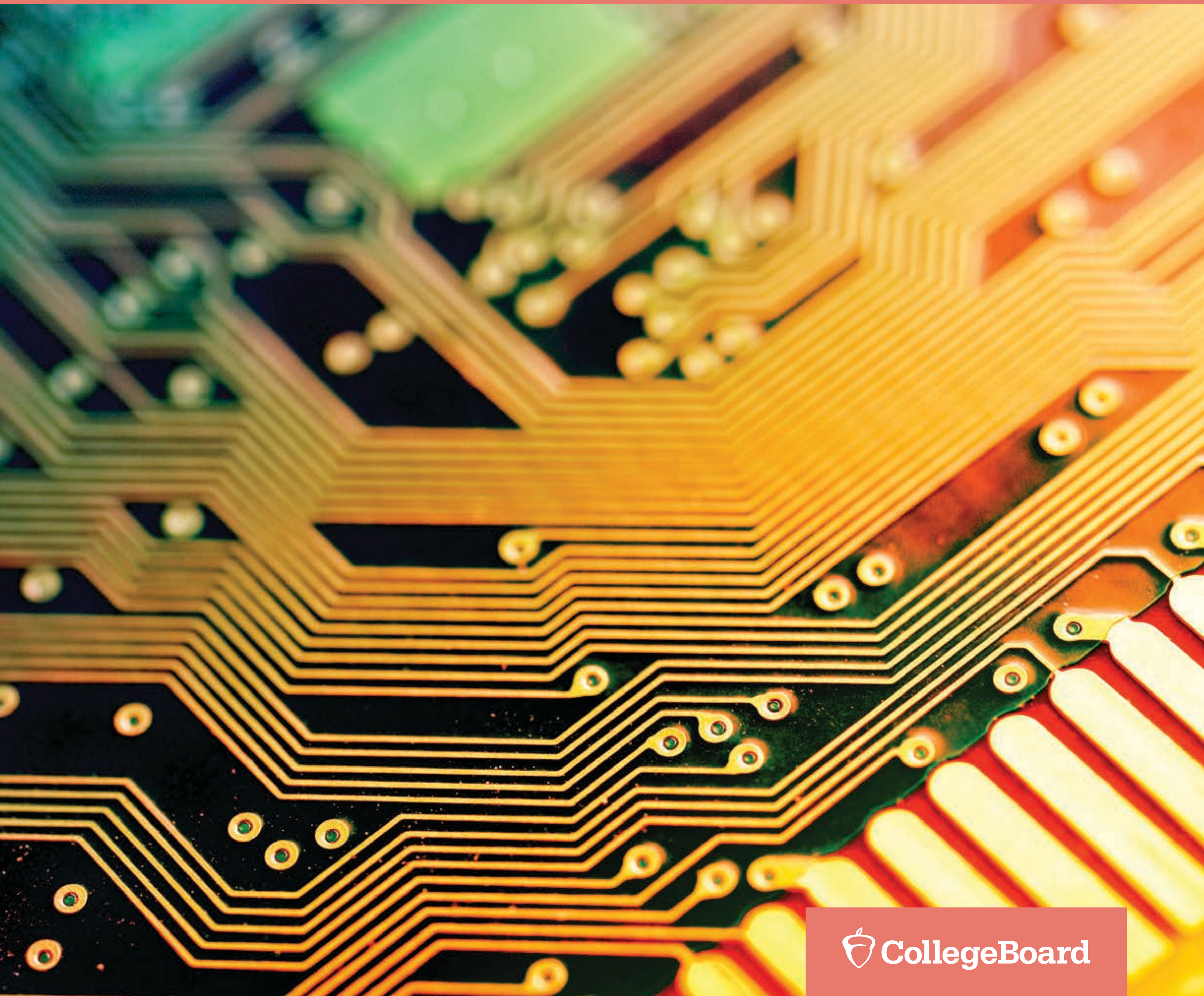
Course and Exam Description

# AP® Physics 2: Algebra-Based

Including: Course Framework and Sample Exam Questions

Updated **Fall 2017**



CollegeBoard

# AP Physics 2: Algebra-Based

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Including: Course Framework and Sample Exam Questions

Effective Fall 2017

# About the College Board

The College Board is a mission-driven not-for-profit organization that connects students to college success and opportunity. Founded in 1900, the 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, the 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 **www.collegeboard.org.**

# AP® Equity and Access Policy

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

# AP Course and Exam Descriptions

AP course and exam descriptions are updated regularly. Please visit AP Central® (**apcentral.collegeboard.org**) to determine whether a more recent course and exam description PDF is available.

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## The AP Physics 2: Algebra-Based Exam



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# About This Edition

This revised edition of the *AP Physics 2*: *Algebra-Based Course and Exam Description* provides a stand-alone course and exam description for the AP Physics 2 course. While the scope, sequence, and course content of AP Physics 2 has not changed, this revised edition provides a content outline of the course that is topically arranged. The content outline is also presented in a tabular format to more clearly show the relationships between enduring understandings, learning objectives, and essential knowledge statements.

Additional conceptual information related to each enduring understanding and learning objective is included in the essential knowledge sections of the content outline. Relevant equations from the AP Physics 2 Equations and Constants tables have also been added to the essential knowledge sections so that teachers and students can see specific instances where they apply.

The AP Physics 1 Course and Exam Description has also been revised in the same way.

# Acknowledgments

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# About AP

The College Board's Advanced Placement Program® (AP®) enables students to pursue college-level studies while still in high school. Through more than 30 courses, each culminating in a rigorous exam, AP provides willing and academically prepared students with the opportunity to earn college credit and/or advanced placement. Taking AP courses also demonstrates to college admission officers that students have sought out the most rigorous course work available to them.

Each AP course is modeled upon a comparable college course, and college and university faculty play a vital role in ensuring that AP courses align with college-level standards. Talented and dedicated AP teachers help AP students in classrooms around the world develop and apply the content knowledge and skills they will need later in college.

Each AP course concludes with a college-level assessment developed and scored by college and university faculty as well as experienced AP teachers. AP Exams are an essential part of the AP experience, enabling students to demonstrate their mastery of college-level course work. Most four-year colleges and universities in the United States and universities in more than 60 countries recognize AP in the admission process and Grant students credit, placement, or both on the basis of successful AP Exam scores. Visit **www.collegeboard.org/apcreditpolicy** to view AP credit and placement policies at more than 1,000 colleges and universities.

Performing well on an AP Exam means more than just the successful completion of a course; it is a gateway to success in college. Research consistently shows that students who receive a score of 3 or higher on AP Exams typically experience greater academic success in college and have higher graduation rates than their non-AP peers.[1] Additional AP studies are available at **www.collegeboard.org/research**.

## Offering AP Courses and Enrolling Students

This *AP Course and Exam Description* details the essential information required to understand the objectives and expectations of an AP course. The AP Program unequivocally supports the principle that each school implements its own curriculum that will enable students to develop the content knowledge and skills described here.

Schools wishing to offer AP courses must participate in the AP Course Audit, a process through with AP teachers' syllabi 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' syllabi meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses. For more information on the AP Course Audit, visit **www.collegeboard.org/apcourseaudit**.

The College Board strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial, and socioeconomic groups that have been traditionally underserved. The College Board also believes that all students should have access to

[1] See the following research studies for more details:

Linda Hargrove, Donn Godin, and Barbara Dodd, *College Outcomes Comparisons by AP and Non-AP High School Experiences* (New York: The College Board, 2008).

Chrys Dougherty, Lynn Mellor, and Shuling Jian, *The Relationship Between Advanced Placement and College Graduation* (Austin, Texas: National Center for Educational Accountability, 2006).

academically challenging course work before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

## How AP Courses and Exams Are Developed

AP courses and exams are designed by committees of college faculty and expert AP teachers who ensure that each AP subject reflects and assesses college-level expectations. A list of each subject's current AP Development Committee members is available on **apcentral.collegeboard.org**. AP Development Committees define the scope and expectations of the course, articulating through a course framework what students should know and be able to do upon completion of the AP course. Their work is informed by data collected from a range of colleges and universities to ensure that AP coursework reflects current scholarship and advances in the discipline.

The AP Development Committees are also responsible for drawing clear and well-articulated connections between the AP course and AP Exam — work that includes designing and approving exam specifications and exam questions. The AP Exam development process is a multi-year endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are high quality and fair and that there is an appropriate spread of difficulty across the questions.

Throughout AP course and exam development, the 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.

## 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 are scored by thousands of college faculty and expert AP teachers at the annual AP Reading. AP Exam 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 fills the role of Chief Reader, who, with the help of AP readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions 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 of 5, 4, 3, 2, or 1.

The score-setting process is both precise and labor intensive, involving numerous psychometric analyses of the results of a specific AP Exam in a specific year and of the particular group of students who took that exam. Additionally, to ensure alignment with college-level standards, part of the score setting process involves comparing the performance of AP students with the performance of students enrolled in comparable courses in colleges throughout the United States. In general, the AP composite score points are set so that the lowest raw score need to earn an AP score of 5 is equivalent to the average score among college students earning grades of A in the college course. Similarly, AP Exam scores of 4 are equivalent to college grades of A–, B+, and B. AP Exam scores of 3 are equivalent to college grades of B–, C+, and C.

## Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and the exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. While colleges and universities are responsible for setting their own credit and placement policies, AP scores signify how qualified students are to receive college credit or placement:

| AP Score | Qualification |
|---|---|
| 5 | Extremely well qualified |
| 4 | Well qualified |
| 3 | Qualified |
| 2 | Possibly qualified |
| 1 | No recommendation |

# Additional Resources

Visit **apcentral.collegeboard.org** for more information about the AP Program.

# About the AP Physics 2 Course

## About This 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.

## The Laboratory Requirement

This course requires that 25 percent of the instructional time be spent in hands-on laboratory work, with an emphasis on inquiry-based investigations that provide students with opportunities to demonstrate the foundational physics principles and apply all seven science practices defined in the course framework.

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.

# Participating in the AP Course Audit

Schools wishing to offer AP courses must participate in the AP Course Audit. Participation in the AP Course Audit requires the online submission of two documents: the AP Course Audit form and the teacher's syllabus. 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. The syllabus, detailing how course requirements are met, is submitted by the AP teacher for review by college faculty.

Please visit **http://www.collegeboard.com/html/apcourseaudit/courses/physics_2.html** for more information to support syllabus development including:

- **Annotated Sample Syllabi** — Provide examples of how the curricular requirements can be demonstrated within the context of actual syllabi.
- **Curricular and Resource Requirements** — Identifies the set of curricular and resource expectations that college faculty nationwide have established for a college-level course.
- **Example Textbook List** — Includes a sample of AP college-level textbooks that meet the content requirements of the AP course.
- **Syllabus Development Guide** — Includes the guidelines reviewers use to evaluate syllabi along with three samples of evidence for each requirement. This guide also specifies the level of detail required in the syllabus to receive course authorization.
- **Syllabus Development Tutorial** — Describes the resources available to support syllabus development and walks through the syllabus development guide requirement by requirement.

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# The AP Physics 2: Algebra-Based Course Framework

Based on the Understanding by Design (Wiggins and McTighe) model, the AP Physics 2 course framework is intended to provide 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, and encourages instruction that allows students to make connections across domains through a broader way of thinking about the physical world.

This course framework is structured around the "big ideas" of physics, which encompass core scientific principles, theories, and processes of the discipline. See Appendix A for a complete presentation of the following big ideas:

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 2:** *Fields existing in space can be used to explain interactions.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

**Big Idea 6:** *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:** *The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.*

A table that illustrates how the foundational physics principles support the development of these big ideas is in Appendix B.

## Overview

The **AP Science Practices** explicitly articulate the behaviors in which students need to engage in order to achieve conceptual understanding in the course. The science practices enable students to establish lines of evidence and use them to develop and refine testable explanations and predictions of natural phenomena. Because content, inquiry, and reasoning are equally important in AP Physics, each learning objective described in the concept outline combines content with inquiry and reasoning skills described in the science practices.

The **content outline** in this framework contains the key concepts and related content that define the course, topically arranged into seven content areas: Fluids; Thermodynamics; Electric Force, Field, and Potential; Electric Circuits; Magnetism and Electromagnetic Induction; Geometric and Physical Optics; and Quantum, Atomic, and Nuclear Physics.

These focus areas are presented in a tabular format. The components of the content outline are as follows:

- **Big ideas**: Each content area begins with a list of the particular big ideas that relate to the topic covered.
- **Enduring understandings:** The first column of the table lists the enduring understandings. These are the long-term takeaways related to the big ideas that a student should retain after exploring the content and skills. These understandings are expressed as generalizations that specify what a student will come to understand about the key concepts in each course. Enduring understandings are numbered to correspond with the appropriate big idea.
- **Learning objectives:** Aligned to the right of each enduring understanding are the corresponding learning objectives. The learning objectives convey what a student needs to be able to do in order to develop the enduring understandings. The learning objectives serve as targets of assessment for each course. Learning objectives are numbered to correspond with the appropriate big idea and enduring understanding (e.g., LO **5.F.1.1** is from Big Idea 5, Enduring Understanding 5.F, and is the first learning objective aligned to that EU). The science practices that align to the learning objective are also designated within brackets (e.g. **[SP 2.1, 2.2, 7.2]**).
- **Essential knowledge:** Aligned to the right of each learning objective are the corresponding essential knowledge statements. These statements describe the facts and basic concepts that a student should know and be able to recall in order to demonstrate mastery of each learning objective. Relevant equations from the AP Physics 2 Equations and Constants tables (Appendix C) are provided to show where they are applicable. Since these equations are provided to students at the exam, students do not need to memorize them, but they do need to know when and how to use them in the correct context. Essential knowledge statements are numbered to correspond with the appropriate big idea, enduring understanding, and learning objective.
- **Boundary statements:** These statements provide guidance to teachers regarding the content boundaries for 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.

# Science Practices for AP Physics

The science practices that follow capture important aspects of the work that scientists engage in, at the level of competence expected of AP Physics students. AP Physics teachers will see within the learning objectives how these practices are integrated with the course content, and they will be able to design instruction with these practices in mind.

## Science Practice 1: *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. More complex models are models of a system of objects, such as an ideal gas. A process can be simplified, too; free fall is an example of a simplified process when we consider only the interaction of the object with the Earth. Models can be both conceptual and mathematical. Ohm's law is an example of a mathematical model, while the model of a current as a steady flow of charged particles is a conceptual model (the charged particles move randomly with some net motion [drift] of particles in a particular direction). Basically, to make a good model, one needs to identify a set of the most important characteristics of a phenomenon or system that may simplify analysis. Inherent in the construction of models that physicists invent is the use of representations. Examples of representations used to model introductory physics are pictures, motion diagrams, force diagrams, graphs, energy bar charts, and ray diagrams. Mathematical representations such as equations are another example. Representations help in analyzing phenomena, making predictions, and communicating ideas. An example here is using a motion diagram and a force diagram to develop the mathematical expression of Newton's second law in component form to solve a dynamics problem.

**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.

**1.3** The student can *refine 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 *reexpress key elements of natural phenomena across multiple representations* in the domain.

## Science Practice 2: *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, we want them to 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 as well as to be aware of the conditions under which the equations/mathematical representations can be used. Students tend to rely too much on mathematical representations. When solving a problem, they need to be able to describe the problem situation in multiple ways, including picture representations, force diagrams, and so on, and then choose an appropriate mathematical representation, instead of first choosing a formula whose variables match the givens in the problem. In addition, students should be able to work with the algebraic form of the equation before they substitute values. They also should be able to evaluate the equation(s) and the answer obtained in terms of units and limiting case analysis: Does the equation lead to results that can be predicted qualitatively if one of the quantities in the problem is zero or infinity? They should be able to translate between functional relations in equations (proportionalities, inverse proportionalities, etc.) and cause-and-effect relations in the physical world. They should also be able to evaluate the numerical result in terms of whether it makes sense. For example, obtaining 35 $m/s^2$ for the acceleration of a bus — about four times the acceleration of a freely falling object — should raise flags in students' minds. In many physics situations, simple mathematical routines may be needed to arrive at a result even though they are not the focus of a learning objective.

**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.

**2.3** The student can *estimate numerically quantities* that describe natural phenomena.

## Science Practice 3: *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 free-falling objects is 9.8 $m/s^2$; $\vec{a} = \frac{\Sigma\vec{F}}{m}$).

At the opposite end of the spectrum, some students may believe that science can solve every important societal problem. Thus, helping students learn how to pose, refine, and evaluate scientific questions is an important instructional and cognitive goal, albeit a difficult skill to learn. Even within a simple physics topic, posing a scientific question can be difficult. When asked what they might want to find out about a simple pendulum, some students may ask, "How high does it swing?" Although this is a starting point from which a teacher may build, students need to be guided toward refining "fuzzy" questions and relating questions to relevant models and theories. As a first step to refining this question, students might first consider in what ways one can measure physical quantities relevant to the pendulum's motion, leading to a discussion of time, angle (amplitude), and mass. Follow-up discussions can lead to how one goes about evaluating questions such as, "Upon what does the period of a simple pendulum depend?" by designing and carrying out experiments and then evaluating data and findings.

**3.1** The student can pose scientific questions.

**3.2** The student can refine scientific questions.

**3.3** The student can evaluate scientific questions.

## **Science Practice 4:** *The student can plan and implement data collection strategies in relation to a particular scientific question.*

*[Note: Data can be collected from many different sources, e.g., investigations, scientific observations, the findings of others, historic reconstruction, and/or archived data.]*

Scientific questions can range in scope from broad to narrow, as well as in specificity, from determining influencing factors and/or causes to determining mechanism. The question posed will determine the type of data to be collected and will influence the plan for collecting data. An example of a broad question is "What caused the extinction of the dinosaurs?" whereas a narrow one is "Upon what does the period of a simple pendulum depend?" Both questions ask for influencing factors and/or causes; an answer to the former might be "An asteroid collision with Earth caused the extinction of the dinosaurs," whereas an answer to the latter might be "The period depends on the mass and length of the pendulum." To test the cause of the pendulum's period, an experimental plan might vary mass and length to ascertain if these factors indeed influence the period of a pendulum, taking care to control variables so as to determine whether one factor, the other, or both influence the period. A question could be posed to ask about mechanism, e.g., "How did the dinosaurs become extinct?" or "How does the period of a simple pendulum depend on the mass and length?" In the second question, the object is to determine a mathematical relationship between period, mass, and length of a pendulum. Designing and improving experimental designs and/or data collection strategies is a learned skill. A class discussion among students in a pendulum experiment might find some who measured the time for a single round-trip, while others timed 10 round-trips and divided by 10. Such discussions can reveal issues of measurement uncertainty and assumptions about the motion. Students need to understand that the result of collecting and using data to determine a numerical answer to a question is 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. Although detailed error analysis is not necessary to convey this pivotal idea, 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.

**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.

**4.3** The student can collect data to answer a particular scientific question.

**4.4** The student can evaluate sources of data to answer a particular scientific question.

## **Science Practice 5:** *The student can perform data analysis and evaluation of evidence.*

Students often think that to make a graph they need to connect the 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 do not fit a linear relationship (such as quadratic or exponential functions).

Students should be able to represent data points as intervals whose size depends 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 (see **Science Practice 6.4**). It is important that students understand that instruments do not produce exact measurements and learn what steps they can take to decrease the 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 two 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 that for some may appear anomalous.

**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.

## Science Practice 6: *The student can work with scientific explanations and theories.*

Scientific explanations may specify a cause-and-effect relationship between variables or describe a mechanism through which a particular phenomenon occurs. Newton's second law, expressed as $\vec{a} = \frac{\Sigma\vec{F}}{m}$, gives the acceleration observed when a given combination of forces is exerted on an object with a certain mass. Liquids dry up because randomly moving molecules can leave liquids if their kinetic energy is higher than the negative potential energy of interaction between them and the liquid. A scientific explanation, accounting for an observed phenomenon, needs to be experimentally testable. One should be able to use it to make predictions about a new phenomenon. A 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. Examples of theories in physics include kinetic molecular theory, quantum theory, and atomic theory. Students should understand the difference between explanations and theories.

In this framework the word "claim" means any answer that a student provides except those that constitute direct and simple observational evidence. To say that all objects fall down is not a claim, but to say that all objects fall with the same acceleration is a claim, as one would need to back it up with evidence and a chain of reasoning. Students should be prepared to offer evidence, to construct reasoned arguments for their claim from the evidence, and to use the claim or explanation to make predictions. A prediction states the expected outcome of a particular experimental design based on an explanation or a claim under scrutiny. Consider the claim that current is directly proportional to potential difference across conductors based on data from an experiment varying voltage across a resistor and measuring current through it. The claim can be tested by connecting other resistors or lightbulbs in the circuit, measuring the voltage, using the linear relationship to predict the current, and comparing the predicted and measured current. This procedure tests the claim. Students should be able to design experiments to test alternative explanations of phenomena by comparing predicted outcomes. For example, students may think that liquids dry because air absorbs moisture. To test the claim they can design an experiment in which the same liquid dries in two conditions: in open air and in a vacuum jar. If the claim is correct, the liquid should dry faster in air. If the outcome does not match the prediction, the explanation is likely to be false. By contrast, if the outcome confirms the prediction, it only means that this experiment does not disprove the explanation; alternate explanations of the given outcome can always be formulated. Looking for experiments that can reject explanations and claims is at the heart of science.

**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.



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**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.

**6.5** The student can evaluate alternative scientific explanations.

## Science Practice 7: *The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.*

Students should have the opportunity to transfer their learning across disciplinary boundaries so that they are able to link, synthesize, and apply the ideas they learn across the sciences and mathematics. Research on how people learn indicates that providing multiple contexts to which major ideas apply facilitates transfer; this allows students to bundle knowledge in memory 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. After learning various conservation laws in the context of mechanics, students should be able to describe what the concept of conservation means in physics and extend the idea to other contexts. For example, what might conservation of energy mean at high-energy scales with particle collisions, where Einstein's mass–energy equivalence plays a major role? What does conservation of energy mean when constructing or evaluating arguments about global warming? Another context in which students may apply ideas from physics across vast spatial and time scales is the origin of human life on Earth coupled with the notion of extraterrestrial intelligent life. If one views the age of the Earth in analogy to a year of time (see Ritger & Cummins, 1991) with the Earth formed on January 1, then life began on Earth around April 5; multicellular organisms appeared on November 6; mammals appeared on December 23. Perhaps most amazingly, humans appeared on December 31 just 28 minutes before midnight. What are the implications of this for seeking intelligent life outside our solar system? What is a reasonable estimate of the probability of finding intelligent life on an earthlike planet that scientists might discover through astronomical observations, and how does one go about making those estimates? Although students are not expected to answer these very complex questions after a single AP science course, they should be able to talk intelligently about them using the concepts they learned.

**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.

# Content Outline

## Content Area 1: Fluids

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system. | **1.A.5.2:** The student is able to 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]** | **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*. |
| **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.1.1:** The student is able to 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]**<br><br>**1.E.1.2:** The student is able to 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]** | **1.E.1:** Matter has a property called density.<br>*Relevant Equation:*<br>$\rho = \frac{m}{V}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.2.1:** The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]** | **EK 3.A.2:** Forces are described by vectors.<br>a. Forces are detected by their influence on the motion of an object.<br>b. Forces have magnitude and direction.<br>**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.* |
| | **3.A.3.2:** The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]**<br>**3.A.3.3:** The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**<br>**3.A.3.4:** The student is able to make claims about the force on an object due to the presence of other objects with the same property: 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.<br>a. An object cannot exert a force on itself.<br>b. Even though an object is at rest, there may be forces exerted on that object by other objects.<br>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.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br><br>(Continued) | **3.A.4.1:** The student is able to 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]**<br><br>**3.A.4.2:** The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**<br><br>**3.A.4.3:** The student is able to 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. |
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.3:** The student is able to reexpress 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]**<br><br>**3.B.1.4:** The student is able to 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]** | **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.<br><br>*Relevant Equation:*<br><br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$<br><br>**Boundary Statement:**<br>*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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.<br><br>(Continued) | **3.B.2.1:** The student is able to 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]** | **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.<br><br>a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.<br><br>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.<br><br>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. |
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.4.1:** The student is able to make claims about various contact forces between objects based on the microscopic cause of those forces. **[SP 6.1]**<br><br>**3.C.4.2:** The student is able to explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. **[SP 6.2]** | **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).<br><br>*Relevant Equations:*<br><br>$F_b = \rho V g$<br><br>$P = \frac{F}{A}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.10.1:** The student is able to use Bernoulli's equation to make calculations related to a moving fluid. **[SP 2.2]**<br><br>**5.B.10.2:** The student is able to use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid. **[SP 2.2]**<br><br>**5.B.10.3:** The student is able to use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid. **[SP 2.2]**<br><br>**5.B.10.4:** The student is able to construct an explanation of Bernoulli's equation in terms of the conservation of energy. **[SP 6.2]** | **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 ($\rho gh$).<br><br>*Relevant Equations:*<br><br>$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2$<br><br>$P = \frac{F}{A}$<br><br>$A_1 v_1 = A_2 v_2$<br><br>$P = P_0 + \rho g h$ |
| **5.F:** Classically, the mass of a system is conserved. | **5.F.1.1:** The student is able to make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation). **[SP 2.1, 2.2, 7.2]** | **5.F.1:** The continuity equation describes conservation of mass flow rate in fluids. Examples include volume rate of flow and mass flow rate.<br><br>*Relevant Equation:*<br><br>$A_1 v_1 = A_2 v_2$<br><br>**Boundary Statement:**<br>*Fluid viscosity is not part of Physics 1.* |

# Content Area 2: Thermodynamics

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

**Big Idea 7:** *The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.*

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system. | **1.A.5.2:** The student is able to 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]** | **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*. |
| **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.3.1:** The student is able to design an experiment and analyze data from it to examine thermal conductivity. **[SP 4.1, 4.2, 5.1]** | **1.E.3:** Matter has a property called thermal conductivity. Thermal conductivity is the measure of a material's ability to transfer thermal energy.<br>*Relevant Equation:*<br>$\frac{Q}{\Delta t} = \frac{kA\Delta T}{\Delta L}$ |
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.2.1:** The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]** | **EK 3.A.2:** Forces are described by vectors.<br>a. Forces are detected by their influence on the motion of an object.<br>b. Forces have magnitude and direction.<br>**Boundary Statement:**<br>*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.* |

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br>(Continued) | **3.A.3.2:** The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]**<br>**3.A.3.3:** The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**<br>**3.A.3.4:** The student is able to make claims about the force on an object due to the presence of other objects with the same property: 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.<br>a. An object cannot exert a force on itself.<br>b. Even though an object is at rest, there may be forces exerted on that object by other objects.<br>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.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ |
| | **3.A.4.1:** The student is able to 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]**<br>**3.A.4.2:** The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**<br>**3.A.4.3:** The student is able to 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** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.3:** The student is able to reexpress 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]**<br><br>**3.B.1.4:** The student is able to 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]** | **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.<br><br>*Relevant Equation:*<br><br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$<br><br>**Boundary Statement:** *AP Physics 2 contains learning objectives 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.* |
| | **3.B.2.1:** The student is able to 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]** | **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.<br><br>a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.<br><br>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.<br><br>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. |
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.4.1:** The student is able to make claims about various contact forces between objects based on the microscopic cause of those forces. **[SP 6.1]**<br><br>**3.C.4.2:** The student is able to explain contact forces (tension, friction, normal, buoyant, spring) as arising from interatomic electric forces and that they therefore have certain directions. **[SP 6.2]** | **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).<br><br>*Relevant Equations:*<br><br>$F_b = \rho V g$<br><br>$P = \frac{F}{A}$ |

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **4.C:** Interactions with other objects or systems can change the total energy of a system. | **4.C.3.1:** The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. **[SP 6.4]** | **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.<br>a. Conduction, convection, and radiation are mechanisms for this energy transfer.<br>b. At a microscopic scale the mechanism of conduction is the transfer of kinetic energy between particles.<br>c. During average collisions between molecules, kinetic energy is transferred from faster molecules to slower molecules. |
| **5.B:** The energy of a system is conserved. | **5.B.2.1:** The student is able to 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, the student can 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]** | **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 object in electric fields and examining changes in internal energy with changes in configuration.]<br>*Relevant Equation:*<br>$\Delta U_E = q\Delta V$<br>**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.* |
| | **5.B.4.1:** The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**<br>**5.B.4.2:** The student is able to 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.<br>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.<br>b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br>(Continued) | **5.B.5.4:** The student is able to 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]**<br><br>**5.B.5.5:** The student is able to 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]**<br><br>**5.B.5.6:** The student is able to 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]** | **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.<br><br>*Relevant Equations:*<br><br>$\Delta E = W = Fd\cos\theta$<br><br>$P = \frac{\Delta E}{\Delta t}$ |
| | **5.B.6.1:** The student is able to 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]** | **5.B.6:** Energy can be transferred by thermal processes involving differences in temperature; this process of transfer is called heat. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br><br>(Continued) | **5.B.7.1:** The student is able to 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]**<br><br>**5.B.7.2:** The student is able to create a plot of pressure versus volume for a thermodynamic process from given data. **[SP 1.1]**<br><br>**5.B.7.3:** The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). **[SP 1.1, 1.4, 2.2]** | **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 P-V diagrams — isovolumetric process, isothermal process, isobaric process, and adiabatic process. 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.<br><br>*Relevant Equations:*<br><br>$W = -P\Delta V$<br><br>$\Delta U = Q + W$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved. | **5.D.1.6:** The student is able to 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]**<br><br>**5.D.1.7:** The student is able to 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]** | **5.D.1:** In a collision between objects, linear momentum is conserved. In an elastic collision, kinetic energy is the same before and after.<br><br>a. In a closed system, the linear momentum is constant throughout the collision.<br><br>b. In a closed system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision.<br><br>*Relevant Equations:*<br><br>$p = mv$<br><br>$K = \frac{1}{2}mv^2$<br><br>**Boundary Statement:**<br>*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 in 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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved.<br><br>(Continued) | **5.D.2.5:** The student is able to 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]**<br><br>**5.D.2.6:** The student is able to 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.<br><br>a. In a closed system, the linear momentum is constant throughout the collision.<br><br>b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.<br><br>*Relevant Equations:*<br><br>$p = mv$<br><br>$K = \frac{1}{2}mv^2$ |
| **7.A:** The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure. | **7.A.1.1:** The student is able to 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]**<br><br>**7.A.1.2:** Treating a gas molecule as an object (i.e., ignoring its internal structure), the student is able to analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, to quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables. **[SP 1.4, 2.2]** | **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.<br><br>*Relevant Equations:*<br><br>$P = \frac{F}{A}$<br><br>$\Delta p = F\Delta t$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **7.A:** The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure.<br><br>(Continued) | **7.A.2.1:** The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. **[SP 7.1]**<br><br>**7.A.2.2:** The student is able to connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and to relate this to thermodynamic processes. **[SP 7.1]** | **7.A.2:** The temperature of a system characterizes the average kinetic energy of its molecules.<br><br>a. The average kinetic energy of the system is an average over the many different speeds of the molecules in the system that can be described by a distribution curve.<br><br>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.<br><br>*Relevant Equation:*<br><br>$K = \frac{3}{2}k_B T$ |
| | **7.A.3.1:** The student is able to 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]**<br><br>**7.A.3.2:** The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables. **[SP 3.2, 4.2]**<br><br>**7.A.3.3:** The student is able to 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]** | **7.A.3:** In an ideal gas, the macroscopic (average) pressure ($P$), temperature ($T$), and volume ($V$), are related by the ideal gas law $PV = nRT$.<br><br>*Relevant Equation:*<br><br>$PV = nRT = Nk_B T$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **7.B:** The tendency of isolated systems to move toward states with higher disorder is described by probability. | **7.B.1.1:** The student is able to 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]** | **7.B.1:** The approach to thermal equilibrium is a probability process.<br><br>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.<br><br>b. The details of the energy transfer depend upon interactions at the molecular level.<br><br>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. |
| | **7.B.2.1:** The student is able to 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]** | **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.<br><br>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.<br><br>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.<br><br>c. The entropy of a closed system never decreases, i.e., it can stay the same or increase.<br><br>d. The total entropy of the universe is always increasing. |

# Content Area 3: Electric Force, Field, and Potential

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 2:** *Fields existing in space can be used to explain interactions.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system. | **1.A.5.2:** The student is able to 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]** | **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.* |
| **1.B:** Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge. | **1.B.1.1:** The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**<br><br>**1.B.1.2:** The student is able to 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]** | **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.<br><br>a. An electrical current is a movement of charge through a conductor.<br><br>b. A circuit is a closed loop of electrical current.<br><br>*Relevant Equation:*<br><br>$I = \frac{\Delta Q}{\Delta t}$<br><br>**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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.B:** Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge.<br><br>(Continued) | **1.B.2.1:** The student is able to construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**<br><br>**1.B.2.2:** The student is able to 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]**<br><br>**1.B.2.3:** The student is able to 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.<br><br>a. Like-charged objects and systems repel, and unlike-charged objects and systems attract.<br><br>b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system. |
| | **1.B.3.1:** The student is able to challenge 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.<br><br>a. The magnitude of the elementary charge is equal to $1.6 \times 10^{-19}$ coulombs.<br><br>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. |
| **1.E**: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. | *[While there is no specific learning objective for it, EK 1.E.4 serves as a foundation for other learning objectives in the course.]* | **1.E.4**: Matter has a property called electric permittivity.<br><br>a. Free space has a constant value of the permittivity that appears in physical relationships.<br><br>b. The permittivity of matter has a value different from that of free space. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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. | *[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.<br>a. Vector fields are represented by field vectors indicating direction and magnitude.<br>b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition.<br>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.<br>a. Scalar fields are represented by field values.<br>b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition.<br>c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources. |
| **2.C:** An electric field is caused by an object with electric charge. | **2.C.1.1:** The student is able to 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]**<br>**2.C.1.2:** The student is able to 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]** | **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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br><br>(Continued) | **2.C.2.1:** The student is able to qualitatively and semiquantitatively 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:** The student is able to 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.<br><br>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<br><br>$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$.<br><br>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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br><br>(Continued) | **2.C.4.1:** The student is able to 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]**<br><br>**2.C.4.2:** The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points. **[SP 1.4, 2.2]** | **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.<br><br>a. When an object is small compared to 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."<br><br>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.<br><br>*Relevant Equation:*<br><br>$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br><br>(Continued) | **2.C.5.1:** The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates. **[SP 1.1, 2.2]**<br><br>**2.C.5.2:** The student is able to 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]**<br><br>**2.C.5.3:** The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field. **[SP 1.1, 2.2, 7.1]** | **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.<br><br>*Relevant Equations:*<br><br>$E = \frac{Q}{\varepsilon_0 A}$<br><br>$E = \frac{\Delta V}{\Delta r}$<br><br>$\Delta V = \frac{Q}{C}$<br><br>$U_C = \frac{1}{2}Q\Delta V = \frac{1}{2}C(\Delta V)^2$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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. | **2.E.1.1:** The student is able to 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]** | **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.]<br><br>*Relevant Equation:*<br><br>$U_G = -\frac{Gm_1m_2}{r}$ |
| | **2.E.2.1:** The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field. **[SP 6.4, 7.2]**<br><br>**2.E.2.2:** The student is able to 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]**<br><br>**2.E.2.3:** The student is able to qualitatively use the concept of isolines to construct isolines of electric potential in an electric field and determine the effect of that field on electrically charged objects. **[SP 1.4]** | **2.E.2:** Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as equipotential lines.<br><br>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.<br><br>b. Since the electric potential has the same value along an isoline, there can be no component of the electric field along the isoline.<br><br>*Relevant Equation:*<br><br>$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$ |

| **Enduring Understanding**<br>(Core concepts that students should retain) | **Learning Objectives**<br>(What students must be able to do) | **Essential Knowledge**<br>(What students need to know) |
|---|---|---|
| **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.<br><br>(Continued) | **2.E.3.1:** The student is able to 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]**<br><br>**2.E.3.2:** The student is able to 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]** | **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.<br><br>*Relevant Equation:*<br><br>$E = \frac{\Delta V}{\Delta r}$ |
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.2.1:** The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]** | **3.A.2:** Forces are described by vectors.<br><br>a. Forces are detected by their influence on the motion of an object.<br><br>b. Forces have magnitude and direction.<br><br>**Boundary Statement:**<br>*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.* |
| | **3.A.3.2:** The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]**<br><br>**3.A.3.3:** The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**<br><br>**3.A.3.4:** The student is able to make claims about the force on an object due to the presence of other objects with the same property: 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.<br><br>a. An object cannot exert a force on itself.<br><br>b. Even though an object is at rest, there may be forces exerted on that object by other objects.<br><br>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.<br><br>*Relevant Equation:*<br><br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br>(Continued) | **3.A.4.1:** The student is able to 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]**<br>**3.A.4.2:** The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**<br>**3.A.4.3:** The student is able to 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. |
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.3:** The student is able to reexpress 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]**<br>**3.B.1.4:** The student is able to 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]** | **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$<br>**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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. (Continued) | **3.B.2.1:** The student is able to 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]** | **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.<br>a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.<br>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.<br>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. |
| **3C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.2.1:** The student is able to use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. **[SP 2.2, 6.4]**<br>**3.C.2.2:** The student is able to connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**<br>**3.C.2.3:** The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry). **[SP 2.2]** | **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.<br>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 nonfundamental forces called contact forces, such as normal force, friction, and tension.<br>b. Electric forces may be attractive or repulsive, depending upon the charges on the objects involved.<br>*Relevant Equations:*<br>$F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$<br>$F_G = \frac{G m_1 m_2}{r^2}$ |
| **3G:** Certain types of forces are considered fundamental. | **3.G.1.2:** The student is able to connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces. **[SP 7.1]** | **3.G.1:** Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales.<br>*Relevant Equation:*<br>$F_G = \frac{G m_1 m_2}{r^2}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3G:** Certain types of forces are considered fundamental.<br><br>Continued | **3.G.2.1:** The student is able to 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]** | **3.G.2:** Electromagnetic forces are exerted at all scales and can dominate at the human scale.<br><br>*Relevant Equation:*<br><br>$F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$ |
| **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. | **4.E.3.1:** The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction. **[SP 6.4]**<br><br>**4.E.3.2:** The student is able to 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]**<br><br>**4.E.3.3:** The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors. **[SP 1.1, 1.4, 6.4]**<br><br>**4.E.3.4:** The student is able to 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]**<br><br>**4.E.3.5:** The student is able to plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is 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]** | **4.E.3:** The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.<br><br>a. Charging can take place by friction or by contact.<br><br>b. An induced charge separation can cause a neutral object to become polarized.<br><br>c. Charging by induction can occur when a polarizing conducting object is touched by another.<br><br>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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.2.1:** The student is able to 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, the student can 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]** | **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 object in electric fields and examining changes in internal energy with changes in configuration.]<br><br>*Relevant Equation:*<br>$\Delta U_E = q\Delta V$<br><br>**Boundary Statement:**<br>*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.* |
| | **5.B.4.1:** The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**<br><br>**5.B.4.2:** The student is able to 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.<br><br>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.<br><br>b. The changes in potential and kinetic energies in a system may be further constrained by the construction of the system.<br><br>**Boundary Statement:**<br>*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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| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br><br>(Continued) | **5.B.5.4:** The student is able to 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]**<br><br>**5.B.5.5:** The student is able to 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]**<br><br>**5.B.5.6:** The student is able to 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]** | **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.<br><br>*Relevant Equations:*<br><br>$\Delta E = W = Fd\cos\theta$<br><br>$P = \frac{\Delta E}{\Delta t}$ |
| **5.C:** The electric charge of a system is conserved. | **5.C.2.1:** The student is able to predict electric charges on objects within a system by application of the principle of charge conservation within a system. **[SP 6.4]**<br><br>**5.C.2.2:** The student is able to 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]**<br><br>**5.C.2.3:** The student is able to 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]** | **5.C.2:** The exchange of electric charges among a set of objects in a system conserves electric charge.<br><br>a. Charging by conduction between objects in a system conserves the electric charge of the entire system.<br><br>b. Charge separation in a neutral system can be induced by an external charged object placed close to the neutral system.<br><br>c. Grounding involves the transfer of excess charge to another larger system (e.g., the Earth). |

# Content Area 4: Electric Circuits

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **1.B:** Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge. | **1.B.1.1:** The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**<br><br>**1.B.1.2:** The student is able to 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]** | **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.<br><br>a. An electrical current is a movement of charge through a conductor.<br><br>b. A circuit is a closed loop of electrical current.<br><br>*Relevant Equation:*<br><br>$I = \frac{\Delta Q}{\Delta t}$<br><br>**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.* |
| | **1.B.2.1:** The student is able to construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**<br><br>**1.B.2.2:** The student is able to 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]**<br><br>**1.B.2.3:** The student is able to challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object. **[SP 6.1]** | **EK 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.<br><br>a. Like-charged objects and systems repel, and unlike-charged objects and systems attract.<br><br>b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system. |



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| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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.2.1:** The student is able to choose and justify the selection of data needed to determine resistivity for a given material. **[SP 4.1]** | **1.E.2:** Matter has a property called resistivity.<br>a. The resistivity of a material depends on its molecular and atomic structure.<br>b. The resistivity depends on the temperature of the material.<br>*Relevant Equation:*<br>$R = \frac{\rho l}{A}$ |
| **4.E:** The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects of systems. | **4.E.4.1:** The student is able to 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]**<br>**4.E.4.2:** The student is able to 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]**<br>**4.E.4.3:** The student is able to 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]** | **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.<br>a. The resistance of a resistor is proportional to its length and inversely proportional to its cross-sectional area.<br>The constant of proportionality is the resistivity of the material.<br>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, $\kappa$, of the material between the plates and the electric permittivity, $\varepsilon_0$.<br>c. The current through a resistor is equal to the potential difference across the resistor divided by its resistance.<br>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.<br>*Relevant Equations:*<br>$R = \frac{\rho l}{A}$<br>$C = \kappa\varepsilon_0 \frac{A}{d}$<br>$I = \frac{\Delta V}{R}$<br>$\Delta V = \frac{Q}{C}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **4.E:** The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects of systems.<br><br>(Continued) | **4.E.5.1:** The student is able to 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]**<br><br>**4.E.5.2:** The student is able to 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]**<br><br>**4.E.5.3:** The student is able to 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**] | **4.E.5:** The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors.<br><br>*Relevant Equations:*<br><br>$I = \frac{\Delta V}{R}$<br><br>$R_S = \sum_i R_i$<br><br>$\frac{1}{R_P} = \sum_i \frac{1}{R_i}$<br><br>$C_P = \sum_i \frac{1}{C_i}$<br><br>$\frac{1}{C_S} = \sum_i \frac{1}{C_i}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.9.4:** The student is able to analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule. ($\Sigma \Delta V = 0$) **[SP 5.1]**<br><br>**5.B.9.5:** The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. **[SP 6.4]**<br><br>**5.B.9.6:** The student is able to 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]**<br><br>**5.B.9.7:** The student is able to 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]**<br><br>**5.B.9.8:** The student is able to translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor. **[SP 1.5]** | **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.]<br><br>a. Energy changes in simple electrical circuits are conveniently represented in terms of energy change per charge moving through a battery and a resistor.<br><br>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.<br><br>c. The electric potential difference across a resistor is given by the product of the current and the resistance.<br><br>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.<br><br>e. Energy conservation can be applied to combinations of resistors and capacitors in series and parallel circuits.<br><br>*Relevant Equations:*<br><br>$\sum \Delta V = 0$<br><br>$\Delta V = IR$<br><br>$P = I\Delta V$<br><br>**Boundary Statement:**<br>*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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.C:** The electric charge of a system is conserved. | **5.C.3.4:** The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation. **[SP 6.4, 7.2]**<br><br>**5.C.3.5:** The student is able to 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]**<br><br>**5.C.3.6:** The student is able to 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]**<br><br>**5.C.3.7:** The student is able to 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]** | **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, 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.]<br><br>*Relevant Equations:*<br><br>$I = \frac{\Delta V}{R}$<br><br>$R_S = \sum_i R_i$<br><br>$\frac{1}{R_P} = \sum_i \frac{1}{R_i}$<br><br>$C_P = \sum_i \frac{1}{C_i}$<br><br>$\frac{1}{C_S} = \sum_i \frac{1}{C_i}$<br><br>$I = \Delta Q / \Delta t$ |

# Content Area 5: Magnetism and Electromagnetic Induction

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 2:** *Fields existing in space can be used to explain interactions.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system. | **1.A.5.2:** The student is able to 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]** | **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*. |
| **1.E:** Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. | *[While there is no specific learning objective for it, EK 1.E.5 serves as a foundation for other learning objectives in the course.]* | **1.E.5**: Matter has a property called magnetic permeability.<br><br>a. Free space has a constant value of the permeability that appears in physical relationships.<br><br>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.<br><br>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.<br><br>b. Permanent magnetism or induced magnetism of matter is a system property resulting from the alignment of magnetic dipole moments within the system. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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. | *[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.<br>a. Vector fields are represented by field vectors indicating direction and magnitude.<br>b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition.<br>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.<br>a. Scalar fields are represented by field values.<br>b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition.<br>c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources. |
| **2.C:** An electric field is caused by an object with electric charge. | **2.C.4.1:** The student is able to 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:** 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.<br>a. When an object is small compared to 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."<br>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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **2.D:** A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects of by magnetic dipoles or combinations of dipoles and never by single poles. | **2.D.1.1:** The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. **[SP 2.2]** | **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.<br>*Relevant Equations:*<br>$F_M = qv \ X \ B$<br>$F_M = qv \ sin\theta \ B$ |
| | **2.D.2.1:** The student is able to create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires. **[SP 1.1]** | **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.<br>a. The magnitude of the magnetic field is proportional to the magnitude of the current in a long straight wire.<br>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.<br>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.<br>*Relevant Equation:*<br>$B = \frac{\mu_o}{2\pi} \frac{I}{r}$ |
| | **2.D.3.1:** The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet. **[SP 1.2]** | **2.D.3:** A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.<br>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.<br>b. A compass needle is a permanent magnetic dipole. Iron filings in a magnetic field become induced magnetic dipoles.<br>c. All magnets produce a magnetic field. Examples include magnetic field pattern of a bar magnet as detected by iron filings or small compasses.<br>d. The Earth has a magnetic field. |

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **2.D:** A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects of by magnetic dipoles or combinations of dipoles and never by single poles.<br><br>(Continued) | **2.D.4.1:** The student is able to use the representation of magnetic domains to 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.<br><br>a. Magnetic domains can be aligned by external magnetic fields or can spontaneously align.<br><br>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.<br><br>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. |
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.2.1:** The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]** | **3.A.2:** Forces are described by vectors.<br><br>a. Forces are detected by their influence on the motion of an object.<br><br>b. Forces have magnitude and direction.<br><br>**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.* |
| | **3.A.3.2:** The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]**<br><br>**3.A.3.3:** The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**<br><br>**3.A.3.4:** The student is able to make claims about the force on an object due to the presence of other objects with the same property: 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.<br><br>a. An object cannot exert a force on itself.<br><br>b. Even though an object is at rest, there may be forces exerted on that object by other objects.<br><br>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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. (Continued) | **3.A.4.1:** The student is able to 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]**<br>**3.A.4.2:** The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**<br>**3.A.4.3:** The student is able to 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. |
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.3:** The student is able to reexpress 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]**<br>**3.B.1.4:** The student is able to 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]** | **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$<br>**Boundary Statement:**<br>*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.* |

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **3B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.<br><br>(Continued) | **3.B.2.1:** The student is able to 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]** | **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.<br><br>a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.<br><br>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.<br><br>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. |
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.3.1:** The student is able to 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]**<br><br>**3.C.3.2:** The student is able to 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]** | **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.<br><br>a. Magnetic dipoles have “north” and “south” polarity.<br><br>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.<br><br>c. In the presence of an external magnetic field, the magnetic dipole moment vector will align with the external magnetic field.<br><br>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.<br><br>*Relevant Equations:*<br><br>$F_M = Il \ X \ B$<br><br>$F_M = Il \ \sin\theta \ B$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.G:** Certain types of forces are considered fundamental. | **3.G.2.1:** The student is able to 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**] | **3.G.2:** Electromagnetic forces are exerted at all scales and can dominate at the human scale.<br>*Relevant Equation:*<br>$F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$ |
| **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. | **4.E.1.1:** The student is able to 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**] | **4.E.1:** The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.<br>a. Ferromagnetic materials can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles.<br>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.<br>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 to the external magnetic field. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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.<br><br>(Continued) | **4.E.2.1:** The student is able to 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]** | **4.E.2:** Changing magnetic flux induces an electric field that can establish an induced emf in a system.<br><br>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.<br><br>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.<br><br>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.<br><br>d. The conservation of energy determines the direction of the induced emf relative to the change in the magnetic flux.<br><br>*Relevant Equations:*<br><br>$\Phi_B = BA$<br><br>$\Phi_B = B \cos\theta\ A$<br><br>$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$<br><br>$\varepsilon = Blv$ |

# Content Area 6: Geometric and Physical Optics

**Big Idea 6:** *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.*

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6.A:** A wave is a traveling disturbance that transfers energy and momentum. | **6.A.1.2:** The student is able to describe representations of transverse and longitudinal waves. **[SP 1.2]**<br><br>**6.A.1.3:** The student is able to 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]** | **6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal.<br><br>a. Mechanical waves can either be transverse or longitudinal. Examples include waves on stretched strings and sound waves.<br><br>b. Electromagnetic waves are transverse waves.<br><br>c. Transverse waves may be polarized.<br><br>**Boundary Statement:** *Physics 1 treats mechanical waves only. Mathematical modeling of waves using sines or cosines is included in Physics 2. Superposition of no more than two wave pulses and properties of standing waves is evaluated in Physics 1. Interference is revisited in Physics 2, where two-source interference and diffraction may be demonstrated with mechanical waves, leading to the development of these concepts in the context of electromagnetic waves, the focus of Physics 2.* |
| | **6.A.2.2:** The student is able to contrast mechanical and electromagnetic waves in terms of the need for a medium in wave propagation. **[SP 6.4, 7.2]** | **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. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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. | **6.B.3.1:** The student is able to 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]** | **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.<br>*Relevant Equation:*<br>$x = A\cos(\omega t) = A\cos(2\pi\ ft)$ |
| **6.C:** Only waves exhibit interference and diffraction. | **6.C.1.1:** The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]**<br>**6.C.1.2:** The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. **[SP 1.4]** | **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. |
| | **6.C.2.1:** The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening, and to 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]** | **6.C.2:** When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.<br>*Relevant Equations:*<br>$\Delta L = m\lambda$<br>$d\sin\theta = m\lambda$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6.C:** Only waves exhibit interference and diffraction. (Continued) | **6.C.3.1:** The student is able to 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 to 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:** The student is able to 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. |
| **6E:** The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media. | **6.E.1.1:** The student is able to 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]** | **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.) |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6E:** The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.<br><br>(Continued) | **6.E.2.1:** The student is able to 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]** | **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.<br><br>*Relevant Equations:*<br><br>$\frac{1}{s_i}+\frac{1}{s_o}=\frac{1}{f}$<br><br>$\left\|M\right\|=\left\|\frac{h_i}{h_o}\right\|=\left\|\frac{s_i}{s_o}\right\|$ |
| | **6.E.3.1:** The student is able to 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]**<br><br>**6.E.3.2:** The student is able to 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]**<br><br>**6.E.3.3:** The student is able to 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]** | **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.<br><br>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.<br><br>b. When light travels from an optically slower substance into an optically faster substance, it bends away from the perpendicular.<br><br>c. At the critical angle, the light bends far enough away from the perpendicular that it skims the surface of the material.<br><br>d. Beyond the critical angle, all of the light is internally reflected.<br><br>*Relevant Equations:*<br><br>$n=\frac{c}{v}$<br><br>$n_1\sin\theta_1=n_2\sin\theta_2$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6E:** The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.<br>(Continued) | **6.E.4.1:** The student is able to 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]**<br>**6.E.4.2:** The student is able to 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]** | **6.E.4:** The reflection of light from surfaces can be used to form images.<br>a. Ray diagrams are very useful for showing how and where images of objects are formed for different mirrors, and how this depends upon the placement of the object. Examples include concave and convex mirrors.<br>b. Ray diagrams are also useful for determining the size of the resulting image compared to the size of the object.<br>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.<br>*Relevant Equations:*<br>$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$<br>$\lvert M \rvert = \left\lvert \frac{h_i}{h_o} \right\rvert = \left\lvert \frac{s_i}{s_o} \right\rvert$ |
| | **6.E.5.1:** The student is able to 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. **[SSP 1.4, 2.2]**<br>**6.E.5.2:** The student is able to 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]** | **6.E.5:** The refraction of light as it travels from one transparent medium to another can be used to form images.<br>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.<br>*Relevant Equations:*<br>$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$<br>$\lvert M \rvert = \left\lvert \frac{h_i}{h_o} \right\rvert = \left\lvert \frac{s_i}{s_o} \right\rvert$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6.F:** Electromagnetic radiation can be modeled as waves or as fundamental particles. | **6.F.1.1:** The student is able to make qualitative comparisons of the wavelengths of types of electromagnetic radiation. **[SP 6.4, 7.2]** | **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.<br>*Relevant Equation:*<br>$\lambda = \frac{v}{f}$ |
| | **6.F.2.1:** The student is able to describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present. **[SP 1.1]** | **6.F.2**: Electromagnetic waves can transmit energy through a medium and through a vacuum.<br>a. Electromagnetic waves are transverse waves composed of mutually perpendicular electric and magnetic fields that can propagate through a vacuum.<br>b. The planes of these transverse waves are both perpendicular to the direction of propagation. |

# Content Area 7: Quantum, Atomic, and Nuclear Physics

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

**Big Idea 3:** *The interactions of an object with other objects can be described by forces.*

**Big Idea 4:** *Interactions between systems can result in changes in those systems.*

**Big Idea 5:** *Changes that occur as a result of interactions are constrained by conservation laws.*

**Big Idea 6:** *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:** *The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.*

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system. | **1.A.2.1:** The student is able to construct representations of the differences between a fundamental particle and a system composed of fundamental particles and to relate this to the properties and scales of the systems being investigated. **[SP 1.1, 7.1]** | **1.A.2:** Fundamental particles have no internal structure.<br>a. Electrons, neutrinos, photons, and quarks are examples of fundamental particles.<br>b. Neutrons and protons are composed of quarks.<br>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.<br>a. The number of protons identifies the element.<br>b. The number of neutrons together with the number of protons identifies the isotope.<br>c. There are different types of radioactive emissions from the nucleus.<br>d. The rate of decay of any radioactive isotope is specified by its half-life. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system.<br><br>(Continued) | **1.A.4.1:** The student is able to construct representations of the energy-level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated. **[SP 1.1, 7.1]** | **1.A.4**: Atoms have internal structures that determine their properties.<br><br>a. The number of protons in the nucleus determines the number of electrons in a neutral atom.<br><br>b. The number and arrangements of electrons cause elements to have different properties.<br><br>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).<br><br>d. Discrete energy state transitions lead to spectra. |
| **1.C:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles. | **1.C.4.1:** The student is able to articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass-energy. **[SP 6.3]** | **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. |
| **1.D:** Classical mechanics cannot describe all properties of objects. | **1.D.1.1:** The student is able to 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]** | **1.D.1:** Objects classically thought of as particles can exhibit properties of waves.<br><br>a. This wavelike behavior of particles has been observed, e.g., in a double-slit experiment using elementary particles.<br><br>b. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.<br><br>*Relevant Equation:*<br><br>$\lambda = \frac{h}{p}$ |
| | *[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.<br><br>a. The classical models of waves do not describe the nature of a photon.<br><br>b. Momentum and energy of a photon can be related to its frequency and wavelength. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **1.D:** Classical mechanics cannot describe all properties of objects.<br><br>(Continued) | **1.D.3.1:** The student is able to 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]** | **1.D.3:** Properties of space and time cannot always be treated as absolute.<br><br>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.<br><br>b. Measurements of length and time depend on speed. (Qualitative treatment only.)<br><br>*Relevant Equation:*<br><br>$E = mc^2$ |
| **3.G:** Certain types of forces are considered fundamental. | **3.G.3.1:** The student is able to identify the strong force as the force that is responsible for holding the nucleus together. **[SP 7.2]** | **3.G.3:** The strong force is exerted at nuclear scales and dominates the interactions of nucleons. |
| **4.C:** Interactions with other objects or systems can change the total energy of a system. | **4.C.4.1:** The student is able to 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]** | **4.C.4:** Mass can be converted into energy, and energy can be converted into mass.<br><br>a. Mass and energy are interrelated by $E = mc^2$ .<br><br>b. Significant amounts of energy can be released in nuclear processes. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.2.1:** The student is able to 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, the student can 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]** | **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 object in electric fields and examining changes in internal energy with changes in configuration.]<br><br>*Relevant Equation:*<br>$\Delta U_E = q\Delta V$<br><br>**Boundary Statement:**<br>*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.* |
| | **5.B.4.1:** The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**<br><br>**5.B.4.2:** The student is able to 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.<br><br>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.<br><br>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:** The student is able to 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.<br><br>*Relevant Equations:*<br>$\Delta E = W = Fd\cos\theta$<br><br>$P = \frac{\Delta E}{\Delta t}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br>(Continued) | **5.B.8.1:** The student is able to 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.<br>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).<br>b. An emission spectrum can be used to determine the elements in a source of light. |
| | **5.B.11.1:** The student is able to 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]** | **5.B.11:** Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.<br>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). |
| **5.C:** The electric charge of a system is conserved. | **5.C.1.1:** The student is able to analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge. **[SP 6.4, 7.2]** | **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 (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved. | **5.D.1.6:** The student is able to 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]**<br><br>**5.D.1.7:** The student is able to 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]** | **5.D.1:** In a collision between objects, linear momentum is conserved. In an elastic collision, kinetic energy is the same before and after.<br>a. In a closed system, the linear momentum is constant throughout the collision.<br>b. In a closed system, the kinetic energy after an elastic collision is the same as the kinetic energy before the collision.<br>*Relevant Equations:*<br>$p = mv$<br>$K = \frac{1}{2}mv^2$<br><br>**Boundary Statement:**<br>*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 in 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.* |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved.<br><br>(Continued) | **5.D.2.5:** The student is able to 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]**<br><br>**5.D.2.6:** The student is able to 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.<br><br>a. In a closed system, the linear momentum is constant throughout the collision.<br><br>b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.<br><br>*Relevant Equations:*<br><br>$p = mv$<br><br>$K = \frac{1}{2}mv^2$ |
| | **5.D.3.2:** The student is able to make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system. **[SP 6.4]**<br><br>**5.D.3.3:** The student is able to 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.]<br><br>a. The center of mass of a system depends upon 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.<br><br>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.<br><br>*Relevant Equation:*<br><br>$x_{cm} = \frac{\Sigma m_i x_i}{\Sigma m_i}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.G:** Nucleon number is conserved. | **5.G.1.1:** The student is able to 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]** | **5.G.1:** The possible nuclear reactions are constrained by the law of conservation of nucleon number. |
| **6.C:** Only waves exhibit interference and diffraction. | **6.C.1.1:** The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. **[SP 6.4, 7.2]**<br>**6.C.1.2:** The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. **[SP 1.4]** | **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. |
| | **6.C.2.1:** The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening and to 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]** | **6.C.2:** When waves pass through an opening whose dimensions are comparable to the wavelength a diffraction pattern can be observed.<br>*Relevant Equations:*<br>$\Delta L = m\lambda$<br>$d\sin\theta = m\lambda$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6.C:** Only waves exhibit interference and diffraction.<br>(Continued) | **6.C.3.1:** The student is able to 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 to 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:** The student is able to 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. |
| **6.F:** Electromagnetic radiation can be modeled as waves or as fundamental particles. | **6.F.3.1:** The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect. **[SP 6.4]** | **6.F.3:** Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where $h$ is Planck's constant and $f$ is the frequency of the associated light wave.<br>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.<br>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.<br>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.<br>*Relevant Equation:*<br>$K_{max} = hf - \Phi$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **6.F:** Electromagnetic radiation can be modeled as waves or as fundamental particles.<br>(Continued) | **6.F.4.1:** The student is able to 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]** | **6.F.4:** The nature of light requires that different models of light are most appropriate at different scales.<br>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 $E_{photon}$.<br>b. The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects it interacts with is comparable to or larger than the wavelength of the radiation. |
| **6.G:** All matter can be modeled as waves or as particles. | **6.G.1.1:** The student is able to 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]** | **6.G.1:** Under certain regimes of energy or distance, matter can be modeled as a classical particle. |
| | **6.G.2.1:** The student is able to 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]**<br>**6.G.2.2:** The student is able to predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (de Broglie wavelength need not be given, so students may need to obtain it.) **[SP 6.4]** | **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.<br>a. A wave model of matter is quantified by the de Broglie wavelength that increases as the momentum of the particle decreases.<br>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.<br>*Relevant Equation:*<br>$\lambda = \frac{h}{p}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **7.C:** At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world. | **7.C.1.1:** The student is able to 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]** | **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.) |
| | **7.C.2.1:** The student is able to 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]** | **7.C.2:** The allowed states for an electron in an atom can be calculated from the wave model of an electron.<br>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.<br>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.<br>*Relevant Equation:*<br>$\lambda = \frac{h}{p}$ |
| | **7.C.3.1:** The student is able to 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]** | **7.C.3:** The spontaneous radioactive decay of an individual nucleus is described by probability.<br>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.<br>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.<br>c. The time for half of a given number of radioactive nuclei to decay is called the half-life.<br>d. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **7.C:** At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.<br><br>(Continued) | **7.C.4.1:** The student is able to 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.<br><br>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).<br><br>b. An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon (spontaneous emission).<br><br>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.<br><br>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. |

# References

The AP course and exam development process relies on groups of nationally renowned subject-matter experts in each discipline, including professionals in secondary and postsecondary education as well as from professional organizations. These experts ensure that AP courses and exams reflect the most up-to-date information available, that the courses and exams are appropriate for a college-level course, and that student proficiency is assessed properly. To help ensure that the knowledge, skills, and abilities identified in the course and exam are articulated in a manner that will serve as a strong foundation for both curriculum and assessment design, the subject-matter experts for AP Physics 1: Algebra-Based and AP Physics 2: Algebra-Based utilized principles and tools from the following works.

Mislevy, R. J., and M. M. Riconscente. 2005. *Evidence-Centered Assessment Design: Layers, Structures, and Terminology* (PADI Technical Report 9). Menlo Park, CA: SRI International and University of Maryland. Retrieved May 1, 2006, from **http://padi.sri.com/downloads/TR9_ECD.pdf**

Riconscente, M. M., R. J. Mislevy, and L. Hamel. 2005. *An Introduction to PADI Task Templates* (PADI Technical Report 3). Menlo Park, CA: SRI International and University of Maryland. Retrieved May 1, 2006, from **http://padi.sri.com/downloads/TR3_Templates.pdf**

Wiggins, G., and J. McTighe. 2005. *Understanding by Design*. 2nd ed. Alexandria, VA: Association for Supervision and Curriculum Development.

# The Laboratory Investigations

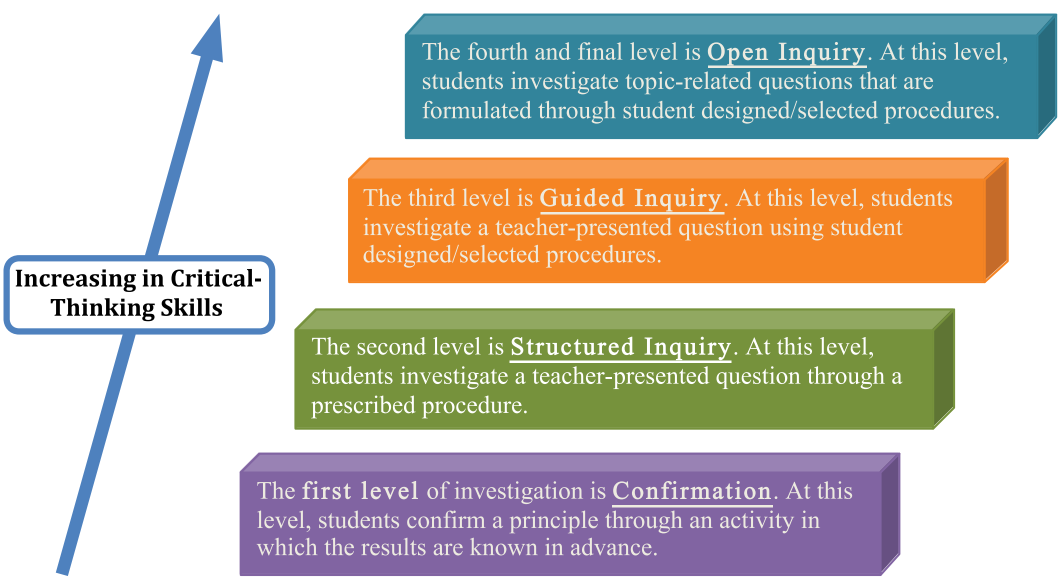
Inquiry-based laboratory experiences support the AP Physics 2 course and AP Course Audit Curricular Requirements by providing opportunities for students to engage in the seven science practices as they design plans for experiments, make predictions, collect and analyze data, apply mathematical routines,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

The science practices that align to the concept outline of the course framework capture important aspects of the work that scientists engage in, at the level of competence that college and university faculty expect students to possess at the end of an introductory college-level course. AP Physics teachers will see within the learning objectives how these practices are integrated with the course content, and they will be able to design laboratory investigations and instruction with these practices in mind.

## Inquiry Instruction in the AP Science Classroom

The 2014 *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual* supports recommendations by the National Science Foundation (NSF) that science teachers should include opportunities in their curricula for students to develop skills in communication, teamwork, critical thinking, and commitment to life-long learning (NSF 1996, NSF, 2012, AAPT 1992). An inquiry approach to laboratory work engages and inspires students to investigate meaningful questions about the physical world and align with the best practices described in *America's Lab Report*, a comprehensive synthesis of research about student learning in science laboratories from the National Research Council.

Scientific inquiry experiences in the AP classroom should be designed and implemented with increasing student involvement to help enhance inquiry learning and the development of critical-thinking and problem-solving skills and abilities. Adaptations of Herron's approach (1971) and that of Rezba, Auldridge, and Rhea (1999) define inquiry instruction for investigations in four incremental ways:



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Typically, the level of investigations in an AP classroom should focus primarily on the continuum between guided inquiry and open inquiry. However, depending on student familiarity with a topic, a given laboratory experience might incorporate a sequence involving all four levels or a subset of them. For instance, students might first carry out a simple confirmation investigation that also familiarizes them with equipment and then proceed to a structured inquiry that probes more deeply into the topic and gives more practice with equipment. At that point students would be presented with a question and asked to design/select their own procedure. A class discussion of results could then lead to questions that could be explored differently by different groups in open inquiry.

The idea of asking questions and inquiry is actually natural to students. However, in the classroom setting it may not seem natural to them as they may have developed more teacher-directed procedural habits and expectations in previous lab courses. As students experience more opportunities for more self-directed investigations with less teacher guidance, they will become more sophisticated in their reasoning and approach to inquiry. The teacher can promote inquiry habits in students throughout the course — during class and in the laboratory — by handing over more of the planning of experiments and manipulation of equipment over to students.



# Expectations for Analysis of Uncertainty in Laboratory Investigations

Some colleges and universities expect students to submit a laboratory notebook to receive credit for laboratory courses. Given the emphasis on time spent in the laboratory, students should be introduced to the methods of error analysis including and supported by mean, standard deviation, percentage error, propagation of error, and linear regression, or the calculation of a line of best fit. Colleges will expect students to be familiar with these methods and to have carried out the procedures on at least some of the laboratory experiments they undertake, particularly since the use of computers and calculators have significantly reduced the need for students to perform computations on their own.

# Time and Resources

Teachers are expected to devote a minimum of 25 percent of instructional time to laboratory work in this course. Additionally, students should be provided with an opportunity to engage in a minimum of seven inquiry-based investigations. The AP Physics 2 course emphasizes depth of understanding over breadth of content. By limiting the scope of content, students have more time to engage in inquiry-based learning experiences that will develop conceptual understanding of content while building expertise in the science practices. Applying this instructional approach to laboratory investigations typically takes more time than simple verification/confirmation labs; however the reduced breadth of content will allow teachers to meet the AP Course Audit curricular requirements of 25 percent of course time that must be devoted laboratory work.

The labs in the *AP Physics 1 and 2 Inquiry-Based Lab Investigations: A Teacher's Manual* are intended to serve as models, **not as required activities**; teachers are encouraged to develop their own teacher-guided or student-directed inquiry-based labs that address the learning objectives in the course framework. They should also consider supporting their physical laboratory work with interactive, online simulations, such as PhET simulations developed by the University of Colorado, Boulder.

# References

National Research Council. *National Science Education Standards*. Washington, DC: The National Academies Press, 1996.

National Research Council. *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press, 2012.

*The Role of Labs in High School Physics*, American Association of Physics Teachers (AAPT), Position Paper, 1992. Accessed on July 27, 2013. **http://www.aapt.org/resources/policy/RoleOfLabs.cfm**

Singer, Susan R., Margaret L. Hilton, and Heidi A. Schweingruber. America's Lab

Report: Investigations in High School Science. Washington, DC: The National Academies Press, 2006.

# The AP Physics 2: Algebra-Based Exam

## Exam Information

The AP Physics 2 exam consists of two sections: multiple choice and free response. The exam is 3 hours long and includes a multiple-choice section and a free-response section of one hour and 30 minutes each. The multiple-choice section accounts for half of each student's exam grade, and the free-response section accounts for the other half. Both sections include questions aligned to the learning objectives and their associated science practices in order to assess students' ability to:

- Provide both qualitative and quantitative explanations, reasoning, or justification of physical phenomena, grounded in physics principles and theories
- Solve problems mathematically — including symbolically — but with less emphasis on only mathematical routines used for solutions
- Interpret and develop conceptual models
- Transfer knowledge and analytical skills developed during laboratory experiences to design and describe experiments and analyze data and draw conclusions based on evidence.

Section I in the AP Physics 2 exam consists of 50 multiple-choice questions, either as discrete questions, questions in sets, or multi-correct questions that represent the knowledge and science practices outlined in the AP Physics 2 learning objectives in the course framework, which students should understand and be able to apply. Multi-correct questions will be in a separate section of the multiple-choice portion of the exam (Part B) and will indicate to students to select the two correct options for each question in the stimulus.

Section II contains three types of free-response questions that each student will have a total of one hour and 30 minutes to complete. The three question types are:

- Experimental design — Pertains to designing and describing an investigation, analysis of authentic lab data, and observations to identify patterns or explain phenomena
- Qualitative/quantitative translation — Requires translating between quantitative and qualitative justification and reasoning
- Short answer questions — One of which will require a paragraph-length coherent argument

| Section | Timing | Scoring | Question Type | Number of Questions |
|---|---|---|---|---|
| **I: Multiple Choice** | One hour and 30 minutes | 50% of exam score | **Part A**: Multiple Choice – Discrete Items and Items in Sets | 45 |
| | | | **Part B**: Multiple Correct – Items with two correct answers | 5 |
| | | | | Total – 50 |
| **II: Free Response** | One hour and 30 minutes | 50% of exam score | Experimental Design | 1 |
| | | | Qualitative/Quantitative Translation | 1 |
| | | | Short-Answer | 2 |
| | | | | Total – 4 |

The sample exam questions in this course and exam description represent the kinds of questions that are included on the AP Physics 2 exam. The concepts, content, application of science practices, and level of difficulty in these sample questions are comparable to what students will encounter on an actual AP Exam. Each sample multiple-choice and free-response question is followed by a text box that shows each question's alignment with the learning objectives and science practices provided in the AP Physics 2 course framework.

Multiple-choice questions will contain four answer options. A student's total score on the multiple-choice section is based on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

## Student Work for Free-Response Sections

In scoring the free-response sections, credit for the answers depends on the quality of the solutions and the explanations given; partial solutions may receive partial credit, so students are advised to *show all their work*. Correct answers without supporting work may lose credit. This is especially true when students are asked specifically to justify their answers, in which case the AP Exam Readers are looking for some verbal or mathematical analysis that shows how the students arrived at their answers. Also, all final numerical answers should include appropriate units.



## Terms Defined

**On the AP Physics 2 exam the words "describe," "explain," "justify," "calculate," "derive," "what is," "determine," "sketch," "plot," "draw," "label," "design," and "outline" have precise meanings.**

Students should pay careful attention to these words in order to obtain maximum credit and should avoid including irrelevant or extraneous material in their answers.

- Students will be asked both to "**describe**" and "**explain**" natural phenomena. Both terms require the ability to demonstrate an understanding of physics principles by providing an accurate and coherent description or explanation. Students will also be asked to "**justify**" a previously given answer. A justification is an argument supported by evidence. Evidence may consist of statements of physical principles, equations, calculations, data, graphs, and diagrams as appropriate. The argument, or equations used to support justifications and explanations, may in some cases refer to fundamental ideas or relations in physics, such as Newton's laws, conservation of energy, or Bernoulli's equation. In other cases, the justification or explanation may take the form of analyzing the behavior of an equation for large or small values of a variable in the equation.
- "**Calculate**" means that a student is expected to show work leading to a final answer, which may be algebraic but more often is numerical. "**Derive**" is more specific and indicates that the students need to begin their solutions with one or more fundamental equations, such as those given on the AP Physics 2 Exam equation sheet. The final answer, usually algebraic, is then obtained through the appropriate use of mathematics. "**What is**" and "**determine**" are indicators that work need not necessarily be explicitly shown to obtain full credit. Showing work leading to answers is a good idea, as it may earn a student partial credit in the case of an incorrect answer. Strict rules regarding significant digits are usually not applied to the scoring of numerical answers. However, in some cases, answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer.

- The words "**sketch**" and "**plot**" relate to student-produced graphs. "Sketch" means to draw a graph that illustrates key trends in a particular relationship, such as slope, curvature, intercept(s), or asymptote(s). Numerical scaling or specific data points are not required in a sketch. "Plot" means to draw the data points given in the problem on the grid provided, either using the given scale or indicating the scale and units when none are provided.
- Exam questions that require the drawing of free-body or force diagrams will direct the students to "**draw** and **label** the forces (not components) that act on the [object]," where [object] is replaced by a reference specific to the question, such as "the car when it reaches the top of the hill." Any components that are included in the diagram will be scored in the same way as incorrect or extraneous forces. In addition, in any subsequent part asking for a solution that would typically make use of the diagram, the following will be included: "If you need to draw anything other than what you have shown in part [x] to assist in your solution, use the space below. Do NOT add anything to the figure in part [x]." This will give students the opportunity to construct a working diagram showing any components that are appropriate to the solution of the problem. This second diagram will not be scored.
- Some questions will require students to "**design**" an experiment or "**outline**" a procedure that investigates a specific phenomenon or would answer a guiding question. Students are expected to provide an orderly sequence of statements that specifies the necessary steps in the investigation needed to reasonably answer the question or investigate the phenomenon.



## The Paragraph-Length Response

A paragraph-length response to a question should consist of a coherent argument that uses the information presented in the question and proceeds in a logical, expository fashion to arrive at a conclusion.

AP Physics students are asked to give a paragraph-length response so that they may demonstrate their ability to communicate their understanding of a physical situation in a reasoned, expository analysis. A student's response should be a coherent, organized, and sequential description of the analysis of a situation. The response should argue from evidence, cite physical principles, and clearly present the student's thinking to the reader. The presentation should not include extraneous information. It should make sense on the first reading.

The style of the exposition is to explain and/or describe, like a paragraph, rather than present a calculation or a purely algebraic derivation, and should be of moderate length, not long and elaborate.

A paragraph-length response will earn points for correct physics principles, as does a response to any other free-response question. However, full credit may not be earned if a paragraph-length response contains any of the following: principles not presented in a logical order, lengthy digressions within an argument, or primarily equations or diagrams with little linking prose.

The argument may include, as needed, diagrams, graphs, equations, and perhaps calculations to support the line of reasoning. The style of such a response may be seen in the example problems in textbooks, which are typically a mix of prose statements, equations, diagrams, etc., that present an orderly analysis of a situation.

In AP Physics 2, the requirement for full credit for a paragraph-length response is more rigorous than it is for AP Physics 1, in that responses must be presented primarily in prose form.

To reiterate, the goal is that students should be able to both analyze a situation and construct a coherent, sequenced, well-reasoned exposition that cites evidence and principles of physics and that makes sense on the first reading.

## Expectations for the Analysis of Uncertainty

On the AP Physics 2 exam, students may be expected to calculate uncertainty. In general, multiple-choice questions will deal primarily with qualitative assessment of uncertainty, while free-response laboratory questions may require some quantitative understanding of uncertainty as described below.

Experiment and data analysis questions on the AP Physics 2 exam will not require students to calculate standard deviations or carry out the propagation of error or a linear regression. Students will be expected to estimate a line of best fit to data that they plot or to a plot they are given. Students may be expected to discuss which measurement or variable in a procedure contributes most to overall uncertainty in the final result and on conclusions drawn from a given data set. They should recognize that there may be no significant difference between two reported measurements if they differ by less than the smallest difference that can be discerned on the instrument used to make the measurements. They should be able to reason in terms of percentage error and to report results of calculations to an appropriate number of significant digits. Students are also expected to be able to articulate the effects of error and error propagation on conclusions drawn from a given data set and how results and conclusions would be affected by changing the number of measurements, measurement techniques, or the precision of measurements. Students should be able to review and critique an experimental design or procedure and decide whether the conclusions can be justified based on the procedure and the evidence presented.

## Calculators and Equation Tables

Students will be allowed to use a calculator on the entire AP Physics 2 exam — including both the multiple-choice and free-response sections. Scientific or graphing calculators may be used, provided that they don't have any unapproved features or capabilities. A list of approved graphing calculators is available at **https://apstudent.collegeboard.org/takingtheexam/exam-policies/calculator-policy**. Calculator memories do not need to be cleared before or after the exam. Since graphing calculators can be used to store data, including text, proctors should monitor that students are using their calculators appropriately. Communication between calculators is prohibited during the exam administration. Attempts by students to use the calculator to remove exam questions and/or answers from the room may result in the invalidation of AP Exam scores. The policy regarding the use of calculators on the AP Physics 2 exam was developed to address the rapid expansion of the capabilities of calculators, which include not only programming and graphing functions but also the availability of stored equations and other data. Students should be allowed to use the calculators to which they are accustomed. However, students should be encouraged to develop their skills in estimating answers and orders of magnitude quickly and in recognizing answers that are physically unreasonable or unlikely.

Tables containing equations commonly used in physics will be provided for students to use during the entire AP Physics 2 exam. In general, the equations for each year's exam are printed and distributed with the course and exam description at least a year in advance so that students can become accustomed to using them throughout the year. However, because the equation tables will be provided with the exam, students will NOT be allowed to bring their own copies to the exam room. The latest version of the equations and formulas list is included in Appendix B to this course and exam description. One of the purposes of providing the tables of commonly employed equations for use with the exam is to address the issue of equity for those students who do not have access to equations stored in their calculators. The availability of these equations to all students means that in the scoring of the exam, little or no credit will be awarded for simply writing down equations or for answers unsupported by explanations or logical development.

In general, the purpose of allowing calculators and equation sheets to be used in both sections of the exam is to place greater emphasis on the understanding and application of fundamental physical principles and concepts. For solving problems and writing essays, a sophisticated scientific or graphing calculator, or the availability of stored equations, is no substitute for a thorough grasp of the physics involved.

## Time Management

Students need to learn to manage their time to allow them to complete all parts of the exam. Time left is announced by proctors, but students are not forced to move to the next question; thus if they do not properly budget their time, they may not wind up with enough time to complete all the multiple-choice questions in Section I and all the free-response questions in Section II. Students often benefit from taking a practice exam under timed conditions prior to the actual administration.

# Sample Questions for the AP Physics 2 Exam

## Multiple-Choice Questions

***NOTE:*** *To simplify calculations, you may use g = 10 m/s² in all problems.*

**Directions:** Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

**Questions 1–3 refer to the following material.**

An isolated, neutral lambda particle $(\Lambda^0)$ is moving to the right with speed *v*. It then decays into a proton and a pion $(\Lambda^0 \rightarrow p^+ + \pi^-)$. The following are the masses of the three particles:

Lambda: $1115.7\, MeV / c^2$

Proton: $938.3\, MeV / c^2$

Pion: $139.6\, MeV / c^2$

1. How much energy is released when the $\Lambda^0$ decays?

   (A) 2193.6 MeV

   (B) 1914.4 MeV

   (C) 317.0 MeV

   (D) 37.8 MeV

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **4.C:** Interactions with other objects or systems can change the total energy of a system. | **4.C.4.1:** The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale. | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

2. Which of the following indicates how the total linear momentum of the $\Lambda^0$ particles after the decay compares to the linear momentum of the before the decay and explains why?

   (A) The momentum is in the same direction but has a smaller magnitude because the proton and pion have opposite charges and attract each other.

   (B) The momentum is in the same direction but has a smaller magnitude because the proton and pion are emitted in opposite directions.

   (C) The momentum is in the same direction and has the same magnitude because no external force acts on the system of particles.

   (D) The momentum is in the same direction and has the same magnitude because the work done by the strong force is greater than the energy emitted during the decay.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved. | **5.D.3.3:** The student is able to make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |

3. At some later time, the proton and pion are both moving to the right in the plane of the page when they enter a magnetic field directed out of the page. Which of the following describes the directions of the magnetic forces on the proton and pion at the instant they enter the field?

   (A) Proton: toward the top of the page Pion: toward the top of the page

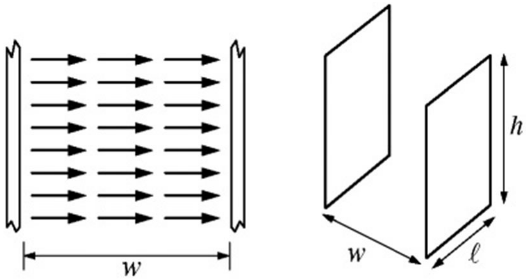
   (B) Proton: toward the top of the page Pion: toward the bottom of the page

   (C) Proton: toward the bottom of the page Pion: toward the bottom of the page

   (D) Proton: toward the bottom of the page Pion: toward the top of the page

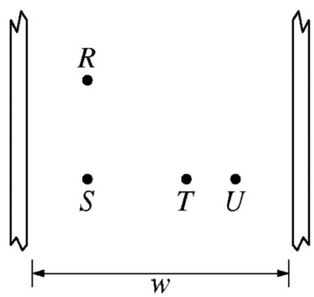
| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.3.1:** The student is able to use right-hand rules to analyze a situation involving 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. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively. |

**Questions 4–7 refer to the following material.**




Note: Figure not drawn to scale.

The figure above on the left represents the horizontal electric field near the center of two large, vertical parallel plates near Earth's surface. The plates have height $h$ and length $\ell$, and they are separated by a distance $w$, as shown on the right. The field has magnitude $E$. A small object with mass $m$ = and charge $+q$, where $m = qE/g$ , is released from rest at a point midway between the plates.




4. Points $R$, $S$, $T$, and $U$ are located between the plates as shown in the figure above, with points $R$ and $T$ equidistant from point $S$. Let $V_{RS}$ , $V_{ST}$ , $V_{TU}$ , and $V_{RU}$ be the magnitudes of the electric potential differences between the pairs of points. How do the magnitudes of these potential differences compare?

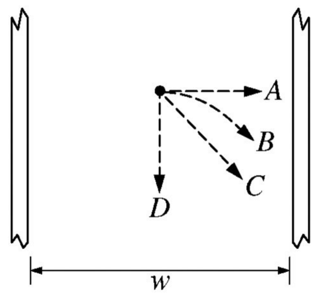
   (A) $V_{RU} > V_{ST} > V_{TU} > V_{RS}$

   (B) $V_{RU} > (V_{RS} = V_{ST} > V_{TU}$

   (C) $V_{Rs} > V_{TU} > V_{ST} > V_{RU}$

   (D) $V_{TU} > (V_{RS} = V_{ST}) > V_{RU}$

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge. | **2.C.5.2:** The student is able to 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. | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |




5. After the object is released from rest, which of the paths shown in the figure above is a possible trajectory for the object?

   (A) *A*

   (B) *B*

   (C) *C*

   (D) *D*

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br>**3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **2.C.1.1:** The student is able to 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.<br>**3.B.1.4:** The student is able to 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. | **6.4:** The student *can make claims and predictions about natural phenomena* based on scientific theories and models.<br>**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. Under which of the following new conditions could the gravitational force on the object be neglected?

   (A) $h >> w$

   (B) $q >> m$

   **(C)** $qE >> mg$

   (D) $Eh >> Ew$

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.<br><br>**3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.B.1.4:** The student is able to 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.<br><br>**3.C.2.2:** The student is able to connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br><br>**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. |

7. The speed of a proton moving in an electric field changes from $v_i$ to $v_f$ over a certain time interval. Let the mass and charge of the proton be denoted as $m_p$ and $e$. Through what potential difference did the proton move during the interval?

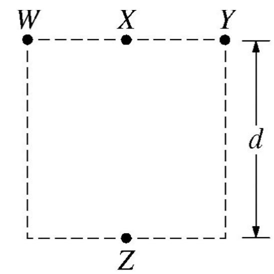
(A) $\frac{m_p}{2}\left(v_f^2 - 2v_i^2\right)$

(B) $\frac{m_p}{2e}\left(v_f^2 - v_i^2\right)$

(C) $\frac{m_p}{2}\left(v_f - v_i\right)$

(D) $\frac{m_p}{2e}\left(v_f - v_i\right)$

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br><br>**5.B:** The energy of a system is conserved. | **2.C.1.1:** The student is able to 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.<br><br>**2.C.1.2:** The student is able to 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.<br><br>**5.B.4.2:** The student is able to calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br><br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena.<br><br>**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. |




8. Four objects, each with charge +q, are held fixed on a square with sides of length *d*, as shown in the figure above. Objects *X* and *Z* are at the midpoints of the sides of the square. The electrostatic force exerted by object *W* on object *X* is *F*. What is the magnitude of the net force exerted on object *X* by objects *W*, *Y*, and *Z* ?

(A) $\frac{F}{4}$

(B) $\frac{F}{2}$

(C) $\frac{9F}{4}$

(D) $3F$

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$.<br><br>**3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.B.2.1:** The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively.<br><br>**3.C.2.3:** The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry). | **1.1:** The student can *create representations and models* of natural or man-made phenomena and systems in the domain.<br><br>**1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br><br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

9. Isolines of potential are drawn for the gravitational field of the Sun-Mercury system. The pattern of the isolines is identical to the pattern of equipotential lines for a system of two electrically charged objects with which of the following properties?

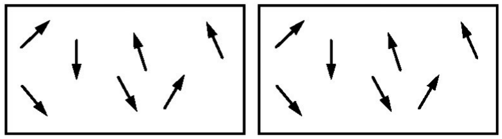
(A) The charges have the same sign and the same magnitude.

(B) The charges have the same sign and different magnitudes.

(C) The charges have opposite signs and the same magnitude.

(D) The charges have opposite signs and different magnitudes.

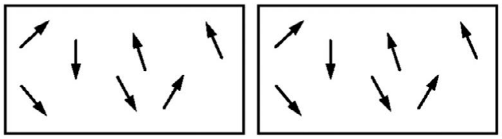
| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **2.E:** Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field. | **2.E.1.1:** The student is able to construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential.<br>**2.E.2.2:** The student is able to 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. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br>**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. |

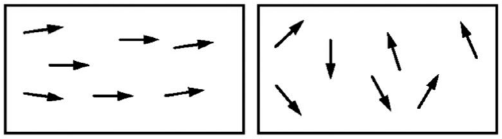


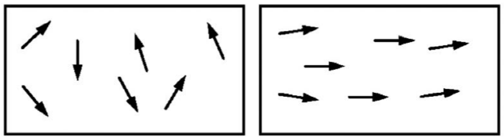
Iron Lead

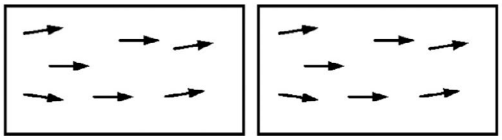
10. The figure above represents the random orientations of the magnetic dipoles in a block of iron and a block of lead. Iron is ferromagnetic and lead is diamagnetic. The two blocks are placed in a magnetic field that points to the right. Which of the following best represents the orientations of the dipoles when the field is present?

Iron Lead

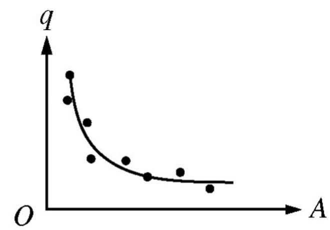
(A) 

(B) 

(C) 

(D) 

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **2.D:** A magnetic field is caused by a magnet or a 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.<br><br>**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. | **2.D.3.1:** The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet.<br><br>**4.E.1.1:** The student is able to 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. | **1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.<br><br>**1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively. |




11. Students are performing an experiment to determine how changing the area of the plates of a parallel-plate capacitor affects its behavior in a circuit. They connect a capacitor with plate area $A$ to a battery and allow it to become fully charged. They take measurements that they believe will allow them to calculate the charge $q$ on one plate of the capacitor. The students then repeat the procedure with other capacitors. The capacitors each have a different plate area but are otherwise identical. The students plot the calculated charge $q$ as a function of plate area $A$. Their results, including a best fit to the data, are represented above. Is this graph a reasonably accurate representation of the relationship between $q$ and $A$?

(A) Yes, because the relationship should result in a graph that is curved and decreasing.

(B) No, because the relationship should result in a graph that is linear and decreasing.

(C) No, because the relationship should result in a graph that is linear and increasing.

(D) No, because the relationship should result in a graph that is curved and increasing.

| Enduring Understanding | Learning Objectives | Science Practice |
|---|---|---|
| **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. | **4.E.4.3:** The student is able to 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.<br><br>**4.E.5.3:** The student is able to 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. | **5.1:** The student can *analyze data* to identify patterns or relationships. |

12. Some students experimenting with an uncharged metal sphere want to give the sphere a net charge using a charged aluminum pie plate. Which of the following steps would give the sphere a net charge of the same sign as the pie plate?

    (A) Bringing the pie plate close to, but not touching the metal sphere, then moving the pie plate away

    (B) Bringing the pie plate close to, but not touching, the metal sphere, then momentarily touching a grounding wire to the metal sphere

    (C) Bringing the pie plate close to, but not touching, the metal sphere, then momentarily touching a grounding wire to the pie plate

    (D) Touching the pie plate to the metal sphere

| Enduring Understandings | Learning Objectives | Science Practice |
|---|---|---|
| **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.<br>**5.C:** The electric charge of a system is conserved. | **4.E.3.5:** The student is able to explain and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure.<br>**5.C.2.2:** The student is able to design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data. | **4.2:** The student can *design a plan* for collecting data to answer a particular scientific question. |

13. An ideal fluid is flowing with a speed of $12\text{cm}/\text{s}$ through a pipe of diameter 5 cm. The pipe splits into three smaller pipes, each with a diameter of 2 cm. What is the speed of the fluid in the smaller pipes?

(A) $4\text{cm}/\text{s}$

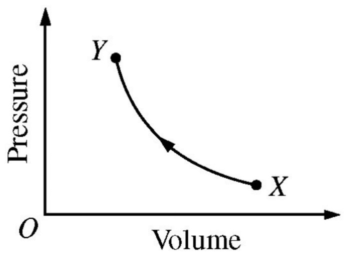
(B) $12\text{cm}/\text{s}$

(C) $25\text{cm}/\text{s}$

(D) $75\text{cm}/\text{s}$

| Enduring Understanding | Learning Objective | Science Practice |
| --- | --- | --- |
| **5.F:** Classically, the mass of a system is conserved. | **5.F.1.1:** The student is able to make calculations of quantities related to flow of a fluid using mass conservation principles (the continuity equation). | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

Sample Questions




14. The graph above shows the pressure as a function of volume for a sample of gas that is taken from state $X$ to state $Y$ at constant temperature. Which of the following indicates the sign of the work done on the gas, and whether thermal energy is absorbed or released by the gas during this process?

| | Work done | Thermal energy |
|---|---|---|
| (A) | Positive | Absorbed |
| (B) | Positive | Released |
| (C) | Negative | Absorbed |
| (D) | Negative | Released |

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.7.1:** The student is able to 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. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |

15. Two samples of ideal gas in separate containers have the same number of molecules and the same temperature, but the molecular mass of gas *X* is greater than that of gas *Y*. Which of the following correctly compares the average speed of the molecules of the gases and the average force the gases exert on their respective containers?

| | Average speed of Molecules | Average Force on container |
|---|---|---|
| (A) | Greater for gas *X* | Greater for gas *X* |
| (B) | Greater for gas *X* | The forces cannot be compared without knowing the volumes of the gases. |
| (C) | Greater for gas *Y* | Greater for gas *Y* |
| (D) | Greater for gas *Y* | The forces cannot be compared without knowing the volumes of the gases. |

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **7.A:** The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure. | **7.A.1.1:** The student is able to 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.<br>**7.A.2.2:** The student is able to connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and to relate this to thermodynamic processes. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br>**7.1:** The student can *connect phenomena and models* across spatial and temporal scales.<br>**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. |

16. Three different gas samples that have the same number of molecules and are at room temperature are kept at different pressures. A lab technician has determined the molecular mass of each gas and recorded the pressure and molecular mass of each sample in the table below.

| Gas | Molecular Mass (u) | Pressure (¥100kPa) |
|---|---|---|
| *X* | 2.0 | 6.0 |
| *Y* | 4.0 | 12 |
| *Z* | 40 | 1.0 |

Which of the following ranks the density $\rho$ of the gas samples?

(A) $\rho_x = \rho_y > \rho_Z$

(B) $\rho_y > \rho_Z > \rho_X$

(C) $\rho_Z > \rho_X = \rho_Y$

(D) $\rho_Z > \rho_Y > \rho_X$

### Enduring Understandings

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

**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 Objectives

**1.A.5.2:** The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures.

**1.E.1.2:** The student is able to select from experimental data the information necessary to determine the density of an object and/ or compare densities of several objects.

### Science Practices

**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.

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

17. Light from a source that produces a single frequency passes through a single slit *A*. The diffraction pattern on a screen is observed. Slit *A* is then replaced by slit *B*, and the new pattern is observed to have fringes that are more closely spaced than those in the first pattern. Which of the following is a possible explanation for why the spacings are different?

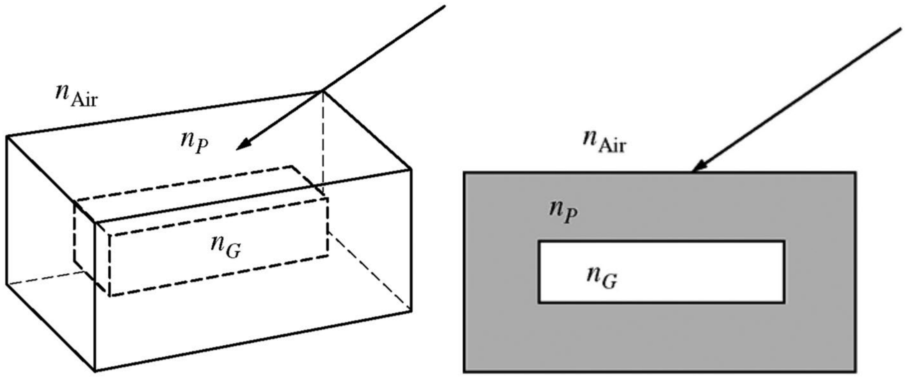
(A) Slit *A* is wider than slit *B*.

(B) Slit *B* is wider than slit *A*.

(C) The distance between the light source and the slit is greater for slit *A* than for slit *B*.

(D) The distance between the light source and the slit is greater for slit *B* than for slit *A*.

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **6.C:** Only waves exhibit interference and diffraction. | **6.C.2.1:** The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening and to 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. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br>**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. |




18. Students in a lab group are given a plastic block with a hollow space in the middle, as shown in the figures above. The index of refraction $n_P$ of the plastic is known. The hollow space is filled with a gas, and the students are asked to collect the data needed to find the index of refraction $n_G$ of the gas. The arrow represents a light beam that they shine into the plastic. They take the following set of measurements:

| | |
|---|---|
| Angle of incidence of the light in the air above the plastic block | 30° |
| Angle of refraction of the beam as it enters the plastic from the air | 45° |
| Angle of refraction of the beam as it enters the plastic from the gas | 45° |

The three measurements are shared with a second lab group. Can the second group determine a value of $n_G$ from only this data?

(A) Yes, because they have information about the beam in air and in the plastic above the gas.

(B) Yes, because they have information about the beam on both sides of the gas.

(C) No, because they need additional information to determine the angle of the beam in the gas.

(D) No, because they do not have multiple data points to analyze.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **6.E:** The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media. | **6.E.3.2:** The student is able to 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). | **5.3:** The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question. |

Sample Questions

19. The ground state of a certain type of atom has energy $-E_0$. What is the wavelength of a photon with enough energy to ionize an atom in the ground state and give the ejected electron a kinetic energy of $2E_0$?

(A) $\frac{hc}{3E_0}$

(B) $\frac{hc}{2E_0}$

(C) $\frac{hc}{E_0}$

(D) $\frac{2hc}{E_0}$

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.8.1:** The student is able to 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. | **1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.<br>**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. |

20. A hypothetical one-electron atom in its highest excited state can only emit photons of energy $2E$, $3E$, and $5E$. Which of the following is a possible energy-level diagram for the atom?

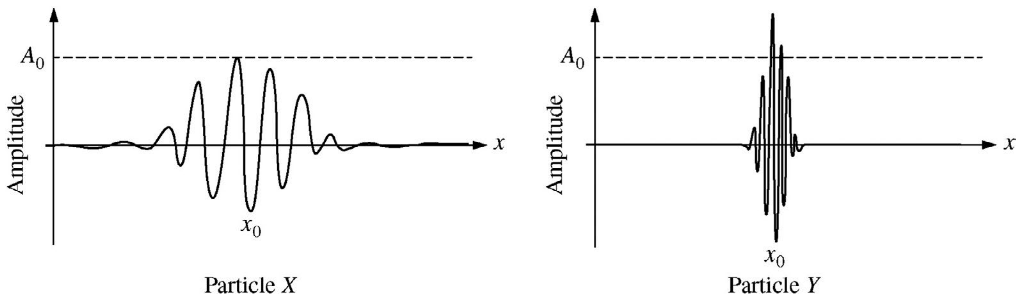
(A)
________ $5E$
________ $3E$
________ $0$

(B)
________ $3E$
________ $2E$
________ $0$

(C)
________ $5E$
________ $3E$
________ $2E$
________ $0$

(D)
________ $10E$
________ $8E$
________ $5E$
________ $0$

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **1.A:** The internal structure of a system determines many properties of the system.<br>**5.B:** The energy of a system is conserved. | **1.A.4.1:** The student is able to construct representations of the energy level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated.<br>**5.B.8.1:** The student is able to 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. | **1.1:** The student can *create representations and models* of natural or man-made phenomena and systems in the domain.<br>**1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain. |




21. The figure above shows graphical representations of the wave functions of two particles, $X$ and $Y$, that are moving in the positive $x$-direction. The maximum amplitude of particle $X$'s wave function is $A_0$ . Which particle has a greater probability of being located at position $x_0$ at this instant, and why?

    (A) Particle $X$, because the wave function of particle $X$ spends more time passing through $x_0$ than the wave function of particle $Y$

    (B) Particle $X$, because the wave function of particle $X$ has a longer wavelength than the wave function of particle $Y$

    (C) Particle $Y$, because the wave function of particle $Y$ is narrower than the wave function of particle $X$

    (D) Particle $Y$, because the wave function of particle $Y$ has a greater amplitude near $x_0$ than the wave function of particle $X$

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **7.C:** At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world. | **7.C.1.1:** The student is able to use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively. |

**Directions:** For questions 22–25 below, two of the suggested answers will be correct. Select the two answers that are best in each case, and then fill in both of the corresponding circles on the answer sheet.

22. On a day that is warm and sunny, a car is parked in a location where there is no shade. The car's windows are closed. The air inside the car becomes noticeably warmer than the air outside. Which of the following factors contribute to the higher temperature? Select two answers.

    (A) Hotter air rises to the roof of the car and cooler air falls to the floor.

    (B) The body of the car insulates the air inside the car.

    (C) Electromagnetic radiation from the Sun enters the car and is absorbed by the materials inside.

    (D) The body of the car reflects electromagnetic radiation.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.6.1:** The student is able to 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. | **1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain. |

23. A fixed amount of ideal gas is kept in a container of fixed volume. The absolute pressure *P*, in pascals, of the gas is plotted as a function of its temperature *T*, in degrees Celsius. Which of the following are properties of a best fit curve to the data? Select two answers.

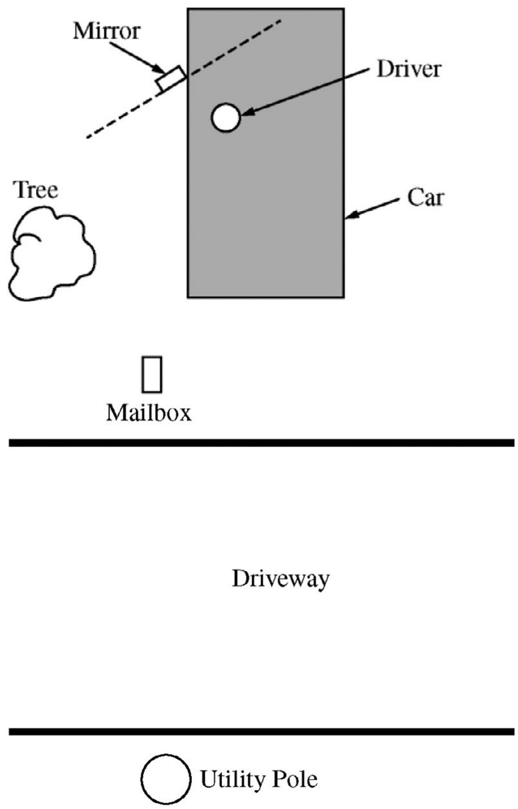
(A) Having a positive slope

(B) Passing through the origin

(C) Having zero pressure at a certain negative temperature

(D) Approaching zero pressure as temperature approaches infinity

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **7.A:** The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure. | **7.A.3.1:** The student is able to 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.<br><br>**7.A.3.3:** The student is able to 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 $PV = nRT$. | **5.1:** The student can *analyze data* to identify patterns or relationships.<br><br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |




24. A driver is backing a car off a lawn into a driveway while using the side-view mirror to check for obstacles. The figure above shows a top view of the car and some objects near the car. The mirror is a plane mirror, and the dashed line shows the angle of its plane. Which of the following should the driver be able to see in the mirror by just turning her head without moving her head from the position shown? Select two answers.

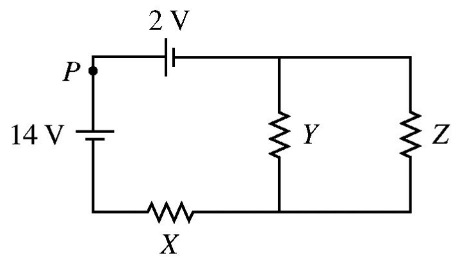
(A) Herself

(B) The tree

(C) The mailbox

(D) The utility pole

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **6.E:** The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media. | **6.E.2.1:** The student is able to 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. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br>**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. |




25. The figure above shows a circuit containing two batteries and three identical resistors with resistance $R$. Which of the following changes to the circuit will result in an increase in the current at point $P$ ? Select two answers.

    (A) Reversing the connections to the 14 V battery

    (B) Removing the 2 V battery and connecting the wires to close the left loop

    (C) Rearranging the resistors so all three are in series

    (D) Removing the branch containing resistor $Z$

| Enduring Understandings | Learning Objectives | Science Practice |
|---|---|---|
| **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.<br><br>**5.B:** The energy of a system is conserved.<br><br>**5.C:** The electric charge of a system is conserved. | **4.E.5.2:** The student is able to 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.<br><br>**5.B.9.5:** The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors.<br><br>**5.C.3.4:** The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |

## Answers to Multiple-Choice Questions

| | |
|---|---|
| 1. D | 14. B |
| 2. C | 15. D |
| 3. D | 16. B |
| 4. A | 17. B |
| 5. C | 18. C |
| 6. C | 19. A |
| 7. B | 20. A |
| 8. A | 21. D |
| 9. B | 22. B, C |
| 10. B | 23. A, C |
| 11. C | 24. C, D |
| 12. D | 25. A, B |
| 13. C | |

## Free-Response Questions

**Directions:** Question 1 is a short free-response question that requires about 15–20 minutes to answer and is worth 10 points. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.

1. Some scientists want to perform electron diffraction experiments on crystals that have an intermolecular spacing of about $10^{-10}$ m. They have two processes by which they can produce energetic electrons that can strike the crystals.

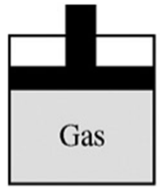
   Process 1 is the beta decay of potassium into calcium: $^{40}\text{K} \rightarrow {}^{40}\text{Ca} + e^{-} + \bar{\nu}_e$. The mass of $^{40}$K is 39.964000 u and the mass of $^{40}$Ca is 39.962591 u. As an approximation, assume that the mass of the neutrino is negligible and that all the decay energy is acquired by the electron.

   Process 2 is the emission of electrons when electromagnetic radiation of wavelength 7.5 nm shines on a copper surface with work function 4.7 eV.

   (a) Describe a single criterion for determining whether each of these processes can be used to produce electrons for the diffraction experiments.

   (b) Determine whether each of these processes could be used to produce electrons appropriate for the diffraction experiments. Justify your answers mathematically.

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **4.C:** Interactions with other objects or systems can change the total energy of a system.<br>**6.F:** Electromagnetic radiation can be modeled as waves or as fundamental particles.<br>**6.G:** All matter can be modeled as waves or as particles. | **4.C.4.1:** The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale.<br>**6.F.3.1:** The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect.<br>**6.G.2.2:** The student is able to predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (de Broglie wavelength need not be given, so students may need to obtain it.) | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena.<br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br>**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. |

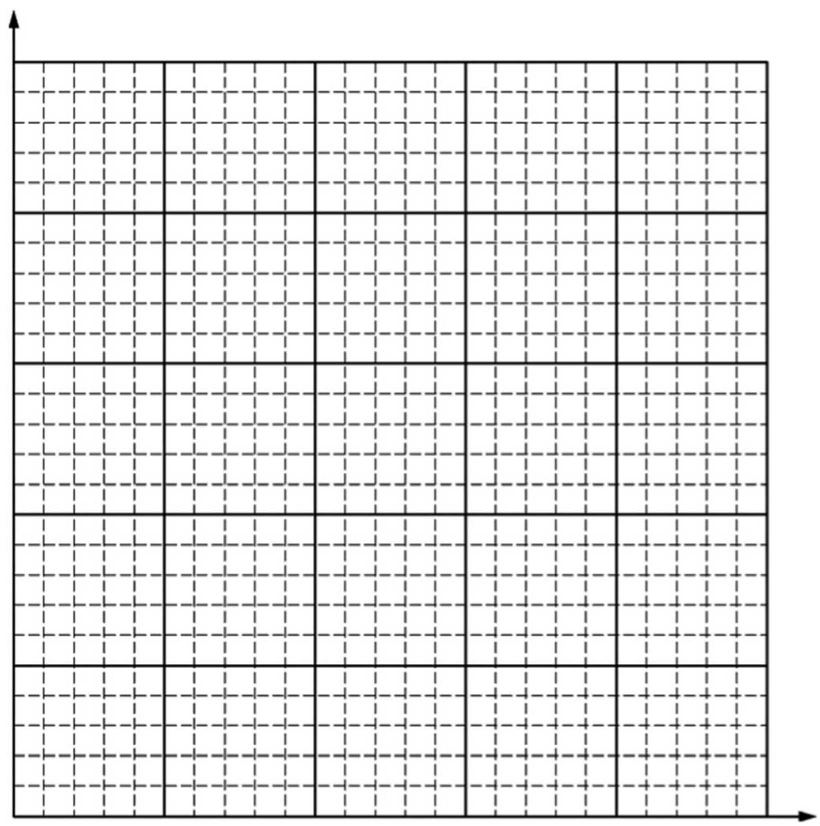



2. The figure above shows a clear plastic container with a movable piston that contains a fixed amount of gas. A group of students is asked to determine whether the gas is ideal. The students design and conduct an experiment. They measure the three quantities recorded in the data table below.

| Trial | Absolute Gas Pressure ($310^5$ Pa) | Volume ($m^3$) | Temperature (K) |
|---|---|---|---|
| 1 | 1.1 | 0.020 | 270 |
| 2 | 1.4 | 0.016 | 270 |
| 3 | 1.9 | 0.012 | 270 |
| 4 | 2.2 | 0.010 | 270 |
| 5 | 2.8 | 0.008 | 270 |
| 6 | 1.2 | 0.020 | 290 |
| 7 | 1.5 | 0.016 | 290 |
| 8 | 2.0 | 0.012 | 290 |
| 9 | 2.4 | 0.010 | 290 |
| 10 | 3.0 | 0.008 | 290 |
| 11 | 1.3 | 0.020 | 310 |
| 12 | 1.6 | 0.016 | 310 |
| 13 | 2.1 | 0.012 | 310 |
| 14 | 2.6 | 0.010 | 310 |
| 15 | 3.2 | 0.008 | 310 |

(a) Describe an experimental procedure the group of students could have used to obtain these data. Include all the equipment needed and a labeled diagram of the setup. Clearly indicate what measurements would be taken and how each of the manipulated variables would be varied. Include enough detail so that someone else could carry out the procedure.

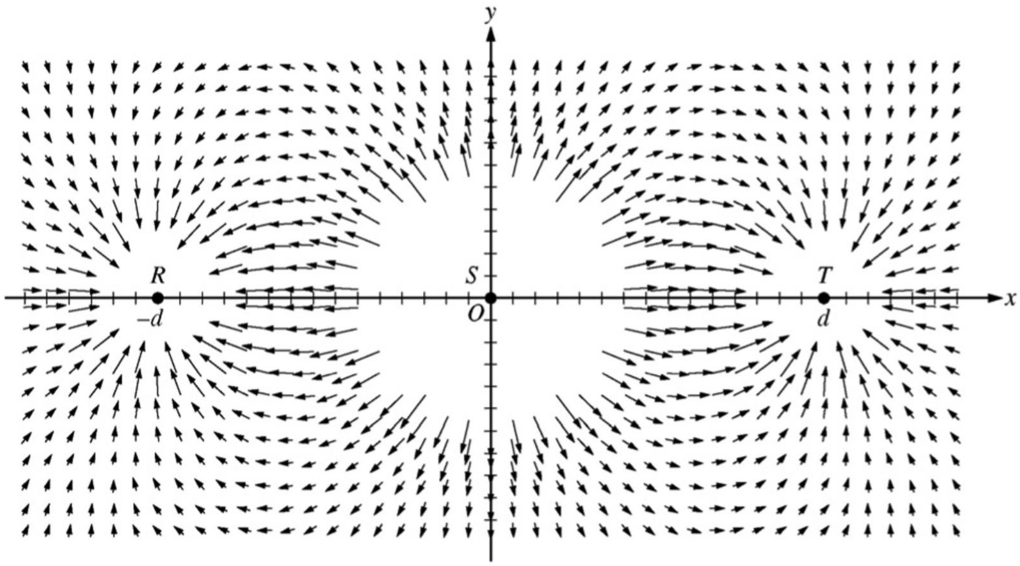
(b) Select a set of data points from the table and plot those points on the axes below to create a graph to determine whether the gas exhibits properties of an ideal gas. Fill in blank columns in the table for any quantities you graph other than the given data. Label the axes and indicate the scale for each. Draw a best-fit line or curve through your data points.



(c) Indicate whether the gas exhibits properties of an ideal gas, and explain what characteristic of your graph provides the evidence.

(d) The students repeat their experiment with an identical container that contains half as much gas. They take data for the same values of volume and temperature as in the table. Would the new data result in a different conclusion about whether the gas is ideal? Justify your answer in terms of interactions between the molecules of the gas and the container walls.

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br><br>**7.A:** The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure. | **5.B.7.2:** The student is able to create a plot of pressure versus volume for a thermodynamic process from given data.<br><br>**7.A.1.1:** The student is able to 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.<br><br>**7.A.3.2:** The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables.<br><br>**7.A.3.3:** The student is able to 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 $PV = nRT$. | **1.1:** The student can *create representations and models* of natural or man-made phenomena and systems in the domain.<br><br>**4.2:** The student can *design a plan* for collecting data to answer a particular scientific question.<br><br>**5.1:** The student can *analyze data* to identify patterns or relationships.<br><br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models.<br><br>**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. The figure above represents the electric field in the vicinity of three small charged objects, *R*, *S*, and *T*. The objects have charges $-q$, $+2q$, and $-q$, respectively, and are located on the *x*-axis at $-d$, 0, and *d*. Field vectors of very large magnitude are omitted for clarity.

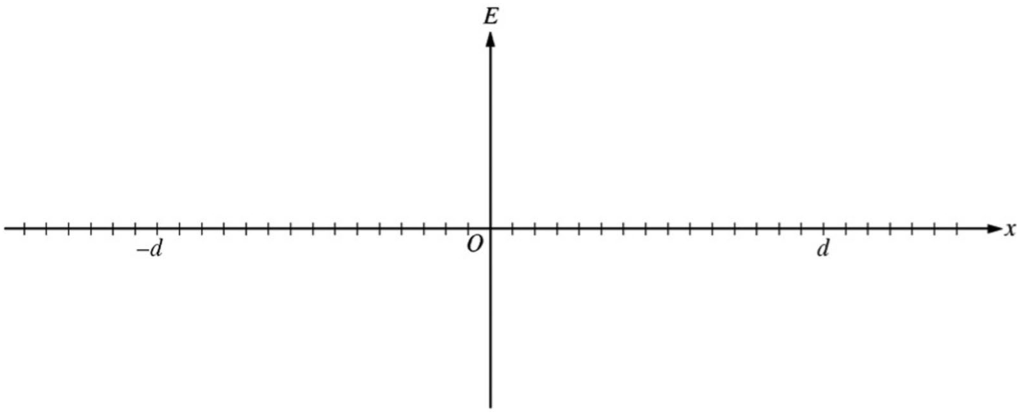
   (a)

   (i) Briefly describe the characteristics of the field diagram that indicate that the sign of the charges of objects *R* and *T* is negative and that the sign of the charge of object *S* is positive.

   (ii) Briefly describe the characteristics of the field diagram that indicate that the magnitudes of the charges of objects *R* and *T* are equal and that the magnitude of the charge of object *S* is about twice that of objects *R* and *T*.

For the following parts, an electric field directed to the right is defined to be positive.

(b) On the axes below, sketch a graph of the electric field $E$ along the $x$-axis as a function of position $x$.




(c) Write an expression for the electric field $E$ along the $x$-axis as a function of position $x$ in the region between objects $S$ and $T$ in terms of $q$, $d$, and fundamental constants, as appropriate.

(d) Your classmate tells you there is a point between $S$ and $T$ where the electric field is zero. Determine whether this statement is true, and explain your reasoning using two of the representations from parts (a), (b), or (c).

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **2.C:** An electric field is caused by an object with electric charge.<br><br>**3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **2.C.1.2:** The student is able to 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.<br><br>**2.C.2.1:** The student is able to qualitatively and semiquantitatively apply the vector relationship between the electric field and the net electric charge creating that field.<br><br>**2.C.4.2:** The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points.<br><br>**3.C.2.1:** The student is able to use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges (interactions between collections of electric point charges are not covered in Physics 1 and instead are restricted to Physics 2).<br><br>**3.C.2.3:** The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry). | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br><br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena.<br><br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |

# Scoring Guidelines

## Scoring Guidelines for Free-Response Question 1 (10 points)

(a) (2 points)

| | |
|---|---|
| For indicating an appropriate quantity to compare — either length or energy | 1 point |
| For indicating the appropriate specific quantities to compare: de Broglie wavelengths of electrons and crystal spacing | 1 point |

OR

kinetic energy of electrons and kinetic energy needed to have a de Broglie wavelength equal to the crystal spacing

Example: The energy of electrons produced by each method is comparable to the energy of electrons with de Broglie wavelengths corresponding to the crystal spacing.

(b) (8 points)

| | |
|---|---|
| For converting the electron energies to de Broglie wavelengths<br>OR<br>using the crystal spacing as a de Broglie wavelength to determine the required electron energy | 2 points |
| Decay process | |
| For determining the mass difference of the atoms | 1 point |
| For converting the mass difference to energy | 1 point |
| For correctly evaluating the energy against the crystal | 1 point |
| Photoelectric process | |
| For determining the energy of the incident light | 1 point |
| For determining the maximum kinetic energy $K$ of the ejected electrons | 1 point |
| For correctly evaluating the kinetic energy against the crystal | 1 point |

Example:

Determine the electron kinetic energy needed for the electron to have a de Broglie wavelength of $10^{-10}\,\text{m}$:

$$10^{-10}\,\text{m} = \left(6.63\times10^{-34}\,\text{J}\cdot\text{s}\right)/p$$

$$K - \frac{1}{2}mv^2 - \frac{1}{2}\frac{m^2v^2}{m} - \frac{p^2}{2m}$$

$$K = p^2/2m = \left(\frac{6.63\times10^{-34}\,\text{J}\cdot\text{s}}{10^{-10}}\right)^2 \frac{1}{2\left(9.11\times10^{-31}\,\text{kg}\right)} = 2.4\times10^{-17}\,\text{J} = 150\ eV$$

Determine the energy released by the decay reaction, which is converted to kinetic energy of the electron:

$$\left[\left(39.964000\ \text{u} - 39.962591\ \text{u}\right)\left(1.66\times10^{-27}\,\text{kg/u}\right) - 9.11\times10^{-31}\,\text{kg}\right]\text{c}^2$$

$$= 1.285\times10^{-13}\,\text{J}$$

NOTE: This is four orders of magnitude larger than $2.4\times10^{-17}\,J$, so the wavelength will be two orders of magnitude smaller than desired. This process will not work well.

Determine the maximum kinetic energy $K$ of electrons emitted in the photoelectric effect:

$$K_{max} = hf - f$$

$$f = c/1 = 3\times10^{8}/7.5\times10^{-9} - 4\times10^{16}\,\text{Hz}$$

$$K_{max} = \left(4.14\times10^{-15}\,\text{eV}\cdot\text{s}\right)\left(4\times10^{-16}\,\text{Hz}\right) - 4.7\text{eV}$$

$$K_{max} = 165.6\text{eV} - 4.7\text{eV} = 160.9\text{ev}$$

NOTE: This is comparable to 150 eV, so this process will work.

### Scoring Guidelines for Free-Response Question 2 (12 points)

(a) (4 points)

| | |
|---|---|
| For clearly indicating which variables are manipulated and which are controlled | 1 point |
| For clearly describing an experimental setup | 1 point |
| For an experimental setup that allows the manipulation and control of the indicated variables | 1 point |
| For an experimental setup that allows multiple measurements of $P$, $V$, and $T$ | 1 point |

Example:

> Hold temperature constant while volume is manipulated and pressure is measured. Then change the temperature and hold it constant again while volume is manipulated and pressure is measured, etc. To do this: Measure the cross-sectional area of the piston in units of meters cubed.

Put the container in an insulated bath that can be filled with water at one of the three different temperatures. Fill the bath with water. Allow some time for the gas in the container to equilibrate in temperature with the surrounding water bath. Measure the temperature of the bath. Measure six fixed heights, in units of meters, along the side of the container. Slowly add weights to the top of the piston so that the piston can be depressed to each height without changing the temperature. Multiply the height by the cross-sectional area of the piston to get the volume.

Divide the weight in newtons by the cross-sectional area of the piston to get the pressure and add atmospheric pressure and the pressure from the piston. Repeat the process twice using water at each of the other two temperatures.

(b) (4 points)

| | |
|---|---|
| For plotting appropriate quantities to examine ideal behavior | 1 point |
| For labeling and scaling the axes | 1 point |
| For plotting the data reasonably correctly | 1 point |
| For plotting a set of data with one variable controlled and drawing a reasonable best-fit line | 1 point |

OR

plotting more than one data set and more than one reasonable best-fit line

Example:

Plot $P$ as a function of $1/v$ for a single value of $T$. Draw a best-fit line through the data.

(c) (2 points)

| | |
|---|---|
| For a correct conclusion with a reasonable attempt at an explanation | 1 point |
| For a correct explanation relating to characteristics exhibited in the ideal gas law | 1 point |

Example:

> $PV = nRT$, so a graph of $P$ versus $1/v$ for an ideal gas should be linear if $n$ and $T$ are held constant. In the graphed set of data, $n$ and $T$ are held constant and the graph is linear, so there is evidence that the gas is ideal.

(d) (2 points)

| | |
|---|---|
| For indicating that the conclusion would be the same, since the amount of gas does not affect the relationship between the state variables | 1 point |
| For indicating that the rate of collision with the walls will be lower, so the pressure would be lower | 1 point |

Example:

> No, the conclusion would be the same. Reducing the amount of gas by half would result in there being half the rate of collisions with the container walls and half as much weight needed to compress the gas to the same volume at the same temperature. The graph of $P$ as a function of $1/v$ would still be linear, but with half the slope.

## Scoring Guidelines for Free-Response Question 3 (12 points)

(a) (3 points)

(i) For indicating that the direction of the field vectors is the telling characteristic and describing how they indicate negative and positive charge — 1 point

Example: The direction of the field vectors. Field vectors near objects point toward negatively charged objects and away from positively charged objects.

(ii) For indicating that the size and distance of the closest field vectors are the telling characteristics — 1 point

For describing how the size and distance of the closest field vectors indicate the magnitudes of the charges — 1 point

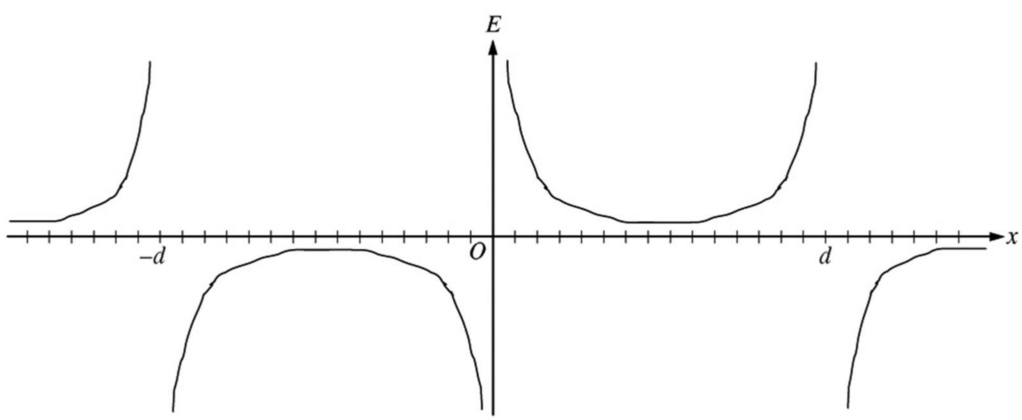
Field vectors nearest *R* and *T* are at about the same distance and have approximately the same length, so the magnitude of their charge is equal.

Field vectors nearest *S* have approximately the same length as field vectors nearest *R* and *T*, but the square of the distance to the field vectors nearest *S* is about twice the square of the distance to the field vectors nearest *R* and *T* –36 (6 tic marks squared) compared with 16 (4 tic marks squared). So the magnitude of the charge of *S* is twice the magnitude of the charges of *R* and *T*.

Example:

The vectors closest to *R* and *T* are about the same length and start at about the same distance. $q_R / d^2 = q_T / d^2$, so the charge on *R* is about the same as the charge on *T*. The closest vectors around *S* are about the same length as those around *R* and *T*. The vectors near *S* start at about 6 units away, while vectors near *R* and *T* start at about 4 units. $q_R / d^2 = q_s / \mathrm{D}^2$, so $q_s / \mathrm{q}_R = D^2 / \mathrm{d}^2 = 36/16 = 2.25$, , and so the charge on *S* is about twice that on *R* and *T*.

(b) (3 points)

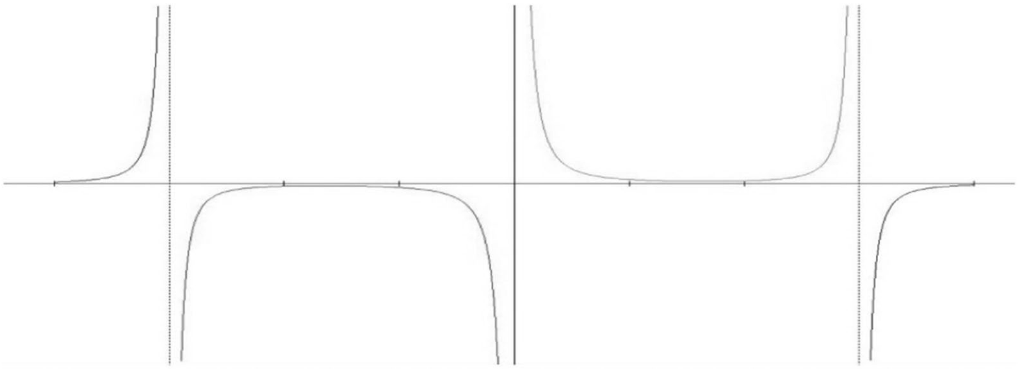



For showing reasonably close to asymptotic behavior on both sides of the charge positions — 1 point

For a general U shape between the charges that does not touch the *x*-axis — 1 point

For all signs consistent with the vector map — 1 point

The following shows a more exact plot. The scale is set to show the asymptotic behavior, which masks the nonzero values between charges and at both sides of the range.



(c) (3 points)

For correctly associating charge values with positions — 1 point

For using the correct sign and power in the expressions for the distance to each charge — 1 point

For the correct sign for the direction of the field for each term — 1 point

$$E = k\left[-\frac{q}{(d-x)^2} \perp \frac{2q}{(x)^2} \perp \frac{q}{(d-x)^2}\right]$$

(d) (3 points)

For indicating that the value of the electric field is nonzero for all values between $S$ and $T$ — 1 point

For justifying the above using one of the representations — 1 point

For justifying the above using a second representation — 1 point

The following are the ideas that should be expressed for each representation:

- The vectors between $S$ and $T$ in the electric field diagram all have nonzero length
- The graph between $S$ and $T$ never crosses the $x$-axis
- The negative term of the equation in part (c) is either always smaller than the other terms in this region or never completely cancels them both

Example:

The statement is not true. The vector diagram shows field vectors in this region with nonzero length, and the vectors not shown have even greater lengths.

The equation in part (c) shows that when $0 < x < d$, the denominator of the negative term is always greater than the denominator of the third term, but the numerator is the same. So the negative term always has a smaller magnitude than the third term, and since the second term is positive, the sum of the terms is always positive.

Note: A response claiming that there is a zero value can receive credit if it is consistent with an incorrect response in either part (b) or (c).

# Appendix A: The Big Ideas in AP Physics 2

**Big Idea 1:** *Objects and systems have properties such as mass and charge. Systems may have internal structure.*

| | |
|---|---|
| **Enduring Understanding 1.A:** The internal structure of a system determines many properties of the system. | **Essential Knowledge 1.A.2:** Fundamental particles have no internal structure.<br><br>**Essential Knowledge 1.A.3:** Nuclei have internal structures that determine their properties.<br><br>**Essential Knowledge 1.A.4:** Atoms have internal structures that determine their properties.<br><br>**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*. |
| **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. | **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.<br><br>**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.<br><br>**Essential Knowledge 1.B.3:** The smallest observed unit of charge that can be isolated is the electron charge, also known as the elementary charge. |
| **Enduring Understanding 1.C:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles. | **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 1.D:** Classical mechanics cannot describe all properties of objects. | **Essential Knowledge 1.D.1:** Objects classically thought of as particles can exhibit properties of waves.<br><br>**Essential Knowledge 1.D.2:** Certain phenomena classically thought of as waves can exhibit properties of particles.<br><br>**Essential Knowledge 1.D.3:** Properties of space and time cannot always be treated as absolute. |

**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.

**Essential Knowledge 1.E.1:** Matter has a property called density.

**Essential Knowledge 1.E.2:** Matter has a property called resistivity.

**Essential Knowledge 1.E.3:** Matter has a property called thermal conductivity.

**Essential Knowledge 1.E.4:** Matter has a property called electric permittivity.

**Essential Knowledge 1.E.5:** Matter has a property called magnetic permeability.

**Essential Knowledge 1.E.6:** Matter has a property called magnetic dipole moment.

## Big Idea 2: *Fields existing in space can be used to explain interactions.*

**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.

**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.

**Essential Knowledge 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.

**Enduring Understanding 2.C:** An electric field is caused by an object with electric charge.

**Essential Knowledge 2.C.1:** The magnitude of the electric force F exerted on an object with electric charge q by an electric field $\vec{F} = q\vec{E}$. 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.

**Essential Knowledge 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.

**Essential Knowledge 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 relyonly on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.

| | |
|---|---|
| | **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.<br><br>**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. |
| **Enduring Understanding 2.D:** A magnetic field is caused by a magnet or a 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. | **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°, or 180° and qualitative for other angles.<br><br>**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.<br><br>**Essential Knowledge 2.D.3:** A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.<br><br>**Essential Knowledge 2.D.4:** Ferromagnetic materials contain magnetic domains that are themselves magnets. |
| **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. | **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.]<br><br>**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.<br><br>**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. |

## Big Idea 3: *The interactions of an object with other objects can be described by forces.*

| | |
|---|---|
| **Enduring Understanding 3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **Essential Knowledge 3.A.2:** Forces are described by vectors.<br><br>**Essential Knowledge 3.A.3:** A force exerted on an object is always due to the interaction of that object with another object.<br><br>**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. |
| **Enduring Understanding 3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **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.<br><br>**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. |
| **Enduring Understanding 3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **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.<br><br>**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.<br><br>**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). Buoyant force is caused by the difference in pressure, or force per unit area, exerted on the different surfaces of the object. |
| **Enduring Understanding 3.G:** Certain types of forces are considered fundamental. | **Essential Knowledge 3.G.1:** Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales.<br><br>**Essential Knowledge 3.G.2:** Electromagnetic forces are exerted at all scales and can dominate at the human scale.<br><br>**Essential Knowledge 3.G.3:** The strong force is exerted at nuclear scales and dominates the interactions of nucleons. |

## Big Idea 4: *Interactions between systems can result in changes in those systems.*

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|---|---|
| **Enduring Understanding 4.C:** Interactions with other objects or systems can change the total energy of a system. | **Essential Knowledge 4.C.3:** Energy is transferred spontaneously from a higher temperature system to a lower temperature system. This process of transferring energy is called heating. The amount of energy transferred is called heat.<br><br>**Essential Knowledge 4.C.4:** Mass can be converted into energy, and energy can be converted into mass. |

| | |
|---|---|
| **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. | **Essential Knowledge 4.E.1:** The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.<br><br>**Essential Knowledge 4.E.2:** Changing magnetic flux induces an electric field that can establish an induced emf in a system.<br><br>**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.<br><br>**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.<br><br>**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 the individual circuit elements such as sources of emf, resistors, and capacitors. |

## Big Idea 5: *Changes that occur as a result of interactions are constrained by conservation laws.*

| | |
|---|---|
| **Enduring Understanding 5.B:** The energy of a system is conserved. | **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 object in electric fields and examining changes in internal energy with changes in configuration.]<br><br>**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.<br><br>**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.]<br><br>**Essential Knowledge 5.B.6:** Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat. |

| | |
|---|---|
| | **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 P-V diagrams — isovolumetric processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of internal energy change from temperature change are required; in this course, examples of these relationships are qualitative and/or semiquantitative.<br><br>**Essential Knowledge 5.B.8:** Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei.<br><br>**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.]<br><br>**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 ($\rho gh$).<br><br>**Essential Knowledge 5.B.11:** Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$. |
| **Enduring Understanding 5.C:** The electric charge of a system is conserved. | **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.<br><br>**Essential Knowledge 5.C.2:** The exchange of electric charges among a set of objects in a system conserves electric charge.<br><br>**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, 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.] |
| **Enduring Understanding 5.D:** The linear momentum of a system is conserved. | **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.<br><br>**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.<br><br>**Essential Knowledge 5.D.3:** The velocity of the center of mass of the system cannot be changed by an interaction within the system. |

| | |
|---|---|
| **Enduring Understanding 5.F:** Classically, the mass of a system is conserved. | **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. |
| **Enduring Understanding 5.G:** Nucleon number is conserved. | **Essential Knowledge 5.G.1:** The possible nuclear reactions are constrained by the law of conservation of nucleon number. |

## Big Idea 6: *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.*

| | |
|---|---|
| **Enduring Understanding 6.A:** A wave is a traveling disturbance that transfers energy and momentum. | **Essential Knowledge 6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal.<br><br>**Essential Knowledge 6.A.2:** For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples should include light traveling through a vacuum and sound not traveling through a vacuum. |
| **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. | **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. |
| **Enduring Understanding 6.C:** Only waves exhibit interference and diffraction. | **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.<br><br>**Essential Knowledge 6.C.2:** When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.<br><br>**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.<br><br>**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. |

| | |
|---|---|
| **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. | **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.)<br><br>**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. |
| **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. | **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.<br><br>**Essential Knowledge 6.E.4:** The reflection of light from surfaces can be used to form images.<br><br>Ess**ential Knowledge 6.E.5:** The refraction of light as it travels from one transparent medium to another can be used to form images. |
| **Enduring Understanding 6.F:** Electromagnetic radiation can be modeled as waves or as fundamental particles. | **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.<br><br>**Essential Knowledge 6.F.2:** Electromagnetic waves can transmit energy through a medium and through a vacuum.<br><br>**Essential Knowledge 6.F.3:** Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck's constant and f is the frequency of the associated light wave.<br><br>**Essential Knowledge 6.F.4:** The nature of light requires that different models of light are most appropriate at different scales. |
| **Enduring Understanding 6.G:** All matter can be modeled as waves or as particles. | **Essential Knowledge 6.G.1:** Under certain regimes of energy or distance, matter can be modeled as a classical particle.<br><br>**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. |

## Big Idea 7: *The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.*

| | |
|---|---|
| **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. | **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.<br><br>**Essential Knowledge 7.A.2:** The temperature of a system characterizes the average kinetic energy of its molecules.<br><br>**Essential Knowledge 7.A.3:** In an ideal gas, the macroscopic (average) pressure ($P$), temperature ($T$), and volume ($V$), are related by the equation $PV = nRT$. |
| **Enduring Understanding 7.B:** The tendency of isolated systems to move toward states with higher disorder is described by probability. | **Essential Knowledge 7.B.1:** The approach to thermal equilibrium is a probability process.<br><br>**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. |
| **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. | **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.)<br><br>**Essential Knowledge 7.C.2:** The allowed states for an electron in an atom can be calculated from the wave model of an electron.<br><br>**Essential Knowledge 7.C.3:** The spontaneous radioactive decay of an individual nucleus is described by probability.<br><br>**Essential Knowledge 7.C.4:** Photon emission and absorption processes are described by probability. |

# Appendix B: Developing Big Ideas from Foundational Physics Principles

The table below helps illustrate how to make connections across the course framework by developing big ideas from the foundational physics principles.

| Physics 2 Principles | Big Ideas |
|---|---|
| Thermodynamics: Laws of Thermodynamics, Ideal Gases, and Kinetic Theory | 1, 3, 4, 5, 7 |
| Fluid Statics and Dynamics | 1, 3, 5 |
| Electrostatics: Electric Force, Electric Field, and Electric Potential | 1, 2, 3, 4, 5 |
| DC Circuits and RC Circuits (Steady-State Only) | 1, 4, 5 |
| Magnetism and Electromagnetic Induction | 2, 3, 4 |
| Geometric and Physical Optics | 6 |
| Quantum, Atomic, and Nuclear Physics | 1, 3, 4, 5, 6, 7 |

# Appendix C: AP Physics 2 Equations and Constants

**Table of Information and Equation Tables for the AP Physics 2 Exam**

The accompanying table of information and equation tables will be provided to students when they take the AP Physics 2 Exam. Therefore, students may NOT bring their own copies of these tables to the exam room, although they may use them throughout the year in their classes in order to become familiar with their content. **The headings list the effective date of the tables. That date will only be changed when there is a revision to any of the tables. Check the Physics course home pages on AP Central for the latest versions of these tables (apcentral.collegeboard.org).**

The table of information and the equation tables are printed near the front cover of both the multiple-choice section and the free-response section. The table of information is identical for both exams except for some of the conventions.

The equations in the tables express the relationships that are encountered most frequently in the AP Physics 2 course and exam. However, the tables do not include all equations that might possibly be used. For example, they do not include many equations that can be derived by combining other equations in the tables. Nor do they include equations that are simply special cases of any that are in the tables. Students are responsible for understanding the physical principles that underlie each equation and for knowing the conditions for which each equation is applicable.

The equation tables are grouped in sections according to the major content category in which they appear. Within each section, the symbols used for the variables in that section are defined. However, in some cases the same symbol is used to represent different quantities in different tables. It should be noted that there is no uniform convention among textbooks for the symbols used in writing equations. The equation tables follow many common conventions, but in some cases consistency was sacrificed for the sake of clarity.

Some explanations about notation used in the equation tables:

1. The symbols used for physical constants are the same as those in the table of information and are defined in the table of information rather than in the right-hand columns of the equation tables.
2. Symbols with arrows above them represent vector quantities.
3. Subscripts on symbols in the equations are used to represent special cases of the variables defined in the right-hand columns.
4. The symbol D before a variable in an equation specifically indicates a change in the variable (e.g., final value minus initial value).
5. Several different symbols (e.g., *d, r, s, h, l*) are used for linear dimensions such as length. The particular symbol used in an equation is one that is commonly used for that equation in textbooks.

## ADVANCED PLACEMENT 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, | $\mu_0 = 4\pi \times 10^{-7}$ (T•m)/A |
| Magnetic constant, | $k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T•m)/A |
| 1 atmosphere pressure, | $1\text{ atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}$ 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 | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\theta$ | 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 <u>on</u> 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.

## ADVANCED PLACEMENT PHYSICS 2 EQUATIONS

### MECHANICS

$v_x = v_{x0} + a_x t$

$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$

$v_x^2 = v_{x0}^2 + 2a_x (x - x_0)$

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

$|\vec{F}_f| \le \mu |\vec{F}_n|$

$a_c = \frac{v^2}{r}$

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

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

$K = \frac{1}{2} m v^2$

$\Delta E = W = F_{\parallel} d = F d \cos\theta$

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

$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$

$\omega = \omega_0 + \alpha t$

$x = A\cos(\omega t) = A\cos(2\pi f t)$

$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$

$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$

$\tau = r_{\perp} F = rF\sin\theta$

$L = I\omega$

$\Delta L = \tau\,\Delta t$

$K = \frac{1}{2} I \omega^2$

$|\vec{F}_s| = k|\vec{x}|$

$U_s = \frac{1}{2} k x^2$

$\Delta U_g = m g \Delta y$

$T = \frac{2\pi}{\omega} = \frac{1}{f}$

$T_s = 2\pi\sqrt{\frac{m}{k}}$

$T_p = 2\pi\sqrt{\frac{\ell}{g}}$

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

$\vec{g} = \frac{\vec{F}_g}{m}$

$U_G = -\frac{G m_1 m_2}{r}$

- $a$ = acceleration
- $A$ = amplitude
- $d$ = distance
- $E$ = energy
- $F$ = force
- $f$ = frequency
- $I$ = rotational inertia
- $K$ = kinetic energy
- $k$ = spring constant
- $L$ = angular momentum
- $\ell$ = 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
- $\alpha$ = angular acceleration
- $\mu$ = coefficient of friction
- $\theta$ = angle
- $\tau$ = torque
- $\omega$ = angular speed

### 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
- $\ell$ = length
- $P$ = power
- $Q$ = charge
- $q$ = point charge
- $R$ = resistance
- $r$ = separation
- $t$ = time
- $U$ = potential (stored) energy
- $V$ = electric potential
- $v$ = speed
- $\kappa$ = dielectric constant
- $\rho$ = resistivity
- $\theta$ = angle
- $\Phi$ = flux

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

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

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

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

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

$\Phi_B = |\vec{B}|\cos\theta|\vec{A}|$

$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t}$

$\mathcal{E} = B\ell v$

# ADVANCED PLACEMENT PHYSICS 2 EQUATIONS

## FLUID MECHANICS AND THERMAL PHYSICS

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

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

$P = P_0 + \rho g h$

$F_b = \rho V g$

$A_1 v_1 = A_2 v_2$

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

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

$PV = nRT = Nk_B T$

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

$W = -P\Delta V$

$\Delta U = Q + W$

$A$ = 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
$\rho$ = 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
$\lambda$ = wavelength
$\phi$ = 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
$\lambda$ = wavelength
$\theta$ = 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
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

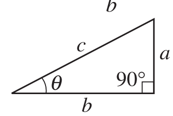
$A$ = area
$C$ = circumference
$V$ = volume
$S$ = surface area
$b$ = base
$h$ = height
$\ell$ = length
$w$ = width
$r$ = radius

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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