors and/or capacitors when placed in a simple circuit based on the geometry of the circuit element and supported by scientific theories and mathematical relationships. **[SP 2.2, 6.4]**

4.E.4.2

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. **[SP 4.1, 4.2]**

ESSENTIAL KNOWLEDGE

4.E.4

The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.

a. The resistance of a resistor is proportional to its length and inversely proportional to its cross-sectional area. The constant of proportionality is the resistivity of the material.

b. The capacitance of a parallel plate capacitor is proportional to the area of one of its plates and inversely proportional to the separation between its plates. The constant of proportionality is the product of the dielectric constant, κ, of the material between the plates and the electric permittivity, ε_0.

c. The current through a resistor is equal to the potential difference across the resistor divided by its resistance.

d. The magnitude of charge of one of the plates of a parallel plate capacitor is directly proportional to the product of the potential difference across the capacitor and the capacitance. The plates have equal amounts of charge of opposite sign.

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LEARNING OBJECTIVE

4.E.4.3

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. **[SP 5.1]**

ESSENTIAL KNOWLEDGE

Relevant Equations:

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

$$C = \kappa \varepsilon_0 \frac{A}{d}$$

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

$$\Delta V = \frac{Q}{C}$$

LEARNING OBJECTIVE

4.E.5.1

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. **[SP 2.2, 6.4]**

4.E.5.2

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. **[SP 6.1, 6.4]**

4.E.5.3

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. **[SP 2.2, 4.2, 5.1]**

ESSENTIAL KNOWLEDGE

4.E.5

The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of individual circuit elements, such as sources of emf, resistors, and capacitors.

Relevant Equations:

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

$$R_s = \sum_i R_i$$

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

$$C_p = \sum_i C_i$$

$$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$$

SCIENCE PRACTICES

Modeling

1.5

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

Mathematical Routines

2.1

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

2.2

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

Experimental Methods

4.1

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

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.3

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

Argumentation

6.4

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

TOPIC 4.4

Kirchhoff's Loop Rule

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.9.4

Analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule: $\sum \Delta V = 0$. **[SP 5.1]**

5.B.9.5

Describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors using conservation of energy principles (Kirchhoff's loop rule). **[SP 6.4]**

5.B.9.6

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. **[SP 2.1, 2.2]**

ESSENTIAL KNOWLEDGE

5.B.9

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

a. Energy changes in simple electrical circuits are conveniently represented in terms of energy change per charge moving through a battery and a resistor.

b. Since electric potential difference times charge is energy, and energy is conserved, the sum of the potential differences about any closed loop must add to zero.

c. The electric potential difference across a resistor is given by the product of the current and the resistance.

d. The rate at which energy is transferred from a resistor is equal to the product of the electric potential difference across the resistor and the current through the resistor.

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LEARNING OBJECTIVE

5.B.9.7

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. **[SP 4.1, 4.2, 5.1, 5.3]**

5.B.9.8

Translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor. **[SP 1.5]**

ESSENTIAL KNOWLEDGE

e. Energy conservation can be applied to combinations of resistors and capacitors in series and parallel circuits.

Relevant Equations:

$$\sum \Delta V = 0$$

$$\Delta V = IR$$

$$P = I\Delta V$$

BOUNDARY STATEMENT:

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

SCIENCE PRACTICES

Modeling

1.4

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 4.5

Kirchhoff's Junction Rule and the Conservation of Electric Charge

Required Course Content

ENDURING UNDERSTANDING

5.C

The electric charge of a system is conserved.

LEARNING OBJECTIVE

5.C.3.4

Predict or describe current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule, and explain the relationship of the rule to the law of charge conservation. **[SP 6.4, 7.2]**

5.C.3.5

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. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

5.C.3

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

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LEARNING OBJECTIVE

5.C.3.6

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. **[SP 1.4, 2.2]**

5.C.3.7

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. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

Relevant Equations:

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

$$R_s = \sum_i R_i$$

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

$$C_P = \sum_i C_i$$

$$\frac{1}{C_S} = \sum_i \frac{1}{C_i}$$

$$I = \frac{\Delta Q}{\Delta t}$$

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AP PHYSICS 2

UNIT 5

Magnetism and Electromagnetic Induction

10–12%
AP EXAM WEIGHTING

~13–15
CLASS PERIODS

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

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

Personal Progress Check 5

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

- Experimental Design
- Paragraph Argument Short Answer

UNIT 5

10–12% AP EXAM WEIGHTING | ~13–15 CLASS PERIODS

Magnetism and Electromagnetic Induction

BIG IDEA 2
Fields **FLD**
- How are magnetic fields both helpful and harmful?
- To what extent can you predict interactions in magnetic fields?

BIG IDEA 3
Force Interactions **INT**
- How can current-carrying wires exert forces on magnets and other current-carrying wires?
- What common characteristics are shared by the magnetic force and other forces?
- How can magnetic forces accelerate objects or systems?

BIG IDEA 4
Change **CHA**
- Why does a relationship exist between electrical currents and magnetic fields?

Unit Overview

In Units 3 and 4, students investigated electrostatic forces and fields and how free charges can be moved through electric fields to produce currents. In Unit 5, students will supplement that knowledge by exploring the relationships between moving charges and the magnetic forces and fields they generate. Students will discover the natural symmetry between electricity and magnetism and make connections between electromagnetic induction and the underlying principles behind most of the technology in modern society, including telephones, television, computers, and the Internet.

This unit will also build on the representations presented in the previous two units by introducing the magnetic field diagram to illustrate the effects of static and dynamic magnetic fields. Students must be able to relate the content and representations that they learned in previous physics courses. Recalling this content will help students overcome misconceptions, such as the existence of a centrifugal force. While students should master how to use specific equations to calculate unknown quantities, it is more important that they are able to derive new expressions from fundamental principles to help them make predictions in unfamiliar, applied contexts. In Unit 6, the idea of electromagnetic induction is used to relate to electromagnetic waves and their oscillating electric and magnetic fields. The concepts introduced in Unit 5 are greatly expanded upon in AP Physics C: Electricity and Magnetism.

Preparing for the AP Exam

When using physical laws and fundamental ideas of physics as justification for claims, students need to explain what stays the same as well as what happens when physical scenarios are modified. Students must be provided with opportunities to investigate changes in systems.

Students also need to be aware that when they are writing justifications for claims, simply referencing an equation, a law, or a physical principle is not enough. For example, stating that the force on a charged particle is to the right because of the “right-hand rule” is not sufficient to earn points on free-response questions. Students must clearly and concisely describe and use physics-based equations, laws, and principles as evidence to support their reasoning and/or to help justify their claims.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~13–15 CLASS PERIODS
1.A	**5.1 Magnetic Systems**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.* 7.1 The student can connect phenomena and models across spatial and temporal scales.	
1.E	**5.2 Magnetic Permeability and Magnetic Dipole Moment**	N/A	
2.A	**5.3 Vector and Scalar Fields**	N/A	
2.C	**5.4 Monopole and Dipole Fields**	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.* 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
2.D	**5.5 Magnetic Fields and Forces**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.	
3.C	**5.6 Magnetic Forces**	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships.	

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

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~13–15 CLASS PERIODS
3.A	**5.7 Forces Review**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.* **6.1** The student can justify claims with evidence. **6.2** The student can construct explanations of phenomena based on evidence produced through scientific practices. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	
4.E	**5.8 Magnetic Flux**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena.* **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	

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

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

UNIT 5 AVAILABLE RESOURCES:

- Classroom Resources > *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*
- Classroom Resources > **AP Physics Featured Question: Charged Particle in a Magnetic Field**

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	5.5	**Desktop Experiments** Give students a battery, three light bulbs, wire, and a cheap compass. Ask students to develop an experiment that shows evidence that magnetic field strength decreases with distance from the wire, and another experiment that shows evidence that magnetic field increases with current through the wire.
2	5.5	**Model Questions/Friends Without Pens** On AP Central, locate "**AP Physics 2 Featured Question: Charged Particle in a Magnetic Field**" and have students work through it in small groups.
3	5.6	**Discussion Groups** Students create right-hand-rule questions and then trade with other students and answer them. Examples: Give charge sign, velocity, and magnetic force directions and determine magnetic field direction; give velocity, force, and magnetic field directions and determine charge sign; give velocity and magnetic field directions and determine the direction of an electric field that would cause balanced forces.
4	5.6	**Graph and Switch** Student A comes up with two related values in a magnetism-focused situation (examples: "radius vs. speed of a circling charge in a magnetic field" or "flux through a spinning coil in a uniform magnetic field as a function of time"). Student B then must sketch the graph and justify either qualitatively or with symbolic equations.
5	5.8	**Discussion Groups** Buy a "Non-Contact Voltage Tester" and hold it up to a wire carrying AC current (it chirps). Hold it to a battery-powered circuit carrying DC current (no chirp). Have students discuss how this object could use magnetism and Faraday's Law principles to detect AC but not DC current.

Unit Planning Notes

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

TOPIC 5.1

Magnetic Systems

Required Course Content

ENDURING UNDERSTANDING

1.A

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

LEARNING OBJECTIVE

1.A.5.2

Construct representations of how the properties of a system are determined by the interactions of its constituent substructures.
[SP 1.1, 1.4, 7.1]

ESSENTIAL KNOWLEDGE

1.A.5

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

SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Making Connections

7.1

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

TOPIC 5.2

Magnetic Permeability and Magnetic Dipole Moment

Required Course Content

ENDURING UNDERSTANDING

1.E

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

LEARNING OBJECTIVE

[While there is no specific learning objective for it, EK 1.E.5 serves as a foundation for other learning objectives in the course.]

ESSENTIAL KNOWLEDGE

1.E.5

Matter has a property called *magnetic permeability*.

a. Free space has a constant value of the permeability that appears in physical relationships.

b. The permeability of matter has a value different from that of free space.

[While there is no specific learning objective for it, EK 1.E.6 serves as a foundation for other learning objectives in the course.]

1.E.6

Matter has a property called *magnetic dipole moment*.

a. Magnetic dipole moment is a fundamental source of magnetic behavior of matter and an intrinsic property of some fundamental particles, such as the electron.

b. Permanent magnetism or induced magnetism of matter is a system property resulting from the alignment of magnetic dipole moments within the system.

TOPIC 5.3

Vector and Scalar Fields

Required Course Content

ENDURING UNDERSTANDING

2.A

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
[While there is no specific learning objective for it, EK 2.A.1 serves as a foundation for other learning objectives in the course.]	**2.A.1** A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector. a. Vector fields are represented by field vectors indicating direction and magnitude. b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition. c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.
[While there is no specific learning objective for it, EK 2.A.2 serves as a foundation for other learning objectives in the course.]	**2.A.2** A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential. a. Scalar fields are represented by field values. b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition. c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources.

SCIENCE PRACTICES

Mathematical Routines

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 5.4

Monopole and Dipole Fields

Required Course Content

ENDURING UNDERSTANDING

2.C

An electric field is caused by an object with electric charge.

LEARNING OBJECTIVE

2.C.4.1

Distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single-point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semiquantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field.
[SP 2.2, 6.4, 7.2]

ESSENTIAL KNOWLEDGE

2.C.4

The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

a. When an object is small compared with the distances involved in the problem, or when a larger object is being modeled as a large number of very small constituent particles, these can be modeled as charged objects of negligible size, or "point charges."

b. The expression for the electric field due to a point charge can be used to determine the electric field, either qualitatively or quantitatively, around a simple, highly symmetric distribution of point charges.

Relevant Equation:

$$|\vec{E}| = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

TOPIC 5.5

Magnetic Fields and Forces

Required Course Content

ENDURING UNDERSTANDING

2.D

A magnetic field is caused by a magnet or moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

LEARNING OBJECTIVE

2.D.1.1

Apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. **[SP 2.2]**

ESSENTIAL KNOWLEDGE

2.D.1

The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity, and the magnitude of the magnetic field. It also depends on the angle between the velocity and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, and 180° and qualitative for other angles.

Relevant Equations:

$$\vec{F}_M = q\vec{v} \times \vec{B}$$

$$\left|\vec{F}_M\right| = \left|q\vec{v}\right|\left|\sin\theta\right|\left|\vec{B}\right|$$

LEARNING OBJECTIVE

2.D.2.1

Create a verbal or visual representation of a magnetic field around a straight wire or a pair of parallel wires. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

2.D.2

The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.

a. The magnitude of the magnetic field is proportional to the magnitude of the current in a long, straight wire.

SCIENCE PRACTICES

Modeling

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

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

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

Mathematical Routines

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

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LEARNING OBJECTIVE

2.D.2.1

Create a verbal or visual representation of a magnetic field around a straight wire or a pair of parallel wires. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

b. The magnitude of the field varies inversely with distance from the wire, and the direction of the field can be determined by a right-hand rule.

c. Determining the force due to the magnetic field from a permanent magnet is a subset of determining the force due to the magnetic field of a current-carrying wire.

Relevant Equation:

$$B = \frac{\mu_0}{2\pi}\frac{I}{r}$$

2.D.3.1

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 Earth and iron filings surrounding a bar magnet. **[SP 1.2]**

2.D.3

A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or Earth, will tend to align with the magnetic field vector.

a. A simple magnetic dipole can be modeled by a current in a loop. The dipole is represented by a vector pointing through the loop in the direction of the field produced by the current as given by the right-hand rule.

b. A compass needle is a permanent magnetic dipole. Iron filings in a magnetic field become induced magnetic dipoles.

c. All magnets produce a magnetic field. Examples include the magnetic field pattern of a bar magnet as detected by iron filings or small compasses.

d. Earth has a magnetic field.

2.D.4.1

Qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material. **[SP 1.4]**

2.D.4

Ferromagnetic materials contain magnetic domains that are themselves magnets.

a. Magnetic domains can be aligned by external magnetic fields or can spontaneously align.

b. Each magnetic domain has its own internal magnetic field, so there is no beginning or end to the magnetic field—it is a continuous loop.

c. If a bar magnet is broken in half, both halves are magnetic dipoles in themselves; there is no magnetic north pole found isolated from a south pole.

TOPIC 5.6

Magnetic Forces

Required Course Content

ENDURING UNDERSTANDING

3.C

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

LEARNING OBJECTIVE

3.C.3.1

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. **[SP 1.4]**

3.C.3.2

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. **[SP 4.2, 5.1]**

ESSENTIAL KNOWLEDGE

3.C.3

A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.

a. Magnetic dipoles have "north" and "south" polarity.

b. The magnetic dipole moment of an object has the tail of the magnetic dipole moment vector at the south end of the object and the head of the vector at the north end of the object.

c. In the presence of an external magnetic field, the magnetic dipole moment vector will align with the external magnetic field.

d. The force exerted on a moving charged object is perpendicular to both the magnetic field and the velocity of the charge and is described by a right-hand rule.

Relevant Equations:

$$\vec{F}_M = I\vec{\ell} \times \vec{B}$$

$$\left|\vec{F}_M\right| = \left|I\vec{\ell}\right|\left|\sin\theta\right|\left|\vec{B}\right|$$

SCIENCE PRACTICES

Modeling

1.4

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

Experimental Methods

4.2

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

SCIENCE PRACTICES

Modeling

1.1
The student can create representations and models of natural or man-made phenomena and systems in the domain.

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

Argumentation

6.1
The student can justify claims with evidence.

6.2
The student can construct explanations of phenomena based on evidence produced through scientific practices.

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

Making Connections

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

TOPIC 5.7

Forces Review

Required Course Content

ENDURING UNDERSTANDING

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

LEARNING OBJECTIVE

3.A.2.1
Represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

3.A.2
Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.
b. Forces have magnitude and direction.

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

LEARNING OBJECTIVE

3.A.3.2
Construct an explanation for why an object cannot exert a force on itself. **[SP 6.1]**

3.A.3.3
Describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

3.A.3
A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.
b. Even though an object is at rest, there may be forces exerted on that object by other objects.
c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

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LEARNING OBJECTIVE

3.A.3.4

Make claims about the force on an object due to the presence of other objects with the same properties: mass, electric charge. **[SP 6.1, 6.4]**

ESSENTIAL KNOWLEDGE

Relevant Equation:

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

3.A.4.1

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

3.A.4.2

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

3.A.4.3

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

3.A.4

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

ENDURING UNDERSTANDING

3.B

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

LEARNING OBJECTIVE

3.B.1.3

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

ESSENTIAL KNOWLEDGE

3.B.1

If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Relevant Equation:

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

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LEARNING OBJECTIVE

3.B.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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

BOUNDARY STATEMENT:

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

LEARNING OBJECTIVE

3.B.2.1

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

ESSENTIAL KNOWLEDGE

3.B.2

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

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

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

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

ENDURING UNDERSTANDING

3.G

Certain types of forces are considered fundamental.

LEARNING OBJECTIVE

3.G.2.1

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. **[SP 7.1]**

ESSENTIAL KNOWLEDGE

3.G.2

Electromagnetic forces are exerted at all scales and can dominate at the human scale.

Relevant Equation:

$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\frac{\left|q_1 q_2\right|}{r^2}$$

TOPIC 5.8

Magnetic Flux

Required Course Content

ENDURING UNDERSTANDING

4.E

The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

LEARNING OBJECTIVE

4.E.1.1

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. **[SP 1.1, 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

4.E.1

The magnetic properties of some materials can be affected by magnetic fields in the system. Students should focus on the underlying concepts and not the use of the vocabulary.

a. Ferromagnetic materials can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles.

b. Paramagnetic materials interact weakly with an external magnetic field, in that the magnetic dipole moments of the material do not remain aligned after the external field is removed.

c. All materials have the property of diamagnetism, in that their electronic structure creates a (usually) weak alignment of the dipole moments of the material opposite the external magnetic field.

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SCIENCE PRACTICES

Modeling

1.1

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

1.4

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

Mathematical Routines

2.2

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

Argumentation

6.4

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

LEARNING OBJECTIVE

4.E.2.1

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. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

4.E.2

Changing magnetic flux induces an electric field that can establish an induced emf in a system.

a. Changing magnetic flux induces an emf in a system, with the magnitude of the induced emf equal to the rate of change in magnetic flux.

b. When the area of the surface being considered is constant, the induced emf is the area multiplied by the rate of change in the component of the magnetic field perpendicular to the surface.

c. When the magnetic field is constant, the induced emf is the magnetic field multiplied by the rate of change in area perpendicular to the magnetic field.

d. The conservation of energy determines the direction of the induced emf relative to the change in the magnetic flux.

Relevant Equations:

$$\Phi_B = \vec{B} \cdot \vec{A}$$

$$\Phi_B = \left|\vec{B}\right| \cos\theta \left|\vec{A}\right|$$

$$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$$

$$\varepsilon = B\ell v$$

AP PHYSICS 2

UNIT 6

Geometric and Physical Optics

12–14%
AP EXAM WEIGHTING

~15–18
CLASS PERIODS

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

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

Personal Progress Check 6

Multiple-choice: ~50 questions
Free-response: 2 questions

- Experimental Design
- Short Answer

UNIT 6

12–14% AP EXAM WEIGHTING | **~15–18** CLASS PERIODS

Geometric and Physical Optics

BIG IDEA 6
***Waves* WAV**

- Can we really make something invisible?
- How do household items make use of various wave properties?
- How can an object not be where it appears to be?
- How can electromagnetic waves be modeled?

Unit Overview

Although the nature of oscillating electric and magnetic fields, explored in Unit 5, sets the foundation for this unit's fundamental topic—electromagnetic waves, or light—Unit 6 demonstrates another distinct shift in both content and the models/representations used to analyze physical scenarios. In this unit, students will be introduced to the different ways of thinking about and modeling light, but the ideas and models used in this unit are fundamentally different from those used earlier in the course, as well as those used in previous physics courses.

This unit presents new challenges for teachers and students, because it introduces many new types of representations, including ray, wave front, and interference diagrams. It is essential that students understand how to *create and use* these diagrams to help answer questions and to use as evidence for claims. A more complete understanding of the different ways of thinking about and modeling light will help students analyze data more effectively; they can then apply this science practice to design a process of data analysis that will help them determine if the experimental design needs to be altered to produce the needed data to justify claims.

In Unit 7, students will continue to explore the behavior of light as an electromagnetic wave and examine additional ways of thinking about and modeling light.

Preparing for the AP Exam

The last five questions of the multiple-choice section of the AP Physics 2 Exam are multiple-correct questions. Students must select both correct answers and none of the incorrect answers to get credit for these questions. These questions can easily intimidate students if they have not had the opportunity to practice answering them throughout the year. A common strategy to tackle multiple-correct questions is to slow down and read the entire prompt. Students who jump right to the answers will be frustrated by choices that are factually correct but do not answer the question.

Remember: Students will only get credit if they choose *both* correct answers.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~15–18 CLASS PERIODS
6.A	**6.1 Waves**	1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain. 5.1 The student can analyze data to identify patterns or relationships. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
6.F	**6.2 Electromagnetic Waves**	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
6.B	**6.3 Periodic Waves**	1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~15–18 CLASS PERIODS
6.E	**6.4 Refraction, Reflection, and Absorption**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.2** The student can refine observations and measurements based on data analysis. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
	6.5 Images from Lenses and Mirrors	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **3.2** The student can refine scientific questions. **4.1** The student can justify the selection of the kind of data needed to answer a particular scientific question. **5.1** The student can analyze data to identify patterns or relationships. **5.2** The student can refine observations and measurements based on data analysis. **5.3** The student can evaluate the evidence provided by data sets in relation to a particular scientific question.	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~15–18 CLASS PERIODS
6.E	**6.6 Interference and Diffraction**	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
	Go to **AP Classroom** to assign the **Personal Progress Check** for Unit 6. Review the results in class to identify and address any student misunderstandings.		

UNIT 6 AVAILABLE RESOURCES:

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

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	6.4	**Desktop Experiment** Put orange Jell-O in a rectangular-prism-shaped container made of thin material. Give students a red laser, a protractor, and paper, and have them determine the index of refraction of orange Jell-O without touching the Jell-O directly.
2	6.5	**Desktop Experiment** Buy a cheap magnifying glass and a cheap light source for each group. Then take several pairs of object and image distance data, and graph them to find the focal length.
3	6.5	**Working Backward** Student A describes a situation with a lens/mirror where the image is real/virtual and larger/smaller than the object (so, eight possibilities). Student B determines whether the instrument is converging/diverging and where to put the object (closer than f, between f and 2f, or beyond 2f) to satisfy Student A's parameters and draws a ray diagram to support the answer.
4	6.5	**Quickwrite** The human eye, without optical deficiencies, will focus the image of a distant object on the retina. If the object is closer, the eye muscles make the eye lens thicker so that the image still focuses on the retina. The closer the object, the more the eye muscles force the eye lens to be thicker. Explain what is happening in terms of s_o, s_i, and f, and use equations to support relationships indicated.
5	6.6	**Desktop Experiment** Give groups a red/green/purple laser and a cheap diffraction grating. Give wavelength, and ask for diffraction slit spacing (or vice versa) experimentally. This can also be performed by finding the width of a human hair or the width of data tracks on a CD or DVD.

Unit Planning Notes

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

SCIENCE PRACTICES

Modeling

1.2
The student can describe representations and models of natural or man-made phenomena and systems in the domain.

Data Analysis

5.1
The student can analyze data to identify patterns or relationships.

Argumentation

6.2
The student can construct explanations of phenomena based on evidence produced through scientific practices.

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

Making Connections

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

TOPIC 6.1
Waves

Required Course Content

ENDURING UNDERSTANDING

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

LEARNING OBJECTIVE

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

6.A.1.3
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. **[SP 5.1, 6.2]**

ESSENTIAL KNOWLEDGE

6.A.1
Waves can propagate via different oscillation modes, such as transverse and longitudinal.

a. Mechanical waves can be either transverse or longitudinal. Examples should include waves on a stretched string and sound waves.
b. Electromagnetic waves are transverse waves.
c. Transverse waves may be polarized.

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

LEARNING OBJECTIVE

6.A.2.2
Contrast mechanical and electromagnetic waves in terms of the need for a medium in wave propagation. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.A.2
For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples include light traveling through a vacuum and sound not traveling through a vacuum.

TOPIC 6.2

Electromagnetic Waves

Required Course Content

ENDURING UNDERSTANDING

6.F

Electromagnetic radiation can be modeled as waves or as fundamental particles.

LEARNING OBJECTIVE

6.F.1.1

Make qualitative comparisons of the wavelengths of types of electromagnetic radiation. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.F.1

Types of electromagnetic radiation are characterized by their wavelengths, and certain ranges of wavelength have been given specific names. These include (in order of increasing wavelength spanning a range from picometers to kilometers) gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.

Relevant Equation:

$$\lambda = \frac{v}{f}$$

LEARNING OBJECTIVE

6.F.2.1

Describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present. **[SP 1.1]**

ESSENTIAL KNOWLEDGE

6.F.2

Electromagnetic waves can transmit energy through a medium and through a vacuum.

a. Electromagnetic waves are transverse waves composed of mutually perpendicular electric and magnetic fields that can propagate through a vacuum.

b. The planes of these transverse waves are both perpendicular to the direction of propagation.

SCIENCE PRACTICES

Modeling

1.1

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

Argumentation

6.4

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

Making Connections

7.2

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

SCIENCE PRACTICE

Modeling

1.5

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

TOPIC 6.3
Periodic Waves

Required Course Content

ENDURING UNDERSTANDING

6.B

A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.

LEARNING OBJECTIVE

6.B.3.1

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. **[SP 1.5]**

ESSENTIAL KNOWLEDGE

6.B.3

A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave.

Relevant Equation:

$$x = A\cos(\omega t) = A\cos(2\pi ft)$$

TOPIC 6.4

Refraction, Reflection, and Absorption

Required Course Content

ENDURING UNDERSTANDING

6.E

The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.

LEARNING OBJECTIVE

6.E.1.1

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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.E.1

When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed (qualitative understanding only).

LEARNING OBJECTIVE

6.E.2.1

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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.E.2

When light hits a smooth reflecting surface at an angle, it reflects at the same angle on the other side of the line perpendicular to the surface (specular reflection); this law of reflection accounts for the size and location of images seen in mirrors.

Relevant Equations:

$$\frac{1}{s_i}+\frac{1}{s_o}=\frac{1}{f}$$

$$|M|=\left|\frac{h_i}{h_o}\right|=\left|\frac{s_i}{s_o}\right|$$

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SCIENCE PRACTICES

Modeling

1.1
The student can create representations and models of natural or man-made phenomena and systems in the domain.

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

Experimental Methods

4.1
The student can justify the selection of the kind of data needed to answer a particular scientific question.

Data Analysis

5.1
The student can analyze data to identify patterns or relationships.

5.2
The student can refine observations and measurements based on data analysis.

5.3
The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

Argumentation

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

Making Connections

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

LEARNING OBJECTIVE

6.E.3.1

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. **[SP 1.1, 1.4]**

6.E.3.2

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). **[SP 4.1, 5.1, 5.2, 5.3]**

6.E.3.3

Make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.E.3

When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called *refraction*.

a. Snell's law relates the angles of incidence and refraction to the indices of refraction, with the ratio of the indices of refraction inversely proportional to the ratio of the speeds of propagation in the two media.

b. When light travels from an optically slower substance into an optically faster substance, it bends away from the perpendicular.

c. At the critical angle, the light bends far enough away from the perpendicular that it skims the surface of the material.

d. Beyond the critical angle, all of the light is internally reflected.

Relevant Equations:

$$\mathrm{n} = \frac{c}{v}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

TOPIC 6.5

Images from Lenses and Mirrors

Required Course Content

ENDURING UNDERSTANDING

6.E

The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.

LEARNING OBJECTIVE

6.E.4.1

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. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**

6.E.4.2

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. **[SP 1.4, 2.2]**

ESSENTIAL KNOWLEDGE

6.E.4

The reflection of light from surfaces can be used to form images.

a. Ray diagrams are very useful for showing how and where images of objects are formed for different mirrors and how this depends on the placement of the object. Examples include concave and convex mirrors.

b. Ray diagrams are also useful for determining the size of the resulting image compared with the size of the object.

c. Plane mirrors, convex spherical mirrors, and concave spherical mirrors are part of this course. The construction of these ray diagrams and comparison with direct experiences are necessary.

Relevant Equations:

$$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$$

$$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$$

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SCIENCE PRACTICES

Modeling

1.4

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

Mathematical Routines

2.2

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

Scientific Questioning

3.2

The student can refine scientific questions.

Experimental Methods

4.1

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

Data Analysis

5.1

The student can analyze data to identify patterns or relationships.

5.2

The student can refine observations and measurements based on data analysis.

5.3

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

LEARNING OBJECTIVE

6.E.5.1

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. **[SP 1.4, 2.2]**

6.E.5.2

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. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**

ESSENTIAL KNOWLEDGE

6.E.5

The refraction of light as it travels from one transparent medium to another can be used to form images.

a. Ray diagrams are used to determine the relative size of object and image, the location of object and image relative to the lens, the focal length, and the real or virtual nature of the image. Examples include converging and diverging lenses.

Relevant Equations:

$$\frac{1}{s_i}+\frac{1}{s_o}=\frac{1}{f}$$

$$|M|=\left|\frac{h_i}{h_o}\right|=\left|\frac{s_i}{s_o}\right|$$

TOPIC 6.6

Interference and Diffraction

Required Course Content

ENDURING UNDERSTANDING

6.C

Only waves exhibit interference and diffraction.

LEARNING OBJECTIVE

6.C.1.1

Make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]**

6.C.1.2

Construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

6.C.1

When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called *superposition*. Examples include interference resulting from diffraction through slits as well as thin-film interference.

LEARNING OBJECTIVE

6.C.2.1

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. **[SP 1.4, 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.C.2

When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.

Relevant Equations:

$$\Delta L = m\lambda$$

$$d \sin\theta = m\lambda$$

continued on next page

SCIENCE PRACTICES

Modeling

1.4

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

Argumentation

6.4

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

Making Connections

7.2

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

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
6.C.3.1 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 compared with the wavelength of the waves. **[SP 1.4, 6.4]**	**6.C.3** When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples include monochromatic double-slit interference.
6.C.4.1 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. **[SP 6.4, 7.2]**	**6.C.4** When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples include hearing around corners but not seeing around them, and water waves bending around obstacles.

AP PHYSICS 2

UNIT 7

Quantum, Atomic, and Nuclear Physics

10–12%
AP EXAM WEIGHTING

~13–15
CLASS PERIODS

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

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

Personal Progress Check 7

Multiple-choice: ~55 questions
Free-response: 2 questions

- Quantitative/Qualitative Translation
- Paragraph Argument Short Answer

UNIT 7

10–12% AP EXAM WEIGHTING | **~13–15** CLASS PERIODS

Quantum, Atomic, and Nuclear Physics

BIG IDEA 5

***Conservation* CON**

- How can nucleon numbers be conserved when there are so many ways for an atom to split and decay?

BIG IDEA 6

***Waves* WAV**

- How does the photoelectric effect support the idea of wave/particle duality?

BIG IDEA 7

***Probability* PRO**

- How does probability govern the behavior of systems?
- How can we best measure/describe/represent what we cannot directly see?

Unit Overview

Unit 7 lays the groundwork for the study of modern physics by resolving the conflicts and questions that were left unanswered by Newtonian mechanics. While new models and representations are introduced in Unit 7 (such as the electron level diagram), students will be able to make connections between the content of this unit and the fundamental principles of physics, principles of conservation, and models and representations used earlier in the course. These connections will help students make predictions about a variety of phenomena—including the rate of radioactive decay or the type of nuclear reaction—in addition to making and justifying claims with evidence about such phenomena. Students must be able to connect what they learn in this unit with the fundamental principles of physics. This is more important than being able to calculate numerical equations. For example, students will be asked to connect the photoelectric experiment to the ideas of energy conservation and the particle model of light.

Unit 7 represents only the first step into the realm of modern physics. Students who continue their study of physics in college will have the opportunity to learn about the developments in physics since the dawn of the 20th century.

Preparing for the AP Exam

Credit for answers in the free-response section depends on the quality of the solutions and the explanations given. Partial solutions may receive only partial credit, so students should always show all their work, starting with the fundamental principles of physics. Answers must be justified through some verbal or mathematical analysis, or full credit will not be given. In general, it is a good practice to have students annotate their calculations and mathematical derivations, as well as laboratory setups, etc., for clarity.

To achieve full credit, students must draw from the fundamental principles of physics to answer the question clearly and concisely.

UNIT AT A GLANCE

Enduring Understanding	Topic	Science Practices	Class Periods ~13–15 CLASS PERIODS
1.A, 3.G	**7.1** Systems and Fundamental Forces	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 7.1 The student can connect phenomena and models across spatial and temporal scales. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.C, 5.D, 5.G	**7.2** Radioactive Decay	2.1 The student can justify the selection of a mathematical routine to solve problems. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
5.B	**7.3** Energy in Modern Physics (Energy in Radioactive Decay and $E = mc^2$)	1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.1 The student can justify the selection of a mathematical routine to solve problems. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~13–15 CLASS PERIODS
1.C, 4.C	**7.4 Mass–Energy Equivalence**	**2.2** The student can apply mathematical routines to quantities that describe natural phenomena. **2.3** The student can estimate numerically quantities that describe natural phenomena. **6.3** The student can articulate the reasons that scientific explanations and theories are refined or replaced. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
1.D, 6.C, 6.G	**7.5 Properties of Waves and Particles**	**1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **6.1** The student can justify claims with evidence. **6.3** The student can articulate the reasons that scientific explanations and theories are refined or replaced. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.1** The student can connect phenomena and models across spatial and temporal scales. **7.2** The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.	
6.F	**7.6 Photoelectric Effect**	**6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models. **7.1** The student can connect phenomena and models across spatial and temporal scales.	

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UNIT AT A GLANCE *(cont'd)*

Enduring Understanding	Topic	Science Practices	Class Periods ~13–15 CLASS PERIODS
7.C	**7.7 Wave Functions and Probability**	**1.1** The student can create representations and models of natural or man-made phenomena and systems in the domain. **1.2** The student can describe representations and models of natural or man-made phenomena and systems in the domain. **1.4** The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. **6.4** The student can make claims and predictions about natural phenomena based on scientific theories and models.	

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

UNIT 7 AVAILABLE RESOURCES:

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

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate instructional approaches into the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 185 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	7.2	**Desktop Experiment** Get 200 dice and put them in a sealed box. On each "turn," shake the box so that all dice are rolled and then open the box and remove all dice that land on 1. Record the remaining number of dice. Repeat (without putting the dice back in the box) until all dice are removed. Graph "dice versus turns," and from it determine the "half-life" of the dice (about 3.8 turns).
2	7.4	**Identify Subtasks** The goal is to determine how many tons of uranium must be mined to meet the electrical energy needs of the United States through only nuclear power. Students identify subtasks in terms of "information we need to research to find" and "calculations we need to make," list the tasks in the order they must be done, and then do them and report their findings.
3	7.5	**Concept-Oriented Demonstration** Show students a hydrogen discharge tube, and give them a diffraction grating, so they can see the red, cyan, and purple. Tell students that the energy levels of hydrogen are $E_n = (-13.6\text{ eV})/n^2$. Have students estimate the wavelengths of the three colors (based on research) and determine which energy level transitions they are seeing (red 3 to 2, cyan 4 to 2, purple 5 to 2).
4	7.6	**Desktop Experiment** Charge a capacitor (at least 10 μF) to 4.5 V or more, and then discharge it across an LED. Have students record the voltage on the LED and determine its light frequency from the LED's color or wavelength (many LEDs come with data sheets with their wavelength listed). Do this for red, orange, yellow, green, and blue LEDs. Graph voltage versus frequency, and the slope will be Planck's constant in eV • s.

Unit Planning Notes

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

SCIENCE PRACTICES

Modeling

1.1

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

Making Connections

7.1

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

7.2

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

TOPIC 7.1

Systems and Fundamental Forces

Required Course Content

ENDURING UNDERSTANDING

1.A

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

LEARNING OBJECTIVE

1.A.2.1

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. **[SP 1.1, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.2

Fundamental particles have no internal structure.

a. Electrons, neutrinos, photons, and quarks are examples of fundamental particles.

b. Neutrons and protons are composed of quarks.

c. All quarks have electric charges, which are fractions of the elementary charge of the electron. Students will not be expected to know specifics of quark charge or quark composition of nucleons.

[While there is no specific learning objective for it, EK 1.A.3 serves as a foundation for other learning objectives in the course.]

1.A.3

Nuclei have internal structures that determine their properties.

a. The number of protons identifies the element.

b. The number of neutrons together with the number of protons identifies the isotope.

c. There are different types of radioactive emissions from the nucleus.

d. The rate of decay of any radioactive isotope is specified by its half-life.

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LEARNING OBJECTIVE

1.A.4.1

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. **[SP 1.1, 7.1]**

ESSENTIAL KNOWLEDGE

1.A.4

Atoms have internal structures that determine their properties.

a. The number of protons in the nucleus determines the number of electrons in a neutral atom.

b. The number and arrangements of electrons cause elements to have different properties.

c. The Bohr model based on classical foundations was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states (represented in energy diagrams by discrete energy levels).

d. Discrete energy-state transitions lead to spectra.

ENDURING UNDERSTANDING

3.G

Certain types of forces are considered fundamental.

LEARNING OBJECTIVE

3.G.3.1

Identify the strong force as the force that is responsible for holding the nucleus together. **[SP 7.2]**

ESSENTIAL KNOWLEDGE

3.G.3

The strong force is exerted at nuclear scales and dominates the interactions of nucleons.

SCIENCE PRACTICES

Mathematical Routines

2.1

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

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 7.2

Radioactive Decay

Required Course Content

ENDURING UNDERSTANDING

5.C

The electric charge of a system is conserved.

LEARNING OBJECTIVE

5.C.1.1

Analyze electric charge conservation for nuclear and elementary particle reactions, and make predictions related to such reactions based on conservation of charge. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

5.C.1

Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples include equations representing nuclear decay.

ENDURING UNDERSTANDING

5.D

The linear momentum of a system is conserved.

LEARNING OBJECTIVE

5.D.1.6

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. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

5.D.1

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

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

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

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LEARNING OBJECTIVE

5.D.1.7

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

ESSENTIAL KNOWLEDGE

Relevant Equations:

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

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

BOUNDARY STATEMENT:

Physics 1 includes a quantitative and qualitative treatment of conservation of momentum in one dimension and a semiquantitative treatment of conservation of momentum in two dimensions. Test items involving solution of simultaneous equations are not included on either the Physics 1 or Physics 2 Exams, but items testing whether students can set up the equations properly and can reason about how changing a given mass, speed, or angle would affect other quantities are included. Physics 1 includes only conceptual understanding of center-of-mass motion of a system without the need for calculation of center of mass. Physics 2 includes full qualitative and quantitative two-dimensional treatment of conservation of momentum and velocity of the center of mass of the system. Physics 1 addresses Enduring Understanding 5.D with topics in the context of mechanical systems. Physics 2 does so with content that involves interactions arising in the context of topics such as nuclear decay, other nuclear reactions, and interactions of subatomic particles with each other and with photons.

5.D.2.5

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

5.D.2

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

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

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

Relevant Equations:

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

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

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.D.2.6 Apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. **[SP 6.4, 7.2]**	**5.D.2** In a collision between objects, linear momentum is conserved. In an inelastic collision, kinetic energy is not the same before and after the collision. a. In a closed system, the linear momentum is constant throughout the collision. b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision. *Relevant Equations:* $\vec{p} = m\vec{v}$ $K = \frac{1}{2}mv^2$
5.D.3.2 Make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system. **[SP 6.4]** **5.D.3.3** Make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system. **[SP 6.4]**	**5.D.3** The velocity of the center of mass of the system cannot be changed by an interaction within the system. [Physics 1 includes no calculations of centers of mass; the equation is not provided until Physics 2. However, without doing calculations, Physics 1 students are expected to be able to locate the center of mass of highly symmetric mass distributions, such as a uniform rod or cube of uniform density, or two spheres of equal mass.] a. The center of mass of a system depends on the masses and positions of the objects in the system. In an isolated system (a system with no external forces), the velocity of the center of mass does not change. b. When objects in a system collide, the velocity of the center of mass of the system will not change unless an external force is exerted on the system. *Relevant Equation:* $x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

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ENDURING UNDERSTANDING

5.G

Nucleon number is conserved.

LEARNING OBJECTIVE

5.G.1.1

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. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

5.G.1

The possible nuclear reactions are constrained by the law of conservation of nucleon number.

SCIENCE PRACTICES

Modeling

1.2

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

1.4

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

Mathematical Routines

2.1

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

2.2

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

Argumentation

6.4

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

Making Connections

7.2

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

TOPIC 7.3

Energy in Modern Physics (Energy in Radioactive Decay and $E = mc^2$)

Required Course Content

ENDURING UNDERSTANDING

5.B

The energy of a system is conserved.

LEARNING OBJECTIVE

5.B.2.1

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

ESSENTIAL KNOWLEDGE

5.B.2

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

Relevant Equation:

$\Delta U_E = q\Delta V$

BOUNDARY STATEMENT:

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

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LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.B.4.1 Describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]** **5.B.4.2** Calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**	**5.B.4** The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system. a. Since energy is constant in a closed system, changes in a system's potential energy can result in changes to the system's kinetic energy. b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.
5.B.5.4 Make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). **[SP 6.4, 7.2]**	**5.B.5** Energy can be transferred by an external force exerted on an object or system that moves the object or system through a distance; this energy transfer is called *work*. Energy transfer in mechanical or electrical systems may occur at different rates. *Power* is defined as the rate of energy transfer into, out of, or within a system. [A piston filled with gas getting compressed or expanded is treated in Physics 2 as a part of thermodynamics.] The work done on a system is defined as $W = -P\Delta V$ for constant pressure or an average pressure. *Relevant Equations:* $\Delta E = W = Fd\cos\theta$ $P = \frac{\Delta E}{\Delta t}$
5.B.8.1 Describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed. **[SP 1.2, 7.2]**	**5.B.8** Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei. a. Transitions between two given energy states of an atom correspond to the absorption or emission of a photon of a given frequency (and hence, a given wavelength). b. An emission spectrum can be used to determine the elements in a source of light.

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LEARNING OBJECTIVE

5.B.11.1

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. **[SP 2.2, 7.2]**

ESSENTIAL KNOWLEDGE

5.B.11

Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.

a. $E = mc^2$ can be used to calculate the mass equivalent for a given amount of energy transfer or an energy equivalent for a given amount of mass change (e.g., fission and fusion reactions).

TOPIC 7.4

Mass–Energy Equivalence

Required Course Content

ENDURING UNDERSTANDING

1.C

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

LEARNING OBJECTIVE

1.C.4.1

Articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass–energy. **[SP 6.3]**

ESSENTIAL KNOWLEDGE

1.C.4

In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.

ENDURING UNDERSTANDING

4.C

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

LEARNING OBJECTIVE

4.C.4.1

Apply mathematical routines to describe the relationship between mass and energy, and apply this concept across domains of scale. **[SP 2.2, 2.3, 7.2]**

ESSENTIAL KNOWLEDGE

4.C.4

Mass can be converted into energy, and energy can be converted into mass.

a. Mass and energy are interrelated by $E = mc^2$.
b. Significant amounts of energy can be released in nuclear processes.

SCIENCE PRACTICES

Mathematical Routines

2.2

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

2.3

The student can estimate numerically quantities that describe natural phenomena.

Argumentation

6.3

The student can articulate the reasons that scientific explanations and theories are refined or replaced.

Making Connections

7.2

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

SCIENCE PRACTICES

Modeling

1.4

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

Argumentation

6.1

The student can justify claims with evidence.

6.3

The student can articulate the reasons that scientific explanations and theories are refined or replaced.

6.4

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

Making Connections

7.1

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

7.2

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

TOPIC 7.5

Properties of Waves and Particles

Required Course Content

ENDURING UNDERSTANDING

1.D

Classical mechanics cannot describe all properties of objects.

LEARNING OBJECTIVE

1.D.1.1

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. **[SP 6.3]**

ESSENTIAL KNOWLEDGE

1.D.1

Objects classically thought of as particles can exhibit properties of waves.

a. This wavelike behavior of particles has been observed (e.g., in a double-slit experiment using elementary particles).

b. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.

Relevant Equation:

$$\lambda = \frac{h}{p}$$

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

1.D.2

Certain phenomena classically thought of as waves can exhibit properties of particles.

a. The classical models of waves do not describe the nature of a photon.

b. Momentum and energy of a photon can be related to its frequency and wavelength.

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LEARNING OBJECTIVE

1.D.3.1

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. [Students will be expected to recognize situations in which nonrelativistic classical physics breaks down and to explain how relativity addresses that breakdown, but students will not be expected to know in which of two reference frames a given series of events corresponds to a greater or lesser time interval, or a greater or lesser spatial distance; they will just need to know that observers in the two reference frames can "disagree" about some time and distance intervals.] **[SP 6.3, 7.1]**

ESSENTIAL KNOWLEDGE

1.D.3

Properties of space and time cannot always be treated as absolute.

a. Relativistic mass–energy equivalence is a reconceptualization of matter and energy as two manifestations of the same underlying entity, fully interconvertible, thereby rendering invalid the classically separate laws of conservation of mass and conservation of energy. Students will not be expected to know apparent mass or rest mass.

b. Measurements of length and time depend on speed (qualitative treatment only).

Relevant Equation:

$E = mc^2$

ENDURING UNDERSTANDING

6.C

Only waves exhibit interference and diffraction.

LEARNING OBJECTIVE

6.C.1.1

Make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]**

6.C.1.2

Construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

6.C.1

When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called *superposition*. Examples include interference resulting from diffraction through slits as well as thin-film interference.

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LEARNING OBJECTIVE

6.C.2.1

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. **[SP 1.4, 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.C.2

When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.

Relevant Equations:

$\Delta L = m\lambda$

$d \sin\theta = m\lambda$

LEARNING OBJECTIVE

6.C.3.1

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 compared with the wavelength of the waves. **[SP 1.4, 6.4]**

ESSENTIAL KNOWLEDGE

6.C.3

When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples include monochromatic double-slit interference.

LEARNING OBJECTIVE

6.C.4.1

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. **[SP 6.4, 7.2]**

ESSENTIAL KNOWLEDGE

6.C.4

When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples include hearing around corners but not seeing around them, and water waves bending around obstacles.

continued on next page

ENDURING UNDERSTANDING

6.G

All matter can be modeled as waves or particles.

LEARNING OBJECTIVE

6.G.1.1

Make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate. **[SP 6.4, 7.1]**

ESSENTIAL KNOWLEDGE

6.G.1

Under certain regimes of energy or distance, matter can be modeled as a classical particle.

LEARNING OBJECTIVE

6.G.2.1

Articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal. **[SP 6.1]**

6.G.2.2

Predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima) based on the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (De Broglie wavelength need not be given, so students may need to obtain it.) **[SP 6.4]**

ESSENTIAL KNOWLEDGE

6.G.2

Under certain regimes of energy or distance, matter can be modeled as a wave. The behavior in these regimes is described by quantum mechanics.

a. A wave model of matter is quantified by the de Broglie wavelength that increases as the momentum of the particle decreases.

b. The wave property of matter was experimentally confirmed by the diffraction of electrons in the experiments of Clinton Joseph Davisson, Lester Germer, and George Paget Thomson.

Relevant Equation:

$$\lambda = \frac{h}{p}$$

SCIENCE PRACTICES

Argumentation

6.4

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

Making Connections

7.1

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

TOPIC 7.6

Photoelectric Effect

Required Course Content

ENDURING UNDERSTANDING

6.F

Electromagnetic radiation can be modeled as waves or as fundamental particles.

LEARNING OBJECTIVE

6.F.3.1

Support the photon model of radiant energy with evidence provided by the photoelectric effect. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

6.F.3

Photons are individual energy packets of electromagnetic waves, with $E = hf$, where h is Planck's constant, and f is the frequency of the associated light wave.

a. In the quantum model of electromagnetic radiation, the energy is emitted or absorbed in discrete energy packets called *photons*. Discrete spectral lines should be included as an example.

b. For the short-wavelength portion of the electromagnetic spectrum, the energy per photon can be observed by direct measurement when electron emissions from matter result from the absorption of radiant energy.

c. Evidence for discrete energy packets is provided by a frequency threshold for electron emission. Above the threshold, emission increases with the frequency and not the intensity of absorbed radiation. The photoelectric effect should be included as an example.

Relevant Equation:

$K_{max} = hf - \phi$

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LEARNING OBJECTIVE

6.F.4.1

Select a model of radiant energy that is appropriate to the spatial or temporal scale of an interaction with matter. **[SP 6.4, 7.1]**

ESSENTIAL KNOWLEDGE

6.F.4

The nature of light requires that different models of light are most appropriate at different scales.

a. The particle-like properties of electromagnetic radiation are more readily observed when the energy transported during the time of the measurement is comparable to E_{photon}.

b. The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects with which it interacts is comparable to or larger than the wavelength of the radiation.

SCIENCE PRACTICES

Modeling

1.1
The student can create representations and models of natural or man-made phenomena and systems in the domain.

1.2
The student can describe representations and models of natural or man-made phenomena and systems in the domain.

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

Argumentation

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

TOPIC 7.7

Wave Functions and Probability

Required Course Content

ENDURING UNDERSTANDING

7.C
At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.

LEARNING OBJECTIVE

7.C.1.1
Use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

7.C.1
The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region (qualitative treatment only, using graphical analysis).

LEARNING OBJECTIVE

7.C.2.1
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. **[SP 1.4]**

ESSENTIAL KNOWLEDGE

7.C.2
The allowed states for an electron in an atom can be calculated from the wave model of an electron.

a. The allowed electron energy states of an atom are modeled as standing waves. Transitions between these levels, due to emission or absorption of photons, are observable as discrete spectral lines.

b. The de Broglie wavelength of an electron can be calculated from its momentum, and a wave representation can be used to model discrete transitions between energy states as transitions between standing waves.

Relevant Equation:

$$\lambda = \frac{h}{p}$$

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LEARNING OBJECTIVE

7.C.3.1

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. **[SP 6.4]**

ESSENTIAL KNOWLEDGE

7.C.3

The spontaneous radioactive decay of an individual nucleus is described by probability.

a. In radioactive decay processes, we cannot predict when any one nucleus will undergo a change; we can only predict what happens on the average to a large number of identical nuclei.

b. In radioactive decay, mass and energy are interrelated, and energy is released in nuclear processes as kinetic energy of the products or as electromagnetic energy.

c. The time for half of a given number of radioactive nuclei to decay is called the *half-life*.

d. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years.

7.C.4.1

Construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that, since the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.] **[SP 1.1, 1.2]**

7.C.4

Photon emission and absorption processes are described by probability.

a. An atom in a given energy state may absorb a photon of the right energy and move to a higher energy state (stimulated absorption).

b. An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon (spontaneous emission).

c. Spontaneous transitions to higher energy states have a very low probability but can be stimulated to occur. Spontaneous transitions to lower energy states are highly probable.

d. When a photon of the right energy interacts with an atom in an excited energy state, it may stimulate the atom to make a transition to a lower energy state with the emission of a photon (stimulated emission). In this case, both photons have the same energy and are in phase and moving in the same direction.

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AP PHYSICS 2

Laboratory Investigations

Lab Experiments

Although laboratory work has often been separated from classroom work, research shows that experience and experimentation are often more instructionally effective. Familiarity with concrete evidence leads to a deeper understanding and gives students a sense of ownership of the knowledge they have constructed.

AP Physics courses require students to engage with data in a variety of ways. The analysis, interpretation, and application of quantitative information are vital skills for students. Scientific inquiry experiences in AP Physics 2 should be designed and implemented with increasing student involvement to help enhance inquiry learning and develop critical thinking and problem-solving skills. Typically, the level of investigations in an AP Physics 2 classroom should focus primarily on the continuum between guided and open inquiry. However, depending on students' familiarity with the topic, a given laboratory experience might incorporate a sequence involving all four levels of inquiry (confirmation, structured inquiry, guided inquiry, and open inquiry).

Lab Manuals and Lab Notebooks

College Board publishes ***AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual*** to support the guided inquiry lab requirement for the course. It includes labs that teachers can choose from to satisfy the guided inquiry lab component for the course. Many publishers and science classroom material distributors offer affordable lab manuals with outlined experiments and activities as well as lab notebooks for recording lab data and observations. Students can use any type of notebook to fulfill the lab notebook requirement, even an online document. Consider the needs of the classroom when deciding what type of lab notebook to use.

Lab Materials

A wide range of equipment may be used in the physics laboratory, from generic lab items such as meter sticks, rubber balls, springs, string, metal spheres, calibrated mass sets, beakers, glass and cardboard tubes, electronic balances, stopwatches, clamps, and ring stands to items more specific to physics, such as tracks, carts, light bulbs, resistors, magnets, and batteries. Successful guided inquiry student work can be accomplished both with simple, inexpensive materials and with more sophisticated physics equipment, such air tracks, force sensors, and oscilloscopes. Remember that the AP lab should provide an experience for students equivalent to that of a college laboratory, so teachers should make every effort to provide a range of experiences—from experiments students contrive from plumbing pipe, string, and duct tape to experiments in which students gather and analyze data using calculators or computer-interfaced equipment.

There are avenues that teachers can explore as a means of getting access to more expensive equipment, such as computers and probes. Probes can often be rented for short periods of time from instrument suppliers. Alternatively, local colleges or universities may allow high school students to complete a lab as a field trip on their campus, or they may allow teachers to borrow their equipment. They may even donate their old equipment. Some schools have partnerships with local businesses that can help with laboratory equipment and materials. Teachers can also utilize online donation sites, such as Donors Choose and Adopt-A-Classroom.

Lab Time

For this AP Physics 2 to be comparable to a college physics course, it is critical that teachers make laboratory work an important part their curriculum. An analysis of data from AP Physics 2 examinees regarding the length of time they spent per week in the laboratory shows that increased laboratory time correlates with higher AP scores. Flexible or modular scheduling must be implemented to meet the time requirements identified in the course outline. At minimum, one double period a week is needed. Furthermore, it is important that the AP Physics 2 laboratory program be adapted to local conditions and funding, as it aims to offer the students a well-rounded experience with experimental physics. Adequate laboratory facilities should be provided so that each student has a work space where equipment and materials can be left overnight if necessary. Sufficient laboratory equipment for the anticipated enrollment and appropriate instruments should be provided. Students in AP Physics 2 should have access to computers with software appropriate for processing laboratory data and writing reports.

How to Set Up a Lab Program

Physics is not just a subject. Rather, it is a way of approaching scientific discovery that requires personal observation and physical experimentation. Being successful in this endeavor requires students to synthesize and use a broad spectrum of knowledge and skills, including mathematical, computational, experimental, and practical skills, and to develop habits of mind that might be characterized as thinking like a physicist. Student-directed, inquiry-based lab experience supports the AP Physics 2 course and AP Course Audit curricular requirements. It provides opportunities for students to design experiments, collect data, apply mathematical routines and methods, and refine testable explanations and predictions. Teachers are expected to devote a minimum of 25% of instructional time to lab investigations to support the learning objectives in the course framework.

The AP Physics 2 Exam directly assesses the learning objectives of the course framework, which means the inclusion of appropriate experiments aligned with those learning objectives is important for student success. Teachers should select experiments that provide students with the broadest laboratory experience possible.

We encourage teachers to be creative in designing their lab program while ensuring students explore and develop understandings of these core techniques. After completion, students should be able to describe how to construct knowledge, model (create an abstract representation of a real system), design experiments, analyze visual data, and communicate physics. Students should also develop an understanding of how changes in the design of the experiments would impact the outcome of their results. Many questions on the AP Exam are written in an experimental context, so these skills will prove invaluable for both concept comprehension and exam performance.

Getting Students Started

There are no prescriptive "steps" to the iterative process of inquiry-based investigations. However, there are some common characteristics of inquiry that will support students in designing their investigations. Often, this simply begins with using the learning objectives to craft a question for students to investigate. Teachers may choose to give students a list of materials they are allowed to use in their design, or require that students request the equipment they feel they need to investigate the question. To use learning objectives when crafting questions, consider the following points:

- Select learning objectives from the course framework that relate to the subject under study and may set forth specific tasks, in the form of "Design an experiment to . . . ."
- Rephrase or refine the learning objectives that align to the unit of study to create an inquiry-based investigation for students.

Students should be given latitude to make design modifications or ask for additional equipment appropriate for their design. It is also helpful for individual groups to report out to the class on their basic design to elicit feedback on feasibility. Guided student groups can proceed through the experiment, with the teacher allowing them the freedom to make mistakes—as long as those mistakes don't endanger students or equipment or lead the groups too far off task. Students should have many opportunities for post-lab reporting so that groups can understand the successes and challenges of individual lab designs.

Communication, Group Collaboration, and the Laboratory Record

Laboratory work is an excellent means through which students can develop and practice communication skills. Success in subsequent work in physics depends heavily on an ability to communicate about observations, ideas, and conclusions. Students must learn to recognize that an understanding of physics is relatively useless unless they can communicate their knowledge effectively to others. By working together in a truly collaborative manner to plan and carry out experiments, students learn oral communication skills and teamwork. Students must be encouraged to take full individual responsibility for the success of the collaboration and not be a sleeping partner ready to blame the rest of the team for failure.

After students are given a question for investigation, they may present their findings either in a written or an oral report to the teacher and the class for feedback and critique on their final design and results. Students should be encouraged to critique and challenge one another's claims based on the evidence collected during the investigation.

Laboratory Safety

Giving students the responsibility for design of their own laboratory experience involves special responsibilities for teachers. To ensure a safe working environment, teachers should first provide the limitations and safety precautions necessary for potential procedures and equipment students may use during their investigation. Teachers should also provide specific guidelines prior to students' discussion on investigation designs for each experiment, so that those precautions can be incorporated into the final student-selected lab design and included in the background or design plan in a laboratory record. It may also be helpful to print the precautions that apply to that specific lab as Safety Notes to place on the desk or wall near student workstations. Additionally, a general set of safety guidelines should be set forth for students at the beginning of the course. The following is a list of possible general guidelines teachers may post:

- Before each lab, make sure you know and record the potential hazards involved in the investigation, as well as the precautions you will take to stay safe.
- Before using equipment, make sure you know the proper use to acquire good data and avoid damage to equipment.
- Know where safety equipment is located in the lab, such as the fire extinguisher, safety goggles, and the first aid kit.
- Follow the teacher's special safety guidelines as set forth prior to each experiment. (Students should record these as part of their design plan for a lab.)
- When in doubt about the safety or advisability of a procedure, check with the teacher before proceeding.

Teachers should interact constantly with students as they work to observe safety practices and anticipate and discuss with them any problems that may arise. Walking among student groups, asking questions, and showing interest in students' work allows teachers to take the pulse of what students are doing and maintain a watchful eye for potential safety issues.

AP PHYSICS 2

Instructional Approaches

Selecting and Using Course Materials

Teachers will benefit from a wide array of materials to help students become proficient with the science practices necessary to develop a conceptual understanding of the relationships, laws, and phenomena studied in AP Physics 2. In addition to using a college-level textbook that will provide required course content, students should have regular opportunities to create and use data, representations, and models. Rich, experimental investigation is the cornerstone of AP Physics 2, and diverse source material allows teachers more flexibility in designing the types of learning activities that will help develop the habits of thinking like a physicist.

Textbooks

While nearly all college-level physics textbooks address the seven units of AP Physics 2, it's important for teachers to identify other types of secondary sources to supplement the chosen textbook accordingly, ensuring that each of the seven topic areas, as well as the science practices, receives adequate attention.

AP Central provides an **example textbook list** to help determine whether a text is considered appropriate in meeting the AP Physics 2 Course Audit resource requirement. Teachers can also select textbooks locally.

Guided Inquiry in AP Physics 2

The more active students are in their science education, the more scientifically literate they will become. Inquiry into authentic questions generated from student experiences should be one of the central strategies when teaching AP Physics 2. By posing questions, planning investigations, and reviewing what is already known in light of experimental evidence, students mirror how scientists analyze the natural world. Inquiry requires identifying assumptions, using critical and logical thinking, and considering alternative explanations. Having students probe for answers to scientific questions will lead to a deeper understanding of scientific concepts.

Science Practice	How to Scaffold Inquiry in the AP Classroom MORE ← AMOUNT OF DIRECTION FROM TEACHER → LESS			
3.1: The student can pose scientific questions.	The student works with a question developed by the teacher.	The student sharpens or clarifies a question provided by the teacher.	The student selects from a set of given questions or can modify a given question.	The student determines the question.
4.1: The student can justify the selection of the kind of data needed to answer a particular scientific question.	The student is given data and told how to analyze it.	The student is given data to analyze.	The student is told to collect and analyze certain data.	The student can determine what constitutes evidence and can collect it.
5.1: The student can analyze data to identify patterns or relationships.	[Science Practice 5.1 has only three levels of inquiry instruction.]	The student is given possible relationships or patterns.	The student is directed toward patterns or relationships.	The student can independently examine data and form links to explanations.
6.1: The student can justify claims with evidence.	The student is provided with evidence to support a claim.	The student is given possible ways to use evidence to create explanations.	The student is guided through the process of formulating explanations from evidence.	The student creates an explanation after summarizing the evidence.
6.4: The student can make claims and predictions about natural phenomena based on scientific theories and models.	The student is given steps and procedures to make claims and predictions.	The student is given broad guidelines to use in the sharpening of claims and predictions.	The student is coached in the development of claims and predictions.	The student can form reasonable and logical arguments to communicate explanations based on scientific theories and models.

Different types of lessons, and therefore different types of inquiry, are used throughout AP Physics 2. There is a continuum from more student-centered types of inquiry to more teacher-centered types. Understanding the different types of inquiry can help teachers scaffold the types of labs and activities to better meet the needs of their students.

Below are four suggestions to make labs and activities more student-centered and inquiry-based:

- Start small: Take out the "data" or "results" section from traditional labs. If the procedure is thorough and simple enough, students can read and design the data and/or results sections on their own.
- Tackle the procedure: Eventually, teachers will want students to design their own experiments, but they may need some practice first. Remove the step numbers and shuffle the steps. Have students work in pairs to put the steps into the correct order. Next, try having them write a procedure as a pre-lab homework assignment, and then work together as a class to develop it further, making sure that the question, variables, and safety are addressed.
- Try a goal-oriented task: Completely remove the procedure, and prompt students with a question that asks them to achieve something they want to do. At this point, it's best to choose a lab that students already understand conceptually and that uses simple, familiar equipment.
- Let them do the thinking: Students choose what they will investigate. Facilitate (rather than walk them through) their thought process without telling them what to do. A pre-lab brainstorming session in small groups is helpful when having students develop a question to investigate. It is important to provide students with some guidelines at this step. For example, students need to think about a question, a hypothesis, and materials before beginning an open-ended lab. Seeing and approving this in the lab groups helps boost students' confidence.

Instructional Strategies

The AP Physics 2 course framework outlines the concepts and science practices students must master in order to be successful on the AP Exam. To address those concepts and science practices effectively, it helps to incorporate a variety of instructional approaches into daily lessons and activities. Teachers can help their students develop the science practices by engaging them in learning activities that allow them to apply their understanding of course concepts. Teachers may consider the following strategies as they plan instruction. Please note they are listed alphabetically and not by order of importance or instruction.

Strategy	Definition	Purpose	Activity
Ask the Expert	Students are assigned as "experts" on problems they have mastered. Groups rotate through the expert stations to learn about problems they have not yet mastered.	Students share their knowledge and learn from one another.	In Unit 7, assign students as "experts" on atomic, quantum, or nuclear questions. Have them rotate through stations in groups, working with the station expert to justify a set of claims with corresponding physical laws as evidence.
Bar Chart	Bar chart tasks have histograms for one or more quantities. Frequently, histograms are given before and after some physical process with one bar left off. Students are asked to complete the bar chart by supplying the value for the missing quantity. This is a new type of representation, requiring students to translate between whatever other representation they are using and this one. Bar chart tasks are usually quite productive in helping students make meaning.	Bar chart tasks help students make meaning by asking them to translate between before and after some physical process.	This strategy can be used with conservation laws. Students can define the system and then create bar charts for before and after some event. For example, have students create an energy bar chart for a ball rolling down an incline. Have them identify the system and then create one set of charts for the top of the incline and a separate set of charts for the bottom of the incline.

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Strategy	Definition	Purpose	Activity
Changing Representations	These tasks require students to translate from one representation (e.g., an electric field diagram) to another (e.g., an equipotential curves or surfaces diagram). Students often learn how to cope with one representation without really learning the role and value of representations and their relationship to problem solving. Getting them to go back and forth between/among different representations for a concept forces them to develop a more robust understanding of each representation. Among the representations that will be employed at times are mathematical relationships, so this task can serve as a bridge between conceptual understanding and traditional problem solving.	Students create pictures, tables, graphs, lists, equations, models, and/or verbal expressions to interpret text or data. This helps organize information using multiple ways to present data and answer a question or show a problem's solution.	As students learn about energy conservation in circuits, ask them to move between different representations of circuits. For example, if given a sketch of a simple circuit, have students create a circuit diagram, a set of equations using Kirchhoff's rules, and a graph of potential around the circuit. Students should be able to move freely between these representations as well as use them for evidence in support of claims.
Concept-Oriented Demonstration	These tasks involve an actual demonstration but with the students doing as much of the description, prediction, and explanation as possible. Although the demonstration should produce results students don't expect, students should nonetheless feel comfortable making predictions about what will happen.	Involving an actual demonstration, students are asked to predict and explain.	Although most students will already know the outcome, the "soda can crushing" experiment can be demonstrated in Unit 2 to challenge students to explain how and/or why the phenomena occurred in terms of physical laws and theories.
Conflicting Contentions	Conflicting contentions tasks present students with two or three statements that disagree in some way, and students decide which contention they agree with and explain why. These tasks are very useful for contrasting statements of students' alternate conceptions with physically accepted statements. This process is facilitated in these tasks because they can be phrased as "Which statement do you agree with and why?" rather than asking which statement is correct or true. These tasks complement the "What if Anything Is Wrong?" tasks.	These tasks help contrast statements of students' alternate conceptions with physically accepted statements.	This strategy is useful for helping students begin to understand how to write a full argument. By providing the arguments and having students identify strong and weak claims, evidence, and reasoning, teachers can help scaffold the instruction of good argumentation for their students.

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Strategy	Definition	Purpose	Activity
Construct an Argument	Students use mathematical reasoning to present assumptions about mathematical situations, support conjectures with mathematically relevant and accurate data, and provide a logical progression of ideas leading to a conclusion that makes sense.	Helps in developing the process of evaluation of mathematical information, developing reasoning skills, and enhancing communication skills in supporting conjectures and conclusions.	This strategy can be used with word problems that do not lend themselves to immediate application of a formula or mathematical process. The teacher can provide distance and velocity graphs that represent a motorist's behavior through several towns on a map and ask students to construct a mathematical argument either in defense of or against a police officer's charge of speeding, given a known speed limit.
Create a Plan	Students analyze the tasks in a problem and create a process for completing the tasks by finding the information needed, interpreting data, choosing how to solve a problem, communicating the results, and verifying accuracy.	Assists in breaking tasks into smaller parts and identifying the steps needed to complete the entire task.	When scaffolding for how to design an experiment, a good first step is assigning small groups to analyze the tasks necessary to design the experiment. Have students identify the steps needed to answer the question by collecting and analyzing data. Included in this discussion is a plan for what to do with the collected data.
Debriefing	Students discuss the understanding of a concept to lead to a consensus on its meaning.	Helps clarify misconceptions and deepen understanding of context.	In order to discern the difference between average velocity and instantaneous velocity, have students roll a ball down a simple ramp and measure the distance the ball travels over time every second for five seconds. While plotting position versus time and sketching a curve of best fit, students can discuss how they might determine the average velocity of the ball over the five seconds and then the instantaneous velocity of the ball at several points. A discussion in which students address the distinction between the ball's velocity between two points and its velocity at a single point helps in clarifying the concept and mathematical process.

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Strategy	Definition	Purpose	Activity
Desktop Experiment Tasks (DETs)	These tasks involve students performing a demonstration at their desks (either in class or at home) using a predict-and-explain format. After doing the experiment, students "reformulate," or reconsider, their previous explanations in light of what happened. DETs are narrow in scope, usually qualitative in nature, and typically use simple equipment.	Students are presented with a small desktop experiment and asked to use the apparatus provided to answer a given question.	Direct Measurement Videos make excellent "desktop" experiments. They can include small experiments with magnets, syringes (to experiment with force and pressure), lenses/mirrors, diffraction gratings, fur, balloons, etc.
Discussion Groups	Students work within groups to discuss content, create problem solutions, and explain and justify a solution.	Aids in understanding through the sharing of ideas, interpretation of concepts, and analysis of problem scenarios.	Once students learn all methods of problem solving and can choose which is the most appropriate given a particular situation, have them discuss in small groups (no writing) why a specific method should be used over another.
Friends Without Pens	Students are given a free-response problem, quiz, or challenging problem. "Friends Without Pens" takes place in two rounds: The first round is the timed "Friends Without Pens" round, in which students are grouped together and can discuss—but not write about—the question. At the end of the time, students return to their desks for the "Pens Without Friends" round, where they tackle the assignment in the traditional, independent sense.	This can be a scaffolding tool if students are being introduced to a new type of assignment or a particularly difficult or challenging AP-level question.	Have students identify, with their peers, adequate claims, evidence, and reasoning. After discussing their various claims, have students return to their desks and develop a complete argument.
Four-Square Problem Solving	Students are given some sort of situation, perhaps one that came from a traditional plug-and-chug problem. They then divide a sheet of paper into four quadrants. In each quadrant, the student(s) are to put some representation of what is going on in the problem. Possible representations include motion maps or graphs, free-body diagrams, energy bar graphs, momentum bar graphs, mathematical models (equations with symbols), well-labeled diagrams, or written responses (two to three strong, clear sentences).	Re-expressing or re-representing data is a key skill necessary for student success in AP Physics 2. This task scaffolds the needed practice for students to get into the habit of creating and using representations to make claims and answer questions.	In Unit 4, students can regularly and repeatedly do four-square problem solving tasks about circuits. The key representations can include a circuit diagram, a circuit sketch, an energy bar chart, or a graph of potential around the circuit.

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Strategy	Definition	Purpose	Activity
Graph and Switch	Students generate a graph (or sketch of a graph) to model a certain function and then switch calculators (or papers) to review each other's solutions.	Allows students to practice creating different representations of functions as well as giving and receiving feedback on each other's work.	As students learn about PV graphs, they can graph pressure versus volume for different processes (isobaric, isochoric, adiabatic, and isothermal). Have students individually graph and explain how their graphs support claims. After, have them share their steps with a partner and exchange feedback on their graphs, claims, evidence, and reasoning.
Graphic Organizer	Students use visual representation for the organization of information.	Builds comprehension and facilitates discussion by representing information in visual form.	To determine the work done on or by a gas and the change in internal energy (and the heat) from a PV graph, have students construct a sign table to help them keep track of their logic as they think through the different processes represented. Have them mark where the heat, work, and internal energy increases, decreases, or remains the same. This process also works well in circuits when switches are opened/closed or when bulbs are removed/added.
Identify Subtasks	Students break a problem into smaller pieces with outcomes leading to a solution.	Helps organize the pieces of a complex problem and reach a complete solution.	Another scaffolding technique: When first exposing students to AP-level questions that involve several steps of reasoning and logic, additional questions can be added to help guide students to the final claim, evidence, and reasoning. For example, ask students to sketch a free-body diagram, discuss the system, and/or draw energy bar charts. After completing the first few units, students should be able to identify (first in groups and then individually) what the subtasks would be (free-body diagram, etc.) to start thinking about the claim, evidence, and reasoning.

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Strategy	Definition	Purpose	Activity
Marking the Text	Students highlight, underline, and/or annotate text to focus on key information to help understand the text or solve the problem.	Helps the student identify important information in the text and make notes in the text about the interpretation of tasks required and concepts to apply to reach a solution.	This strategy can be used with AP-level problems as well as problems from the textbook and sample laboratory procedures. Have students read through the question, experimental design, or another student's experimental design; underline the pronouns, equipment, key information (i.e., the car begins at *rest*), etc., to identify important information and to be able to ask clarifying questions.
Meaningful, Meaningless Calculations	Students are presented with an unreduced expression for a calculation for a physical quantity describing a physical situation. They must decide whether the calculation is meaningful (i.e., it gives a value that tells us something legitimate about the physical situation) or is meaningless (i.e., the expression is a totally inappropriate use of a relation). These calculations should not be trivially meaningless, such as substituting a wrong numerical value into the expression. These items are best when the quantity calculated fits with students' alternative conceptions.	Students are presented with an unreduced calculation for a physical calculation that involves a mathematical relationship, and students are asked if the calculation makes any sense.	These calculations can take many forms, but the most useful are those where the "meaningless" calculations illustrate common student misconceptions. For example, when calculating current through individual resistors, students might see sample calculations that use the voltage of the battery instead of the voltage across the individual resistor. Have students identify the calculation(s) that have physical meaning. Ask students about a situation in which there is a uniform magnetic field of specified magnitude, directed toward the left, with an electron traveling parallel to the field at a speed of 300 m/s. Have students find the magnetic force acting on the electron as the product of the speed, the charge, and the magnitude of the field. Ask students if this a meaningful (or meaningless) calculation for this situation.

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Strategy	Definition	Purpose	Activity
Model Questions	Students answer items from released AP Physics Exams.	Provides rigorous practice and assesses students' ability to apply multiple physical practices on content, either a multiple-choice or a free-response question.	Model questions can be AP-released or AP-level questions. They can be given as is, or scaffolded for students earlier in the year to provide them with support.
Note Taking	Students create a record of information while reading a text or listening to a speaker.	Helps in organizing ideas and processing information.	Have students write down verbal descriptions of the steps needed to solve a problem so that a record of the processes can be referred to at a later point in time.
Predict and Explain	These tasks describe a physical situation that is set up at a point where some event is about to occur. Students predict and explain what they think will happen. These tasks must have situations with which the students are familiar or have sufficient background information in to enable the students to understand the situation. This is important because otherwise students usually do not feel comfortable enough to attempt to answer.	Stimulates thinking by asking students to make, check, and correct predictions based on evidence from the outcome.	When a circuit is set up with a capacitor, bulb, and switch, ask students: "What will happen to the brightness of the bulb when the switch is closed or opened? What happens immediately versus what happens after a long time? What would happen if the capacitor was replaced with a second bulb?"
Qualitative Reasoning	These tasks can take a variety of forms, with their common denominator being qualitative analysis. Frequently, students are presented with an initial and final situation and asked how some quantity or aspect will change. Qualitative comparisons (e.g., the quantity increases, decreases, or stays the same) are often the appropriate answer. Qualitative reasoning tasks can frequently contain elements found in some of the other task formats (e.g., different qualitative representations and a prediction or explanation).	Students are presented with a physical situation and asked to apply a principle to qualitatively reason out what will happen. These questions are commonly found in other multiple-choice question subtypes.	Ask students what would happen to the image created by a convex lens if the object were moved farther from or closer to the lens or focal point. Additional questions could include, "What happens if a second lens is added?" or "What would happen to the image if the whole experiment were put under water?"

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Strategy	Definition	Purpose	Activity
Quickwrite	Students write for a short, specific amount of time about a designated topic.	Helps generate ideas in a short amount of time.	To help synthesize concepts after having learned how to analyze single- and double-slit experiments, have students list as many ways as possible to change the interference pattern on the screen and explain how each change affects the pattern.
Ranking	A ranking task is an exercise that presents students with a set of variations—sometimes three or four but usually six to eight—on a basic physical situation. The variations differ in value (numeric or symbolic) for the variables involved but also frequently include variables that are not important to the task. The students' task is to rank the variations on the basis of a specified physical quantity. Students must also explain the reasoning for their ranking scheme and rate their confidence in their ranking.	These tasks require students to engage in a comparison reasoning process that they seldom have opportunities to do in traditional problem solving.	Given six different arrows launched from the ground with different speeds at different angles, have students rank the arrows on the basis of the highest acceleration at the top, the longest time in the air, and the largest velocity at the top.
Sharing and Responding	Students communicate with another person or a small group of peers who respond to a proposed problem solution.	Gives students the opportunity to discuss their work with peers, make suggestions to improve the work of others, and/or receive appropriate and relevant feedback on their own work.	Group students to review individual work (graphs, derivations, problem solutions, experimental designs, etc.). Have the groups make any necessary corrections and build a single complete solution together.
Simplify the Problem	Students use "friendlier" numbers or functions to help solve a problem.	Provides insight into the problem or the strategies needed to solve the problem.	Have students use resistors with resistances that add easily in parallel. Two resistors with resistances of 30 ohms and 60 ohms in parallel add nicely to 20 ohm total resistance for the combination.

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Strategy	Definition	Purpose	Activity
Troubleshooting	Troubleshooting tasks are variations on "What if Anything Is Wrong?" tasks. Students are explicitly told that there is an error in the given situation. Their job is to determine what the error is and explain how to correct it. These tasks can often produce interesting insights into students' thinking, because they will, at times, identify some correct aspect of the situation as erroneous. Once again, this helps develop additional items.	Allows students to troubleshoot errors and misconceptions by focusing on problems that may arise when they do the same procedures themselves.	Give students a derivation or problem solution and ask them to find the incorrect step(s). Have them identify and explain the mistake or misunderstanding that led to the error. This can also be done with bar charts, diagrams, and other representations.
"What if Anything Is Wrong?"	Requires students to analyze a statement or diagrammed situation to determine if it is correct or not. If everything is correct, the student is asked to explain the statement/situation and why it works as described. If something is incorrect, the student has to identify the error and explain how to correct it. These are open-ended exercises, so they provide insights into students' ideas, since they will often have interesting reasons for accepting incorrect situations and for rejecting legitimate situations. Often, students' responses provide ideas for other items.	Allows students to troubleshoot errors and focus on problems that may arise when they do the same procedures themselves.	Give students a ray diagram that may or may not have incorrect rays drawn. Or, give them a sketch of a circuit and a corresponding circuit diagram and ask them to identify if the diagram matches the sketch. This technique can also be used in derivations and problem solving where students are given the "complete" solution and are asked to verify that it was done correctly.
Write and Switch	Like graph and switch, but with writing. Make observations or collect data or make a claim, and then switch papers.	Allows students to practice writing and both give and receive feedback on each other's work.	As students learn about creating an argument, have them draft an initial argument themselves; share their claim, evidence, and reasoning with a partner; and receive feedback on their argument.
Working Backward	This task reverses the order of the problem steps. For example, the given information could be an equation with specific values for all, or all but one, of the variables. The students must then construct a physical situation for which the given equation would apply. Such working backward tasks require students to take numerical values, including units, and translate them into physical variables. Working backward problems also require students to reason about these situations in an unusual way, and they often allow for more than one solution.	Provides another way to check possible answers for accuracy.	Give students an equation, such as $-16m = \left(2\frac{m}{s}\right)t - \left(5\frac{m}{s^2}\right)t^2$, and ask them to create another representation from this equation. For example, position versus time graphs, velocity versus time graphs, motion maps, etc., are all written scenarios that this equation represents.

Developing the Science Practices

Throughout the course, students will develop and apply science practices that are fundamental to the discipline of physics. Since these practices represent the complex skills that adept physicists demonstrate, students will benefit from multiple opportunities to develop them in a scaffolded manner. Through the use of guided questioning, discussion techniques, and other instructional strategies, Teachers can help their students apply these science practices in new contexts, providing an important foundation for their college and career readiness.

Science Practice 1: Modeling

The student can use representations and models to communicate scientific phenomena and solve scientific problems.

The real world is extremely complex. When physicists describe and explain phenomena, they try to simplify real objects, systems, and processes to make the analysis manageable. These simplifications, or models, are used to predict how new phenomena will occur. A simple model may treat a system as an object, neglecting the system's internal structure and behavior, while more complex models illustrate a system of objects, such as an ideal gas.

To create an accurate model, students must identify a set of the most important characteristics of the phenomenon or system that may simplify analysis.

Inherent in the construction of models that physicists invent is the use of representations, such as force diagrams, graphs, energy bar charts, ray diagrams, and circuit diagrams. Representations help in analyzing phenomena, making predictions, and communicating ideas. AP Physics 2 requires students to use and/or analyze and/or re-express models and representations of natural or man-made systems.

The table on the following page provides examples of questions and instructional strategies for implementing modeling resources into the course.

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
1.1 *The student can create representations and models of natural or man-made phenomena and systems in the domain.*	▪ What kind of model or representation would be appropriate for this physical system? ▪ What physical characteristics can be modeled or represented for this physical situation?	Have students divide their paper into four quarters. In each quarter of the paper, have them create a representation of the physical situation. Representations can include equations and sentences (or paragraphs) as well as bar charts, circuit diagrams, or sketches of physical situations.	▪ Four-Square Problem Solving ▪ "What if Anything Is Wrong?" ▪ Graph and Switch ▪ Changing Representations
1.2 *The student can describe representations and models of natural or man-made phenomena and systems in the domain.*	▪ What does the representation show?	Have students describe the physical features and meaning of figures and representations, including figures and representations from the textbook and other reference sources.	▪ Label and Describe ▪ "What if Anything Is Wrong?" ▪ Graph and Switch ▪ Discussion Groups
1.3 *The student can refine representations and models of natural or man-made phenomena and systems in the domain.*	▪ What assumptions are inherent in the representation or model? ▪ How can these assumptions be modified in the representation or model? ▪ What would the representation or model look like if these assumptions were modified?	In groups, have students create a representation for a certain physical situation. The groups then switch papers and discuss modifications that can be made to the representations or models based on assumptions that may have been made or that could be made about the physical situation.	▪ Graph and Switch ▪ "What if Anything Is Wrong?"
1.4 *The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*	▪ What does the representation show? ▪ What features of the representation provide information relevant to the question or problem?	Have students analyze slopes, areas under curves, and y and x intercepts to help them solve problems. They should be able to analyze situations using graphs/models/representations as easily as they can with numbers and equations.	▪ "What if Anything Is Wrong?" ▪ Changing Representations ▪ Bar Chart
1.5 *The student can re-express key elements of natural phenomena across multiple representations in the domain.*	▪ What characteristic or physical quantity of the situation does each representation illustrate? ▪ How do the representations show consistency?	Have students divide their paper into four quarters and provide four different representations for a given physical situation. Representations can include an equation, a written sentence (or paragraph), a graph, a bar chart, or a sketch of the physical scenario.	▪ "What if Anything Is Wrong?" ▪ Changing Representations ▪ Four-Square Problem Solving

Science Practice 2: Mathematical Routines

The student can use mathematics appropriately.

Physicists commonly use mathematical representations to describe and explain phenomena, as well as to solve problems. When students work with these representations, they should understand the connections between the mathematical description, the physical phenomena, and the concepts represented in the mathematical descriptions. When using equations or mathematical representations, students need to be able to justify why using a particular equation to analyze a particular situation is useful and to be aware of the conditions under which the equations/mathematical representations can be used.

The following table provides examples of questions and instructional strategies for implementing mathematical resources into the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
2.1 *The student can justify the selection of a mathematical routine to solve problems.*	▪ What quantities are given? ▪ What quantity is needed to answer the question? ▪ What relationship(s) link the needed quantities with the given quantities?	Have students work backward from a given mathematical routine to a physical situation. For instance, give them an equation such as $-16m = \left(2\frac{m}{s}\right)t - \left(5\frac{m}{s^2}\right)t^2$ and ask them to create another representation—such as a written scenario about this equation, position versus time graphs, velocity versus time graphs, motion maps, etc.—from this equation.	▪ Working Backward ▪ Simplify the Problem ▪ Ask the Expert
2.2 *The student can apply mathematical routines to quantities that describe natural phenomena.*	▪ What laws, definitions, or mathematical relationships exist that relate the given problem? ▪ What are the rules, assumptions, or limitations surrounding the use of the chosen law, definition, or relationship? ▪ Did the calculation begin with an equation or a fundamental physics relationship, law, or definition? ▪ Are the steps clearly written out and annotated? ▪ Are any steps skipped? ▪ Is the unknown quantity clearly labeled as the final answer, complete with units?	Have students perform a task in which the calculations are already done—a task that will require them to focus on making important distinctions that physicists consider critical. For example, have students determine whether a specified calculation is meaningful or meaningless. This is entirely different from plugging numerical values into an equation and turning the crank. Meaningful/meaningless calculation tasks are another tool to get students to process information about a concept or principle in a different way.	▪ Model Questions ▪ Discussion Groups ▪ Meaningful, Meaningless Calculations
2.3 *The student can estimate numerically quantities that describe natural phenomena.*	▪ How can the mathematical routine be simplified to give an estimated or order-of-magnitude calculation? ▪ How can this estimated value be used as a guide when calculating an unknown value?	Have students practice estimating numerical quantities by, for example, doing order-of-magnitude calculations to estimate the strength of an electric or a magnetic field at a point.	▪ Meaningful, Meaningless Calculations ▪ Simplify the Problem

Science Practice 3: Scientific Questioning

The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.

Research scientists pose and answer meaningful questions. Students may easily miss this point since, depending on how a science class is taught, it may seem that science is about compiling and passing down a large body of known facts (e.g., the acceleration of a free-falling object is 9.8 m/s^2). Helping students learn how to pose, refine, and evaluate scientific questions is an important but difficult instructional and cognitive goal. Students need to be guided away from asking "fuzzy" questions about queries that can be measured and tested. A first step in refining questions might be to guide students to consider all the ways one might measure relevant physical quantities, leading to further discussions about how one would evaluate questions by designing and carrying out experiments and then evaluating data and findings.

The following table provides examples of questions and instructional strategies for implementing scientific questioning into the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
3.1 *The student can pose scientific questions.*	▪ What does it mean for a question to be "scientific"? ▪ How can questions be modified to make them testable?	Have students practice posing scientific questions by giving them opportunities to discuss what is scientifically measurable and determinable with certain laboratory equipment.	▪ Desktop Experiment Tasks ▪ Write and Switch
3.2 *The student can refine scientific questions.*	▪ How can scientific questions be modified to make them testable? ▪ How can a scientific question be refined concerning a proposed incorrect relationship between variables?	Have students practice engaging in scientific questioning by, for example asking questions about the relationships between pressure, temperature, and volume in an ideal gas. As a first step, students might consider the ways in which one can measure physical quantities relevant to the gas, leading to a discussion of pressure, temperature, volume, and number of gas particles (in moles). Follow-up discussions can lead to how one goes about evaluating questions such as, "Upon what does the pressure in an ideal gas depend?" by designing and carrying out experiments and then evaluating data and findings.	▪ Desktop Experiment Tasks ▪ Write and Switch ▪ Predict and Explain
3.3 *The student can evaluate scientific questions.*	This science practice is not directly tested on the AP Physics 2 Exam. However, through laboratory investigation, students need to be able to determine what makes a good scientific question. This is especially important if students are going to continue in their studies of science.	N/A	N/A

Science Practice 4: Experimental Methods

The student can plan and implement data collection strategies in relation to a particular scientific question.

Scientific questions can range in scope, as well as in specificity, from determining influencing factors and/or causes to determining mechanism. The question posed determines the type of data required, as well as the plan for collecting data. Although class discussion can reveal issues of measurement uncertainty and assumptions in the data collection, designing and improving experimental designs and/or data collection strategies is a learned skill. Students must ultimately understand that the results of collecting and using data to determine a numerical answer to a question are best thought of as an interval, not a single number. This interval, the *experimental uncertainty*, is due to a combination of uncertainty in the instruments used and the process of taking the measurement. Detailed error analysis is not necessary to convey this pivotal idea; however, it is important that students make some reasoned estimate of the interval within which they know the value of a measured data point and express their results in a way that makes this clear.

The following table provides examples of questions and instructional strategies for implementing data collection resources into the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
4.1 *The student can justify the selection of the kind of data needed to answer a particular scientific question.*	▪ What data is necessary to answer the scientific question? ▪ What physical law, equation, or relationship links the scientific question with the collected data?	Have students practice justifying the selection of the kind of data needed to answer a particular scientific question. For example, have students design an experiment and analyze data from it to determine thermal conductivity.	▪ Discussion Groups ▪ Create a Plan ▪ Write and Switch
4.2 *The student can design a plan for collecting data to answer a particular scientific question.*	▪ What information will be needed to answer the scientific question? ▪ What equipment is needed to collect the necessary data? ▪ How will each piece of equipment be used to collect the necessary data? ▪ What will be done with the data (data analysis) to answer the scientific question?	Have students practice designing plans for collecting data to answer scientific questions. Laboratory design procedures do *not* always have to be carried out. For example, have students design an experiment and analyze graphical data where the area under a curve is needed to determine the work done on or by the object or system.	▪ Create a Plan ▪ Troubleshooting ▪ Desktop Experiment Tasks

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Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
4.3 *The student can collect data to answer a particular scientific question.*	▪ What information will be needed to answer the scientific question? ▪ What equipment is needed to collect the necessary data? ▪ How will each piece of equipment be used to collect the necessary data? ▪ What will be done with the data (data analysis) to answer the scientific question?	Have students follow through with the plans they have designed to collect data to answer a scientific question. Students can also be given a procedure to follow and can practice collecting careful data from a teacher's or classmate's written instructions.	▪ Write and Switch ▪ Desktop Experiment Tasks
4.4 *The student can evaluate sources of data to answer a particular scientific question.*	▪ Can the data set given or collected be trusted? ▪ Could there be anomalies in the data that need to be resolved?	Expose students to data that might have anomalies or might not be accurate. Have them discuss the possible reasons why a particular data set is or is not reliable.	▪ Troubleshooting ▪ Desktop Experiment Tasks

Science Practice 5: Data Analysis

The student can perform data analysis and evaluation of evidence.

The analysis, interpretation, and application of quantitative information are vital skills for students in AP Physics 2. Analysis skills can be taught using any type of data, so it's critical that students are fluent in pattern recognition and comfortable using models and representations.

Students often think that to make a graph, they need to connect data points or that the best-fit function is always linear. Thus, it is important that they can construct a best-fit curve even for data that does not fit a linear relationship. Students should be able to represent data points as intervals with sizes dependent on the experimental uncertainty. After students find a pattern in the data, they need to ask why this pattern is present and try to explain it using the knowledge that they have. When dealing with a new phenomenon, they should be able to devise a testable explanation of the pattern, if possible. It is important that students understand that instruments do not produce exact measurements and must learn what steps they can take to decrease uncertainty. Students should be able to design a second experiment to determine the same quantity and then check for consistency across the two measurements, comparing the results by writing them both as intervals and not as single, absolute numbers. Finally, students should be able to revise their reasoning based on the new data, data for some that may appear anomalous.

The following table provides examples of questions and instructional strategies for implementing data analysis resources into the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
5.1 *The student can analyze data to identify patterns or relationships.*	▪ How should the data be graphed so that the best-fit curve shows a relationship? ▪ How can data intervals be used to show experimental uncertainty? ▪ What do the data or graphs show? ▪ What trends and patterns can you identify from the data? ▪ Why is the pattern present in the data? ▪ What does the pattern show about the relationship between quantities?	Have students practice analyzing data to find patterns and relationships. For example, have them analyze data (or a visual representation) to identify patterns that indicate that a mechanical wave is polarized. Next, have students construct an explanation based on the fact that the wave must have a vibration perpendicular to the direction of the energy propagation.	▪ Friends Without Pens ▪ Write and Switch ▪ Graph and Switch ▪ Predict and Explain

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Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
5.2. *The student can refine observations and measurements based on data analysis.*	▪ What changes can be made to observations and measurements to refine the data? ▪ How can a second experiment be designed to answer the same scientific question? ▪ What steps can be taken to decrease the uncertainty in the measurements and data?	Have students practice refining observations and measurements. For example, have them perform data analysis and evaluation of the evidence for 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).	▪ Desktop Experiment Tasks ▪ Write and Switch ▪ Graph and Switch
5.3. *The student can evaluate the evidence provided by data sets in relation to a particular scientific question.*	▪ How does the presented evidence provide support for the claim or scientific question? ▪ Does the data set present clear and complete evidence in relation to the scientific question, or is the data flawed? ▪ If the data is flawed, what new data or procedure should be completed to obtain data in relation to the scientific question?	Have students refine and analyze a scientific question for an experiment using Kirchhoff's loop rule for circuits that includes determining the internal resistance of the battery and an analysis of a non-ohmic resistor.	▪ Sharing and Responding ▪ Conflicting Contentions

Science Practice 6: Argumentation

The student can work with scientific explanations and theories.

A scientific explanation, accounting for an observed phenomenon, needs to be experimentally testable. One should be able to use it to make predictions about new phenomena. A theory—such as the kinetic molecular theory or atomic theory—uses a unified approach to account for a large set of phenomena and gives accounts that are consistent with multiple experimental outcomes within the range of applicability of the theory. Understanding the difference between explanations and theories is essential.

Students should be prepared to offer evidence, construct reasoned arguments based on that evidence, and make a claim or provide an explanation to support predictions. A prediction states that the expected outcome of a particular experimental design is based on an explanation or a claim under scrutiny.

Physicists examine data and evidence to develop claims about physical phenomena. As they articulate their claims, physicists use reasoning processes that rely on their awareness of different types of relationships, connections, and patterns within the data and evidence. They then formulate a claim and develop an argument that explains how the claim is supported by the available evidence. AP Physics 2 teachers should help students learn how to create persuasive and meaningful arguments by improving their proficiency with each of these practices.

The following table provides examples of strategies for implementing argumentation resources into the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
6.1. *The student can justify claims with evidence.*	▪ What is evidence and how does it differ from reasoning?	Have students identify and explain the evidence that supports their claim, with an emphasis on *how* the evidence supports the claim. Give students a question such as, *"Which of the following is most responsible for … ?"* Students should analyze possibilities and the evidence for and against each position. Have students choose a position and write a defensible claim or thesis that reflects their reasoning and evidence.	▪ Conflicting Contentions
6.2. *The student can construct explanations of phenomena based on evidence produced through scientific practices.*	▪ What possible claims could you make based on the question and the evidence? ▪ What is your purpose (to define, show causality, compare, or explain a process)? ▪ What evidence supports your claim? ▪ How does the evidence support your explanation?	Have students construct an explanation of physical phenomena based on evidence. A scientific explanation includes a claim, evidence, and reasoning. For example, have them construct an explanation of the inverse square dependence of the electric field surrounding a spherically symmetric, electrically charged object.	▪ Conflicting Contentions ▪ Concept-Oriented Demonstration ▪ Discussion Groups

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Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
6.3 *The student can articulate the reasons that scientific explanations and theories are refined or replaced.*	▪ What evidence is there that refutes the old scientific explanation or theory? ▪ What evidence is there that supports the new scientific explanation or theory? ▪ Are there still phenomena that cannot be explained by scientific explanation or theory?	Have students list and discuss reasons that a scientific explanation and/or theory was refined or replaced. For example, have them explain why classical mechanics cannot describe all properties of objects by listing the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties.	▪ Discussion Groups
6.4 *The student can make claims and predictions about natural phenomena based on scientific theories and models.*	▪ What reasoning (physical laws or theories) supports your claim? ▪ How does the reasoning support your claim? ▪ How does the evidence support your claim? Use transitions such as *because* or *therefore*.	Have students make claims about a physical situation that is set up at a point where some event is about to occur. Next, have students predict what will happen in the situation and explain why they think that will occur. For example, have students make claims and predictions about the net disturbance that occurs when two waves overlap (superposition).	▪ Predict and Explain ▪ Discussion Groups ▪ Conflicting Contentions
6.5 *The student can evaluate alternative scientific explanations.*	▪ Not tested in AP Physics 2	N/A	▪ N/A

Science Practice 7: Making Connections

The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.

Throughout the course, students will have opportunities to transfer their learning across disciplinary boundaries to link, synthesize, and apply the ideas they learn across the sciences and mathematics. Teachers are encouraged to provide multiple contexts in which major ideas facilitate transfer, allowing students to bundle knowledge together with the multiple contexts to which it applies. Students should also be able to recognize seemingly appropriate contexts to which major concepts and ideas do not apply.

The following table provides examples of questions and instructional strategies for making connections throughout the course:

Science Practice	Key Questions	Instructional Notes or Sample Activities	Instructional Strategies
7.1 *The student can connect phenomena and models across spatial and temporal scales.*	▪ What models and/or representations can help connect these phenomena with other phenomena? ▪ What important features of the models and/or representations connect the phenomena across spatial and temporal scales?	Have students practice connecting phenomena across spatial and temporal scales. Problem solving in isolation of one unit will *not* prepare students for the AP Physics 2 Exam. For example, have students connect representations between topics and big ideas. Students should be able to make predictions about the scale of the physical situation to determine when a wave or particle model is more appropriate.	▪ Meaningful, Meaningless Calculations ▪ Model Questions ▪ "What if Anything Is Wrong?"
7.2 *The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*	▪ What big ideas can link these phenomena with other phenomena? ▪ How can the ideas used to explain this phenomenon be generalized to extrapolate across enduring understandings? ▪ How can the ideas used to explain this phenomenon be generalized to extrapolate across big ideas?	Have students practice connecting phenomena across domains and making generalizations across enduring understandings and big ideas. For example, have students predict and explain, using representations and models, how waves can transfer energy around corners and behind obstacles by using diffraction as a property of waves, including with sound and light.	▪ Meaningful, Meaningless Calculations ▪ Model Questions ▪ "What if Anything Is Wrong?"

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AP PHYSICS 2

Exam Information

Exam Overview

The AP Physics 2 Exam assesses student application of the science practices and understanding of the course learning objectives outlined in the course framework. The exam is 3 hours long and includes 50 multiple-choice questions and 4 free-response questions. The four free-response questions may appear in any order on the AP Exam. A four-function, scientific, or graphing calculator is allowed on both sections of the exam. The details of the exam, including exam weighting and timing, can be found below:

Section	Question Type	Number of Questions	Weighting	Timing
IA	**Single-select multiple-choice questions (discrete or in sets)**	**45**	**50%**	**90 minutes**
IB	**Multiple-select multiple-choice items (all discrete)**	**5**		
II	**Free-response questions**	**4**	**50%**	**90 minutes**
	Question 1: Experimental Design (12 points)			
	Question 2: Quantitative/Qualitative Translation (12 points)			
	Question 3: Paragraph Argument Short Answer Question (10 points)			
	Question 4: Short Answer Question (10 points)			

The exam assesses content from each of the seven big ideas for the course:
Big Idea 1: Systems
Big Idea 2: Fields
Big Idea 3: Force Interactions
Big Idea 4: Change
Big Idea 5: Conservation
Big Idea 6: Waves
Big Idea 7: Probability

The exam also assesses each of the seven units of the course with the following weightings on the multiple-choice question section of the AP Exam:

Exam Weighting for the Multiple-Choice Section of the AP Exam

Unit of Instruction	Exam Weighting
Unit 1: Fluids	10–12%
Unit 2: Thermodynamics	12–18%
Unit 3: Electric Force, Field, and Potential	18–22%
Unit 4: Electric Circuits	10–14%
Unit 5: Magnetism and Electromagnetic Induction	10–12%
Unit 6: Geometric and Physical Optics	12–14%
Unit 7: Quantum, Atomic, and Nuclear Physics	10–12%

How Student Learning is Assessed on the AP Exam

Section I: Multiple-Choice

Science practices 1, 2, 4, 5, 6, and 7 are all assessed in in the multiple-choice section, with the following weighting (science practice 3 will not be assessed in the multiple-choice section):

Exam Weighting for the Multiple-Choice Section of the AP Exam

Science Practice	Exam Weighting
Science Practice 1: Modeling	**28–30%**
Science Practice 2: Mathematical Routines	**16–18%**
Science Practice 4: Experimental Method	**2–4%**
Science Practice 5: Data Analysis	**10–12%**
Science Practice 6: Argumentation	**26–28%**
Science Practice 7: Making Connections	**12–16%**

Section II: Free-Response

Science practices 1, 2, 4, 5, 6, and 7 are all assessed in the free-response section, with the following weighting (science practice 3 will not be assessed in the free-response section):

Exam Weighting for the Free-Response Section of the AP Exam

Science Practice	Exam Weighting
Science Practice 1: Modeling	**11–23%**
Science Practice 2: Mathematical Routines	**18–30%**
Science Practice 4: Experimental Method	**6–14%**
Science Practice 5: Data Analysis	**6–16%**
Science Practice 6: Argumentation	**22–41%**
Science Practice 7: Making Connections	**2–11%**

The Physics 2 free-response section includes four free-response questions: two 12-point questions and two 10-point questions. Every exam includes one experimental design question, one quantitative/qualitative translation question, one paragraph argument short answer question, and one additional short answer question. These questions may appear in any order on the AP Exam.

Experimental Design Question (12 points; 3–5 question parts)

This question type assesses student ability to design and describe a scientific investigation, analyze authentic laboratory data, and identify patterns or explain phenomena.

Quantitative/Qualitative Translation Question (12 points; 3–5 question parts)

This question type assesses student ability to translate between qualitative and quantitative justification and reasoning.

Paragraph Argument Short Answer Question (10 points; 2–4 question parts)

This question type assesses student ability to create a paragraph-length response, which consists of a coherent argument about a physics phenomenon that uses the information presented in the question and proceeds in a logical, expository fashion to arrive at a conclusion.

Short Answer Question (10 points; 2–4 question parts)

This question focuses on practices and learning objectives not focused on in the other question types.

Task Verbs Used in Free-Response Questions

The following task verbs are commonly used in the free-response questions.

Calculate: Perform mathematical steps to arrive at a final answer, including algebraic expressions, properly substituted numbers, and correct labeling of units and significant figures. Also phrased as "What is?"

Compare: Provide a description or explanation of similarities and/or differences.

Derive: Perform a series of mathematical steps using equations or laws to arrive at a final answer.

Describe: Provide the relevant characteristics of a specified topic.

Determine: Make a decision or arrive at a conclusion after reasoning, observation, or applying mathematical routines (calculations).

Evaluate: Roughly calculate numerical quantities, values (greater than, equal to, less than), or signs (negative, positive) of quantities based on experimental evidence or provided data. When making estimations, showing steps in calculations are not required.

Explain: Provide information about how or why a relationship, process, pattern, position, situation, or outcome occurs, using evidence and/or reasoning to support or qualify a claim. Explain "how" typically requires analyzing the relationship, process, pattern, position, situation, or outcome; explain "why" typically requires analysis of motivations or reasons for the relationship, process, pattern, position, situation, or outcome.

Justify: Provide evidence to support, qualify, or defend a claim, and/or provide reasoning to explain how that evidence supports or qualifies the claim.

Label: Provide labels indicating unit, scale, and/or components in a diagram, graph, model, or representation.

Plot: Draw data points in a graph using a given scale or indicating the scale and units, demonstrating consistency between different types of representations.

Sketch/Draw: Create a diagram, graph, representation, or model that illustrates or explains relationships or phenomena, demonstrating consistency between different types of representations. Labels may or may not be required.

State/Indicate/Circle: Indicate or provide information about a specified topic, without elaboration or explanation. Also phrased as "What…?" or "Would…?" interrogatory questions.

Verify: Confirm that the conditions of a scientific definition, law, theorem, or test are met in order to explain why it applies in a given situation. Also, use empirical data, observations, tests, or experiments to prove, confirm, and/or justify a hypothesis.

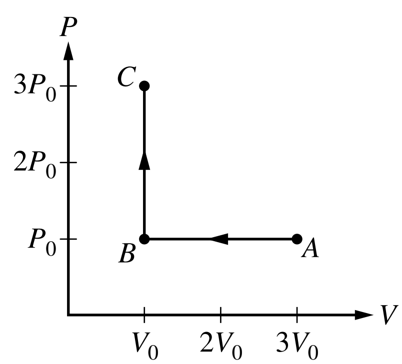
Sample Exam Questions

The sample exam questions that follow illustrate the relationship between the course framework and AP Physics 2 Exam and serve as examples of the types of questions that appear on the exam. After the sample questions, teachers will find a table that shows which science practice(s), learning objective(s), and unit each question relates to. The table also provides the answers to the multiple-choice questions.

Section I: Multiple-Choice Questions

The following are examples of the kinds of multiple-choice questions found on the exam.

Questions 1 and 2 refer to the following material.



A sealed cylinder with a moveable piston contains N molecules of an ideal gas. The gas is initially in state A shown on the above PV diagram, where P is pressure and V is volume. The gas is then taken through the two processes shown.

1. Which of the following correctly ranks the average speed v of the molecules in states A, B, and C?

   (A) $(v_B = v_C) > v_A$

   (B) $v_C > v_B > v_A$

   (C) $(v_A = v_C) > v_B$

   (D) $v_B > (v_A = v_C)$

2. Which of the following correctly ranks the magnitude of the force F the gas exerts on the piston in states A, B, and C?

   (A) $F_A > F_C > F_B$

   (B) $F_C > F_B > F_A$

   (C) $(F_A = F_C) > F_A$

   (D) $F_C > (F_A = F_B)$

3. A cylindrical resistor is connected to a battery with an emf of 15.0 V, resulting in a current of 3.0 A in the circuit. The resistor is removed, and a new resistor of the same material with twice the radius and twice the length of the original resistor is connected to the battery. What is the new current in the circuit?

(A) 1.5 A

(B) 3.0 A

(C) 6.0 A

(D) 12.0 A

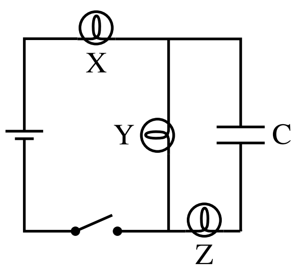
4. Water of density 1000 kg/m^3 is pumped through a straight, horizontal hose and out a nozzle that has an opening with a cross-sectional area 10 times smaller than that of the hose. The water exits the nozzle at a speed of 10.0 m/s. The difference between the pressure of the fluid when it is in the hose near the pump and as it exits the nozzle is

(A) $4.5 \times 10^3\text{ Pa}$

(B) $4.95 \times 10^4\text{ Pa}$

(C) $9.9 \times 10^4\text{ Pa}$

(D) $4.95 \times 10^6\text{ Pa}$



5. In the circuit shown above, bulbs X, Y, and Z are identical and capacitor C is initially uncharged. The switch is closed at time $t = 0$. Which of the following describes the brightness of bulbs Y and Z after the switch is closed?

(A) Both bulbs light and remain lit.

(B) Bulbs Y and Z are both initially lit, and bulb Y eventually goes out.

(C) Bulbs Y and Z are both initially lit, and bulb Z eventually goes out.

(D) Bulb Y is always lit and bulb Z is always out.

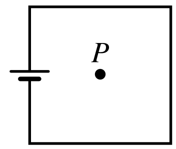
6. A student in a classroom sees a tree outside that is far from the classroom window and uses a concave mirror to form an image of the tree on a screen. Which of the following best describes the image?

(A) Real and near the center of curvature of the mirror

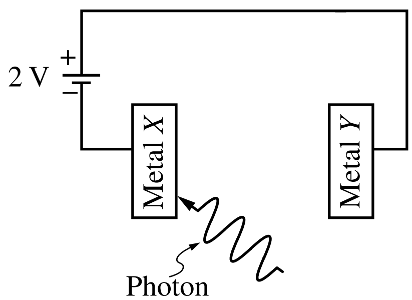
(B) Real and near the focal point of the mirror

(C) Virtual and near the center of curvature of the mirror

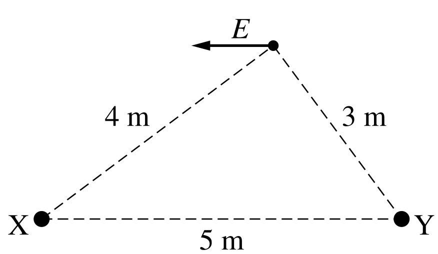
(D) Virtual and near the focal point of the mirror



7. A circuit consists of a battery and some wire with significant resistance. The wire is bent so that the circuit is in the shape of a square, and the circuit is aligned in the plane of the page, as shown above. Which of the following best describes the direction of the magnetic field near point *P*?
   (A) Clockwise around point *P*
   (B) Out of the page
   (C) Into the page
   (D) The field has no direction because the magnitude of the field is zero.



8. A photon with energy 4 eV is incident on metal *X*, which has a work function of 3 eV. Metal *X* is electrically connected to metal *Y* through a 2V voltage supply with the polarity shown in the figure above. What is the maximum kinetic energy an emitted electron could have when it reaches metal *Y*?
   (A) 1 eV
   (B) 2 eV
   (C) 3 eV
   (D) 5 eV



9. Two charged spheres, X and Y, are held fixed at two vertices of a triangle, as shown above. The direction of the electric field *E* at the third vertex due to the two spheres is also shown. Which of the following correctly indicates the sign of the charges on the spheres?

(A)

Sphere X	*Sphere Y*
Positive	Positive

(B)

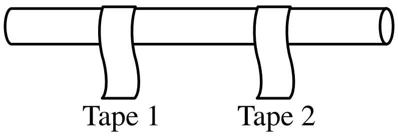
Sphere X	*Sphere Y*
Positive	Negative

(C)

Sphere X	*Sphere Y*
Negative	Positive

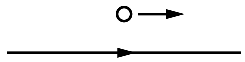
(D)

Sphere X	*Sphere Y*
Negative	Negative



	Tape 1	Tape 2
Positively charged object	Attracted	Repelled
Negatively charged object	Repelled	Attracted
Uncharged object	Attracted	Attracted

10. Two pieces of transparent adhesive tape, labeled 1 and 2, are stuck together. The pieces of tape are then quickly pulled apart and stuck to an insulating rod, as shown above. Three objects are brought near each piece of tape, one at a time. One of the objects is positively charged, one is negatively charged, and one is uncharged. The reaction of each piece of tape is recorded in the table above. Based on the results, what can be concluded about the signs of the charges on the tapes, and why?
    (A) Tape 1 is positively charged, because it is attracted to the positively charged object. Tape 2 is negatively charged because it is repelled by the positively charged object.
    (B) Tape 1 is negatively charged, because it is repelled by the negatively charged object. Tape 2 is positively charged, because it is repelled by the positively charged object.
    (C) Tape 1 and tape 2 are both positively charged because they are both attracted to the uncharged object.
    (D) Tape 1 and tape 2 are both negatively charged because they are both attracted to the uncharged object.



11. At the instant shown above, a particle with a positive charge travels to the right near a wire carrying a current to the right. What is the direction of the force exerted by the charge on the wire?
    (A) Toward the bottom of the page
    (B) Toward the top of the page
    (C) Out of the page
    (D) Into the page

12. A beam of electrons is incident on a crystal, creating a diffraction pattern. How should the speed of the electrons be changed to increase the separation of the spacing of the maxima in the pattern, and why would the pattern change?

(A) The speed should be increased, because that would increase the de Broglie wavelength of the electrons.

(B) The speed should be increased, because that would decrease the de Broglie wavelength of the electrons.

(C) The speed should be decreased, because that would increase the de Broglie wavelength of the electrons.

(D) The speed should be decreased, because that would decrease the de Broglie wavelength of the electrons.

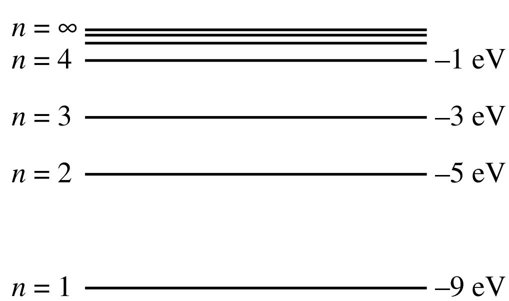
13. A canister and the hydrogen gas it contains are at 100°C. The canister is placed in a vacuum, and the temperature of the canister and gas begins to decrease. Which of the following statements of reasoning best explains how the canister-gas system loses energy?

(A) High-energy hydrogen molecules collide with lower-energy molecules and the walls inside the canister, losing energy during the collisions.

(B) The molecules collide with the walls of the canister, causing the canister molecules to vibrate and carry energy from the canister to the canister's surroundings.

(C) Energy is released from the canister as infrared radiation that can travel through the vacuum, causing a decrease in the average energy of the canister and the molecules.

(D) Energy is released from the canister and travels through the vacuum by convection, causing a decrease in the average energy of the canister and the molecules.



14. The figure above shows the energy levels for a hypothetical atom. For which transitions will the emitted photon have an energy of 4 eV? Select two answers.

(A) $n = 4$ to $n = 3$

(B) $n = 4$ to $n = 2$

(C) $n = 3$ to $n = 1$

(D) $n = 2$ to $n = 1$

15. A student is asked to use the steps listed below to induce a positive charge on an aluminum soda can. In what order could the steps be done to accomplish the task? Select two answers.

Step W: Bring a negatively charged rod near, but not touching, the can.

Step X: Ground the can.

Step Y: Remove the ground from the can.

Step Z: Move the charged rod away from the can.

(A) W, X, Y, Z

(B) W, X, Z, Y

(C) X, W, Y, Z

(D) X, W, Z, Y

Section II: Free-Response Questions

The following are examples of the kinds of free-response questions found on the exam. Note that on the actual AP Exam, there will be one experimental design question, one quantitative/qualitative translation question, one paragraph argument short answer question, and one additional short answer question.

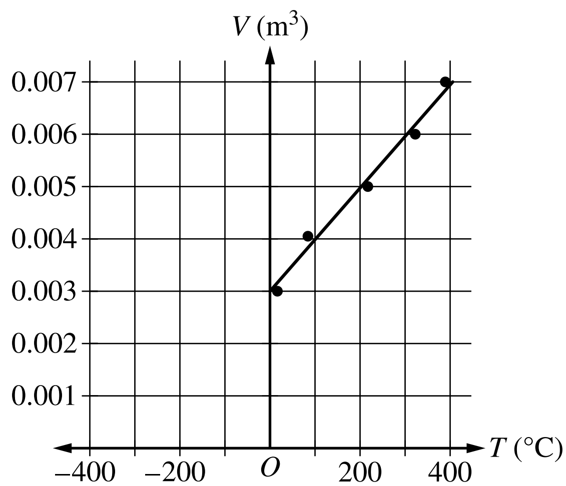
1. Students use a sample of gas to investigate the behavior of the pressure P of the gas at constant temperature T as the volume V changes. The gas is in a cylinder with a movable piston and volume markings. Pressure and temperature probes can be inserted into the cylinder. A hot water bath and a cold water bath are also available.

   (A) Describe a procedure that would allow the students to obtain data for the pressure P of the gas at constant temperature T as volume changes.

   (B) One student suggests that the temperature probe is not needed. Is the student correct? Briefly explain your answer.

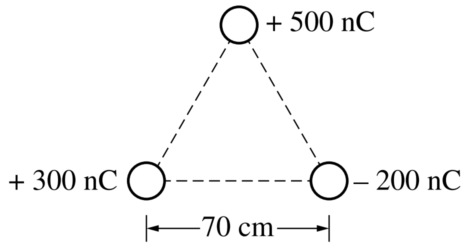
   (C) Describe a method of analyzing the pressure and volume data that could be used to determine whether the gas is ideal. Explicitly indicate the results of the analysis that would indicate an ideal gas.

   The students are now given a sample of ideal gas in a similar container with a piston. They investigate the behavior of the temperature T of the gas at known constant pressure P as the volume V changes. Their graph of the data, including a best-fit line, is shown below.



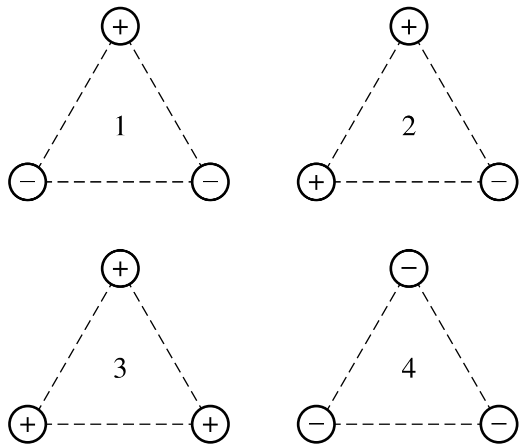
   (D) Describe a method for using the graph to determine the number of moles of gas in the container.

   (E) From the graph, determine the students' experimental value for absolute zero temperature on the Celsius scale. Describe the method you used.



2. Three small spheres, with net charges indicated above, are held fixed at the corners of an equilateral triangle with sides of length 70°cm.

   (A) Calculate the magnitude of the net electric force acting on the sphere with charge +500°nC at the top of the triangle due to the other two spheres.



   Spheres with positive or negative charges of equal magnitude are now held fixed at the corners of four identical equilateral triangles, as shown above. Each triangle is isolated from all other charges.

   (B) For which of the triangles will the net electric field at the center of the triangle be zero?

   ___ 1 ___2 ___ 3 ___ 4

   Briefly describe the method you used to arrive at your answer.

   (C) Rank the electric potentials V_1, V_2, V_3, and V_4 at the center of the triangles.

   Briefly describe the method you used to arrive at your answer.

Answer Key and Question Alignment to Course Framework

Multiple-Choice Question	Answer	Science Practice	Learning Objective	Unit
1	C	7.1 5.1	7.A.2.1 7.A.3.3	2
2	D	6.4	7.A.1.1	2
3	C	2.2 6.4	4.E.4.1 4.E.5.1	4
4	B	2.2	5.B.10.3	1
5	C	6.4	4.E.5.2	4
6	B	1.4	6.E.4.2	6
7	C	1.1	2.D.2.1	5
8	C	1.4 2.2 6.4	5.B.4.2 6.F.3.1	7
9	C	6.4	2.C.2.1	3
10	B	5.1	5.C.2.2	3
11	B	7.2 1.4	3.A.4.2 3.C.3.1	3
12	C	6.4	6.G.2.2	7
13	C	1.1 6.2	6.F.2.1 7.B.1.1	2, 6
14	B, D	1.1	7.C.4.1	7
15	A, C	4.2	4.E.3.5	3

Free-Response Question	Question Type	Question Part	Science Practice	Learning Objective	Unit
1	Experimental Design	(A)	4.2	7.A.3.2	2
		(B)	4.2	7.A.3.2	2
		(C)	5.1	7.A.3.3	2
		(D)	5.1	7.A.3.3	2
		(E)	6.4	7.A.3.1	2
2	Short Answer	(A)	2.2	3.C.2.3	3
		(B)	1.4 2.2	2.C.4.2	3
		(C)	6.4 7.2	2.E.2.1	3

The scoring information for the questions within this course and exam description, along with further exam resources, can be found on the **AP Physics 2 Exam Page** on AP Central.

AP PHYSICS 2

Scoring Guidelines

Question 1: Experimental Design

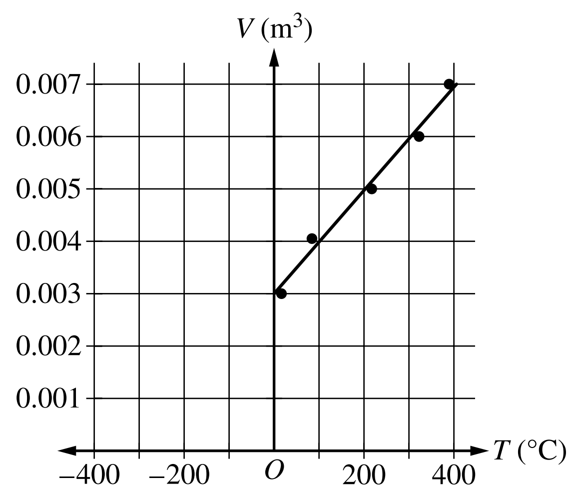
1. Students use a sample of gas to investigate the behavior of the pressure P of the gas at constant temperature T as the volume V changes. The gas is in a cylinder with a movable piston and volume markings. Pressure and temperature probes can be inserted into the cylinder. A hot water bath and a cold water bath are also available.

   (A) Describe a procedure that would allow the students to obtain data for the pressure P of the gas at constant temperature T as volume changes.

   (B) One student suggests that the temperature probe is not needed. Is the student correct? Briefly explain your answer.

   (C) Describe a method of analyzing the pressure and volume data that could be used to determine whether the gas is ideal. Explicitly indicate the results of the analysis that would indicate an ideal gas.

   The students are now given a sample of ideal gas in a similar container with a piston. They investigate the behavior of the temperature T of the gas at known constant pressure P as the volume V changes. Their graph of the data, including a best-fit line, is shown below.



   (D) Describe a method for using the graph to determine the number of moles of gas in the container.

   (E) From the graph, determine the students' experimental value for absolute zero temperature on the Celsius scale. Describe the method you used.

Scoring Guidelines for Question 1: Experimental Design — 12 points

Learning Objectives: 7.A.3.2 7.A.3.2 7.A.3.3 7.A.3.3 7.A.3.1

(A) Describe a procedure that would allow the students to obtain data for the pressure P of the gas at constant temperature T as volume changes.

One point for using one of the baths to regulate the temperature. — **1 point** 4.2

One point for using the piston to change the volume of the gas. — **1 point** 4.2

One point for waiting for the temperature to reach equilibrium before measuring pressure — **1 point** 4.2

One point for explicitly taking more than two measurements. — **1 point** 4.2

Total for part (A) — 4 points

(B) One student suggests that the temperature probe is not needed. Is the student correct? Briefly explain your answer. — **1 point** 4.2

One point for indicating that the student is incorrect with an acceptable explanation that addresses the need to know the gas temperature.

Example of acceptable explanation (claim, evidence, and reasoning):

- *The student is not correct* (claim). *As the pressure and volume change the temperature also changes* (evidence). *The gas temperature would need to be measured to verify that it has reached equilibrium with the water bath* (reasoning).

(C) Describe a method of analyzing the pressure and volume data that could be used to determine whether the gas is ideal.

One point for indicating an appropriate analysis method. — **1 point** 5.1

One point for indicating the information from the analysis that would indicate an ideal gas. — **1 point** 5.1

- Example 1: Graph pressure as a function of volume. If the gas is ideal the best fit to the data will be linear.
- Example 2: For each pressure-volume data pair, multiply the pressure and the volume. If the values are reasonably the same, the gas is ideal.

Total for part (C) — 2 points

(D) Describe a method for using the graph to determine the number of moles of gas in the container.

One point for using the slope of the graph. — **1 point** 5.1

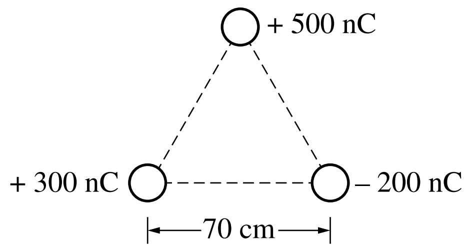
One point for indicating that the slope equals $\frac{nR}{P}$. — **1 point** 5.1

One point for noting that the fundamental constant R and the value at which P is held constant are known. — **1 point** 5.1

Total for part (D) — 3 points

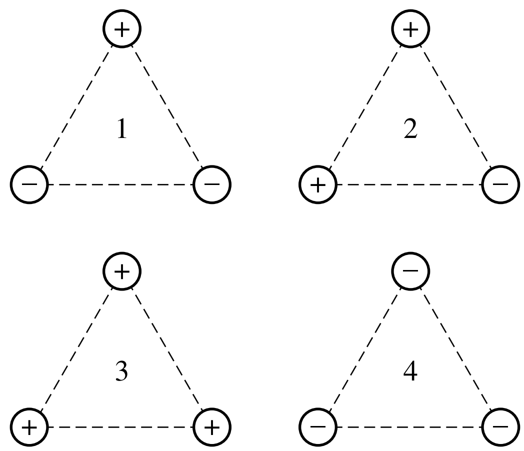
(E)	Determine the students' experimental value for absolute zero temperature on the Celsius scale.	**1 point**
	One point for indicating a value near 300° C (but not so precise as 273° C since the graph cannot be read that precisely).	6.4
	Describe the method you used.	**1 point**
	One point for describing the extrapolation of the line to zero volume to determine absolute zero.	6.4
	Total for part (E)	**2 points**
	Total for question 1	**12 points**

Question 2: Short Answer



2. Three small spheres, with net charges indicated above, are held fixed at the corners of an equilateral triangle with sides of length 70°cm.

   (A) Calculate the magnitude of the net electric force acting on the sphere with charge +500°nC at the top of the triangle due to the other two spheres.



   Spheres with positive or negative charges of equal magnitude are now held fixed at the corners of four identical equilateral triangles, as shown above. Each triangle is isolated from all other charges.

   (B) For which of the triangles will the net electric field at the center of the triangle be zero?

   ___ 1 ___2 ___ 3 ___ 4

   Briefly describe the method you used to arrive at your answer.

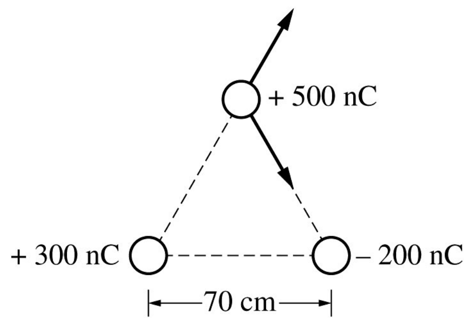
   (C) Rank the electric potentials V_1, V_2, V_3, and V_4 at the center of the triangles.

   Briefly describe the method you used to arrive at your answer.

Scoring Guidelines for Question 2: Short Answer — 10 points

Learning Objectives: 3.C.2.3 2.C.2.4 2.E.2.1

(A) Calculate the magnitude of the net electric force acting on the sphere with charge +500°nC at the top of the triangle due to the other two spheres. **1 point** 2.2



As shown above, the vertical components of the forces subtract and the horizontal components add.

One point for correct substitutions for the magnitude of the force from each of the charges.

$$F = \frac{kq_1q_2}{r^2}$$

The magnitude for the positive charge is:

$$F = \frac{\left(9.0\times10^9 \frac{Nm^2}{C^2}\right)(500\times10^{-9}\text{ C})(300\times10^{-9}\text{ C})}{(0.7\text{ m})^2} = 2.8\times10^{-3}\text{ N}$$

The magnitude for the negative charge is:

$$F = \frac{\left(9.0\times10^9 \frac{Nm^2}{C^2}\right)(500\times10^{-9}\text{ C})(200\times10^{-9}\text{ C})}{(0.7\text{ m})^2} = 1.8\times10^{-3}\text{ N}$$

One point for evidence of taking components of the forces or adding the forces as vectors. **1 point** 2.2

One point for subtracting the vertical components and adding the horizontal components. **1 point** 2.2

The net vertical force is $(2.8-1.8)(\times10^{-3}\text{ N})\sin60° = 8.6\times10^{-4}$ N.

The net horizontal force is $(2.8+1.8)(\times10^{-3}\text{ N})\cos60° = 2.3\times10^{-3}$ N.

One point for adding the sum of the squares of the components to find the magnitude of the net force. **1 point** 2.2

$$F_{net} = \sqrt{(8.6\times10^{-4})^2 + (2.3\times10^{-3})^2}\text{ N} = 2.5\times10^{-3}\text{ N}$$

Total for part (A) **4 points**

(B)	For which of the triangles will the net electric field at the center of the triangle be zero? Briefly describe the method you used to arrive at your answer. One point for indicating triangles 3 and 4 with an attempt at a relevant description.	**1 point** 1.4
	One point for treating the electric fields as vectors.	**1 point** 1.4
	One point for using the symmetry of the triangular arrangement. Example of an acceptable description: • In triangles 3 and 4, the fields from each of the three spheres all point toward the center of the triangle or away from it. This is a symmetrical arrangement, so the net force is zero.	**1 point** 1.4
	Total for part (B)	**3 points**
(C)	Rank the electric potentials V_1, V_2, V_3, and V_4 a t the center of the triangles. Briefly describe the method you used to arrive at your answer. One point for a correct ranking with an attempt at a relevant description. $V_3 > V_2 > V_1 > V_4$	**1 point** 6.4
	One point for treating the electric potentials as scalars.	**1 point** 6.4
	One point for indicating that positive charges produce a positive potential and negative charges produce a negative potential. Example of an acceptable description: • *Potential is not a vector, so the potentials from each sphere simply add. Positive charges produce positive potential, and negative charges produce negative potential. The charges are equal, so all charges produce the same magnitude of potential at the center.* V_3 *is caused by a net of 3 positive charges,* V_2 *by 2 positives,* V_1 *by 2 negatives, and* V_4 *by 3 negatives.*	**1 point** 6.4
	Total for part (C)	**3 points**
	Total for question 2	**10 points**

AP PHYSICS 2

Appendix

AP PHYSICS 2

Table of Information: Equations

AP® PHYSICS 2 TABLE OF INFORMATION

CONSTANTS AND CONVERSION FACTORS	
Proton mass, $m_p = 1.67 \times 10^{-27}$ kg	Electron charge magnitude, $e = 1.60 \times 10^{-19}$ C
Neutron mass, $m_n = 1.67 \times 10^{-27}$ kg	1 electron volt, $1 \text{ eV} = 1.60 \times 10^{-19}$ J
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Speed of light, $c = 3.00 \times 10^{8}$ m/s
Avogadro's number, $N_0 = 6.02 \times 10^{23}\ \text{mol}^{-1}$	Universal gravitational constant, $G = 6.67 \times 10^{-11}\ \text{m}^3/\text{kg}\cdot\text{s}^2$
Universal gas constant, $R = 8.31$ J/(mol•K)	Acceleration due to gravity at Earth's surface, $g = 9.8\ \text{m/s}^2$
Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	

1 unified atomic mass unit,	$1\text{ u} = 1.66 \times 10^{-27}\text{ kg} = 931\ \text{MeV}/c^2$
Planck's constant,	$h = 6.63 \times 10^{-34}\ \text{J}\cdot\text{s} = 4.14 \times 10^{-15}\ \text{eV}\cdot\text{s}$
	$hc = 1.99 \times 10^{-25}\ \text{J}\cdot\text{m} = 1.24 \times 10^{3}\ \text{eV}\cdot\text{nm}$
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2$
Coulomb's law constant,	$k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$
Vacuum permeability,	$\mu_0 = 4\pi \times 10^{-7}\ (\text{T}\cdot\text{m})/\text{A}$
Magnetic constant,	$k' = \mu_0/4\pi = 1 \times 10^{-7}\ (\text{T}\cdot\text{m})/\text{A}$
1 atmosphere pressure,	$1\text{ atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}\ \text{Pa}$

UNIT SYMBOLS								
	meter,	m	mole,	mol	watt,	W	farad,	F
	kilogram,	kg	hertz,	Hz	coulomb,	C	tesla,	T
	second,	s	newton,	N	volt,	V	degree Celsius,	°C
	ampere,	A	pascal,	Pa	ohm,	Ω	electron volt,	eV
	kelvin,	K	joule,	J	henry,	H		

PREFIXES		
Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES

θ	0°	30°	37°	45°	53°	60°	90°
$\sin\theta$	0	$1/2$	$3/5$	$\sqrt{2}/2$	$4/5$	$\sqrt{3}/2$	1
$\cos\theta$	1	$\sqrt{3}/2$	$4/5$	$\sqrt{2}/2$	$3/5$	$1/2$	0
$\tan\theta$	0	$\sqrt{3}/3$	$3/4$	1	$4/3$	$\sqrt{3}$	∞

The following conventions are used in this exam.

I. The frame of reference of any problem is assumed to be inertial unless otherwise stated.
II. In all situations, positive work is defined as work done on a system.
III. The direction of current is conventional current: the direction in which positive charge would drift.
IV. Assume all batteries and meters are ideal unless otherwise stated.
V. Assume edge effects for the electric field of a parallel plate capacitor unless otherwise stated.
VI. For any isolated electrically charged object, the electric potential is defined as zero at infinite distance from the charged object

AP® PHYSICS 2 EQUATIONS

MECHANICS

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

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

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

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

$$|\vec{F}_f| \le \mu |\vec{F}_n|$$

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

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

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

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

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

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

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

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

$$x = A\cos(\omega t) = A\cos(2\pi f t)$$

$$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$$

$$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$$

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

$$L = I\omega$$

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

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

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

a = acceleration
A = amplitude
d = distance
E = energy
F = force
f = frequency
I = rotational inertia
K = kinetic energy
k = spring constant
L = angular momentum
ℓ = length
m = mass
P = power
p = momentum
r = radius or separation
T = period
t = time
U = potential energy
v = speed
W = work done on a system
x = position
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed

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

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

$$T = \frac{2\pi}{\omega} = \frac{1}{f}$$

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

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

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

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

$$U_G = -\frac{Gm_1 m_2}{r}$$

ELECTRICITY AND MAGNETISM

$$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0}\frac{|q_1 q_2|}{r^2}$$

$$\vec{E} = \frac{\vec{F}_E}{q}$$

$$|\vec{E}| = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

$$\Delta U_E = q\Delta V$$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

$$|\vec{E}| = \left|\frac{\Delta V}{\Delta r}\right|$$

$$\Delta V = \frac{Q}{C}$$

$$C = \kappa\varepsilon_0\frac{A}{d}$$

$$E = \frac{Q}{\varepsilon_0 A}$$

$$U_C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$$

$$I = \frac{\Delta Q}{\Delta t}$$

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

$$P = I\,\Delta V$$

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

$$R_s = \sum_i R_i$$

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

$$C_p = \sum_i C_i$$

$$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$$

$$B = \frac{\mu_0}{2\pi}\frac{I}{r}$$

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
ℓ = length
P = power
Q = charge
q = point charge
R = resistance
r = separation
t = time
U = potential (stored) energy
V = electric potential
v = speed
κ = dielectric constant
ρ = resistivity
θ = angle
Φ = flux

$$\vec{F}_M = q\vec{v} \times \vec{B}$$

$$|\vec{F}_M| = |q\vec{v}||\sin\theta||\vec{B}|$$

$$\vec{F}_M = I\vec{\ell} \times \vec{B}$$

$$|\vec{F}_M| = |I\vec{\ell}||\sin\theta||\vec{B}|$$

$$\Phi_B = \vec{B}\cdot\vec{A}$$

$$\Phi_B = |\vec{B}|\cos\theta|\vec{A}|$$

$$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t}$$

$$\mathcal{E} = B\ell v$$

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

$\rho = \frac{m}{V}$

$P = \frac{F}{A}$

$P = P_0 + \rho g h$

$F_b = \rho V g$

$A_1 v_1 = A_2 v_2$

$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$

$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$

$PV = nRT = Nk_B T$

$K = \frac{3}{2}k_B T$

$W = -P\Delta V$

$\Delta U = Q + W$

A = area
F = force
h = depth
k = thermal conductivity
K = kinetic energy
L = thickness
m = mass
n = number of moles
N = number of molecules
P = pressure
Q = energy transferred to a system by heating
T = temperature
t = time
U = internal energy
V = volume
v = speed
W = work done on a system
y = height
ρ = density

MODERN PHYSICS

$E = hf$

$K_{max} = hf - \phi$

$\lambda = \frac{h}{p}$

$E = mc^2$

E = energy
f = frequency
K = kinetic energy
m = mass
p = momentum
λ = wavelength
ϕ = work function

WAVES AND OPTICS

$\lambda = \frac{v}{f}$

$n = \frac{c}{v}$

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$

$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

d = separation
f = frequency or focal length
h = height
L = distance
M = magnification
m = an integer
n = index of refraction
s = distance
v = speed
λ = wavelength
θ = angle

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

Triangle
$A = \frac{1}{2}bh$

Circle
$A = \pi r^2$
$C = 2\pi r$

Rectangular solid
$V = \ell w h$

Cylinder
$V = \pi r^2 \ell$
$S = 2\pi r\ell + 2\pi r^2$

Sphere
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

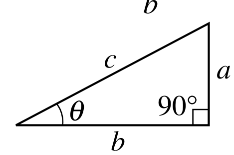
A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

Right triangle
$c^2 = a^2 + b^2$

$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

$\tan\theta = \frac{a}{b}$



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