Course and Exam Description

# AP® Physics 1: Algebra-Based

Including: Course Framework and Sample Exam Questions

Updated **Fall 2017**

CollegeBoard

AP® CollegeBoard

# AP Physics 1: Algebra-Based

*Course and Exam Description*

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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# About This Edition

This revised edition of the *AP Physics 1: Algebra-Based Course and Exam Description* provides a stand-alone course and exam description for the AP Physics 1 course. While the scope, sequence, and course content of AP Physics 1 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 1 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 2 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

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).

underserved. 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.

## 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.


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# 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 1 Course

## About This Course

AP Physics 1 is an algebra-based, introductory college-level physics course. Students cultivate their understanding of Physics through inquiry-based investigations as they explore these topics: kinematics; dynamics; circular motion and gravitation; energy; momentum; simple harmonic motion; torque and rotational motion; electric charge and electric force; DC circuits; and mechanical waves and sound.

## College Course Equivalent

AP Physics 1 is a full-year course that is the equivalent of a first-semester introductory college course in algebra-based physics.

## Prerequisites

There are no prerequisite courses. Students should have completed geometry and be concurrently taking Algebra II or an equivalent course. Although the Physics 1 course includes basic use of trigonometric functions, this understanding can be gained either in the concurrent math course or in the AP Physics 1 course itself.

## 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.



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Please visit **http://www.collegeboard.com/html/apcourseaudit/courses/physics_1.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 1: Algebra-Based Course Framework

Based on the Understanding by Design (Wiggins and McTighe) model, the AP Physics 1 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 six “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.*

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 content 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 10 content areas: Kinematics; Dynamics; Circular Motion and Gravitation; Energy; Momentum; Simple Harmonic Motion; Torque and Rotational Motion; Electric Charge and Electric Force; DC Circuits; and Mechanical Waves and Sound.

These content 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 are the main focus points for 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 content area. 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 1 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 $m/s^2$; $\vec{a} = \frac{\sum \vec{F}}{m}$ ).

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 appropriate for 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 $\vec{a} = \frac{\sum \vec{F}}{m}$, 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.

**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: Kinematics

**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) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1**: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]**<br><br>**3.A.1.2:** The student is able to design an experimental investigation of the motion of an object. **[SP 4.2]**<br><br>**3.A.1.3:** The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. **[SP 5.1]** | **3.A.1:** An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.<br><br>a. Displacement, velocity, and acceleration are all vector quantities.<br><br>b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values.<br><br>*Relevant Equations:*<br><br>$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$<br><br>$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$<br><br>c. A choice of reference frame determines the direction and the magnitude of each of these quantities.<br><br>d. There are three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects.<br><br>e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force. |

| 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) | | f. The kinematic equations only apply to constant acceleration situations. Circular motion and projectile motion are both included. Circular motion is further covered in Content Area 3. The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are:<br><br>$v_x = v_{x0} + a_x t$<br><br>$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$<br><br>$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$<br><br>g. For rotational motion there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are:<br><br>$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$<br><br>$\omega = \omega_0 + \alpha t$<br><br>$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$<br><br>Circular motion is included, and is further discussed in Content Area 3. |
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **4.A.1.1** The student is able to use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semiquantitatively. **[SP 1.2, 1.4, 2.3, 6.4]** | **4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.<br><br>a. The variables $x$, $v$, and $a$ all refer to the center-of-mass quantities.<br><br>*Relevant Equations:*<br><br>$v_x = v_{x0} + a_x t$<br><br>$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$<br><br>$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ |

| **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.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$.<br>(Continued) | **4.A.2.1:** The student is able to make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. **[SP 6.4]**<br><br>**4.A.2.3:** The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system. **[SP 1.4, 2.2]** | **4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.<br><br>a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.<br><br>b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.<br><br>c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of the position of the center of mass with time.<br><br>d. The variables $x$, $v$, and $a$ all refer to the center-of-mass quantities.<br><br>*Relevant Equations:*<br><br>$\vec{a} = \frac{\sum \vec{F}}{m_{system}}$<br><br>$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$<br><br>$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$ |

# Content Area 2: Dynamics

**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. | *[While there is no specific learning objective for it, EK 1.A.1 serves as a foundation for other learning objectives in the course.]* | **1.A.1:** A system is an object or a collection of objects. Objects are treated as having no internal structure.<br>a. A collection of particles in which internal interactions change little or not at all, or in which changes in these interactions are irrelevant to the question addressed, can be treated as an object.<br>b. Some elementary particles are fundamental particles (e.g., electrons). Protons and neutrons are composed of fundamental particles (i.e., quarks) and might be treated as either systems or objects, depending on the question being addressed.<br>c. The electric charges on neutrons and protons result from their quark compositions. |
| | **1.A.5.1:** The student is able to model verbally or visually the properties of a system based on its substructure and to relate this to changes in the system properties over time as external variables are changed. **[SP 1.1, 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.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.1.1:** The student is able to design an experiment for collecting data to determine the relationship between the net force exerted on an object its inertial mass and its acceleration. **[SP 4.2]** | **1.C.1:** Inertial mass is the property of an object or a system that determines how its motion changes when it interacts with other objects or systems.<br>a. $\vec{a} = \frac{\sum \vec{F}}{m}$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **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.<br>(Continued) | **1.C.3.1:** The student is able to design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]** | **1.C.3:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles. |
| **2.B:** A gravitational field is caused by an object with mass. | **2.B.1.1:** The student is able to apply $\vec{F}=m\vec{g}$ to calculate the gravitational force on an object with mass $m$ in a gravitational field of strength $g$ in the context of the effects of a net force on objects and systems. **[SP 2.2, 7.2]** | **2.B.1:** A gravitational field $\vec{g}$ at the location of an object with mass $m$ causes a gravitational force of magnitude $mg$ to be exerted on the object in the direction of the field.<br>a. On Earth, this gravitational force is called weight.<br>b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.<br>c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location.<br>*Relevant Equation:*<br>$\vec{F} = m\vec{g}$ |
| **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>a. Forces are detected by their influence on the motion of an object.<br>b. Forces have magnitude and 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) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br><br>(Continued) | **3.A.3.1:** The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]**<br><br>**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]** | **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. |
| | **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. |

| 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.B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.1:** 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 with acceleration in one dimension. **[SP 6.4, 7.2]**<br><br>**3.B.1.2:** The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**<br><br>**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]** | **3.B.1:** If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces. Projectile motion and circular motion are both included in AP Physics 1.<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 for 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.<br><br>d. Free-body diagrams are depicted where the forces exerted on an object are represented as arrows pointing outward from a dot, and also diagrams that show at what point on the object each force is exerted. |

| **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.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>$\lvert\vec{F}_f\rvert \le \mu\lvert\vec{F}_n\rvert$<br>$\lvert\vec{F}_s\rvert = k\lvert\vec{x}\rvert$ |
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **4.A.1.1** The student is able to use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semiquantitatively. **[SP 1.2, 1.4, 2.3, 6.4]** | **4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.<br><br>The variables $x$, $v$, and $a$; all refer to the center-of-mass quantities.<br><br>*Relevant Equation:*<br>$v_x = v_{x0} + a_x t$<br>$x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$<br>$v_x^2 = v_{x0}^2 + 2a_x(x - x_0)$ |
| | **4.A.2.2:** The student is able to evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]** | **4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.<br><br>a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.<br><br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m_{system}}$<br><br>b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.<br><br>*Relevant Equations:*<br>$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$<br>$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$ |

| Enduring Understanding (Core concepts that students should retain) | Learning Objectives (What students must be able to do) | Essential Knowledge (What students need to know) |
|---|---|---|
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. (Continued) | | c. The acceleration of the center of mass of a system is equal to the rate of change of the center of mass velocity with time, and the center of mass velocity is equal to the rate of change of the position of the center of mass with time.<br>d. The variables $x$, $v$, and $a$ all refer to the center-of-mass quantities.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ |
| | **4.A.3.1:** The student is able to apply Newton's second law to systems to calculate the change in the center-of-mass velocity when an external force is exerted on the system. **[SP 2.2]**<br>**4.A.3.2:** The student is able to use visual or mathematical representations of the forces between objects in a system to predict whether or not there will be a change in the center-of-mass velocity of that system. **[SP 1.4]** | **4.A.3:** Forces that that systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system.<br>*Relevant Equation:*<br>$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$ |

# Content Area 3: Circular Motion and Gravitation

**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.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. | *[While there is no specific learning objective for it, EK 1.C.2 serves as a foundation for other learning objectives in the course.]* | **1.C.2**: Gravitational mass is the property of an object or a system that determines the strength of the gravitational interaction with other objects, systems, or gravitational fields.<br>a. The gravitational mass of an object determines the amount of force exerted on the object by a gravitational field.<br>b. Near the Earth's surface, all objects fall (in a vacuum) with the same acceleration, regardless of their inertial mass. |
| | **1.C.3.1:** The student is able to design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]** | **1.C.3:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles. |
| **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.<br>**Boundary Statement:** *Physics 1 treats gravitational fields; Physics 2 treats electric and magnetic fields.* |

| **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.B:** A gravitational field is caused by an object with mass. | **2.B.1.1:** The student is able to apply $\vec{F}=m\vec{g}$ to calculate the gravitational force on an object with mass $m$ in a gravitational field of strength $g$ in the context of the effects of a net force on objects and systems. **[SP 2.2, 7.2]** | **2.B.1:** A gravitational field $\vec{g}$ at the location of an object with mass $m$ causes a gravitational force of magnitude $mg$ to be exerted on the object in the direction of the field.<br>a. On Earth, this gravitational force is called weight.<br>b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.<br>c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in Newtons/kilogram) at that location.<br>*Relevant Equation:*<br>$\vec{g}=\frac{\vec{F}_g}{m}$ |
| | **2.B.2.1:** The student is able to apply $g=G\frac{M}{r^2}$ to calculate the gravitational field due to an object with mass $M$, where the field is a vector directed toward the center of the object of mass $M$. **[SP 2.2]**<br>**2.B.2.2:** The student is able to approximate a numerical value of the gravitational field ($g$) near the surface of an object from its radius and mass relative to those of the Earth or other reference objects. **[SP 2.2]** | **2.B.2:** The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object.<br>a. The gravitational field caused by a spherically symmetric object is a vector whose magnitude outside the object is equal to $G\frac{M}{r^2}$.<br>b. Only spherically symmetric objects will be considered as sources of the gravitational field.<br>*Relevant Equation:*<br>$\vec{a}=\frac{\Sigma\vec{F}}{m}=\frac{\vec{F}_{net}}{m}$ |
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]** | **3.A.1:** An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.<br>a. Displacement, velocity, and acceleration are all vector quantities.<br>b. Displacement is change in position. Velocity is the rate of change of position with time. Acceleration is the rate of change of velocity with time. Changes in each property are expressed by subtracting initial values from final values. |

| **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.1.2:** The student is able to design an experimental investigation of the motion of an object. **[SP 4.2]**<br><br>**3.A.1.3:** The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical and graphical representatives. **[SP 5.1]** | *Relevant Equations:*<br>$\vec{v}_{avg} = \frac{\Delta \vec{x}}{\Delta t}$<br>$\vec{a}_{avg} = \frac{\Delta \vec{v}}{\Delta t}$<br><br>c. A choice of reference frame determines the direction and the magnitude of each of these quantities.<br><br>d. We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The fundamental forces determine both the structure of objects and the motion of objects.<br><br>e. In inertial reference frames, forces are detected by their influence on the motion (specifically the velocity) of an object. So force, like velocity, is a vector quantity. A force vector has magnitude and direction. When multiple forces are exerted on an object, the vector sum of these forces, referred to as the net force, causes a change in the motion of the object. The acceleration of the object is proportional to the net force.<br><br>f. The three kinematic equations only apply to constant acceleration situations (this includes projectile motion). The three kinematic equations describing linear motion with constant acceleration in one and two dimensions are:<br>$v_x = v_{x0} + a_x t$<br>$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$<br>$v_x^2 = v_{x0}^2 + 2a_x (x - x_0)$<br><br>g. For rotational motion there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are:<br>$\omega = \omega_0 + \alpha t$<br>$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$<br>$\omega^2 = \omega_0^2 + 2\alpha\theta$ |

| 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) | | h. This also includes situations where there is both a radial and tangential acceleration for an object moving in a circular path.<br><br>*Relevant Equation:*<br><br>$a_c = \frac{v^2}{r}$<br><br>i. For uniform circular motion of radius $r$, $v$ is proportional to omega (for a given $r$), and proportional to $r$ (for a given omega). Given a radius $r$ and a period of rotation $T$, students derive and apply $v = (2\pi r)/T$.<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.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. |
| | **3.A.3.1:** The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]**<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]** | **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.<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. |
| **3.B**: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.2:** The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**<br><br>**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]** | **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>**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) |
|---|---|---|
| **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>(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. |
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.1.1:** The student is able to use Newton's law of gravitation to calculate the gravitational force the two objects exert on each other and use that force in contexts other than orbital motion. **[SP 2.2]**<br>**3.C.1.2:** The student is able to use Newton's law of gravitation to calculate the gravitational force between two objects and use that force in contexts involving orbital motion (for circular orbital motion only in Physics 1). **[SP 2.2]** | **3.C.1:** Gravitational force describes the interaction of one object with mass with another object with mass.<br>a. The gravitational force is always attractive.<br>b. The magnitude of force between two spherically symmetric objects of mass $m_1$ and $m_2$ is $\frac{Gm_1m_2}{r^2}$ where $r$ is the center-to-center distance between the objects.<br>c. In a narrow range of heights above the Earth's surface, the local gravitational field, $g$, is approximately constant.<br>*Relevant Equations:*<br>$\lvert\vec{F}_g\rvert = G\frac{m_1m_2}{r^2}$<br>$\vec{g} = \frac{\vec{F}_g}{m}$ |

| **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.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.<br><br>(Continued) | **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]** | **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>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><br>b. Electric forces may be attractive or repulsive, depending upon the charges on the objects involved.<br><br>*Relevant Equations:*<br><br>$F_G = \frac{Gm_1m_2}{r^2}$<br><br>$F_E = \frac{kq_1q_2}{r^2}$ |
| **3.G:** Certain types of forces are considered fundamental. | **3.G.1.1:** The student is able to articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. **[SP 7.1]** | **3.G.1:** Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales. |
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **4.A.2.2:** The student is able to evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]** | **4.A.2:** The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.<br><br>a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.<br><br>b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.<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) |
|---|---|---|
| **4.C:** Interactions with other objects or systems can change the total energy of a system. | **4.C.1.1:** The student is able to calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]** | **4.C.1:** The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples should include gravitational potential energy, elastic potential energy, and kinetic energy.<br><br>a. A rotating, rigid body may be considered to be a system, and may have both translational and rotational kinetic energy.<br><br>b. Although thermodynamics is not part of Physics 1, included is the idea that during an inelastic collision, some of the mechanical energy dissipates as (converts to) thermal energy.<br><br>*Boundary Statement:*<br>Thermodynamics is treated in Physics 2 only.<br><br>*Relevant Equations:*<br>$K = \frac{1}{2}mv^2$<br>$K = \frac{1}{2}I\omega^2$<br>$\Delta U_g = mg\Delta y$<br>$U_G = -\frac{Gm_1m_2}{r}$<br>$U_S = \frac{1}{2}kx^2$ |

# Content Area 4: Energy

**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) |
|---|---|---|
| **3.E:** A force exerted on an object can change the kinetic energy of the object. | **3.E.1.1:** The student is able to make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. **[SP 6.4, 7.2]**<br><br>**3.E.1.2:** The student is able to use net force and velocity vectors to determine qualitatively whether kinetic energy of an object would increase, decrease, or remain unchanged. **[SP 1.4]**<br><br>**3.E.1.3:** The student is able to use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether kinetic energy of that object would increase, decrease, or remain unchanged. **[SP 1.4, 2.2]**<br><br>**3.E.1.4:** The student is able to apply mathematical routines to determine the change in kinetic energy of an object given the forces on the object and the displacement of the object. **[SP 2.2]** | **3.E.1:** The change in the kinetic energy of an object depends on the force exerted on the object and on the displacement of the object during the interval that the force is exerted.<br><br>a. Only the component of the net force exerted on an object parallel or antiparallel to the displacement of the object will increase (parallel) or decrease (antiparallel) the kinetic energy of the object.<br><br>b. The magnitude of the change in the kinetic energy is the product of the magnitude of the displacement and of the magnitude of the component of force parallel or antiparallel to the displacement.<br><br>*Relevant Equation:*<br><br>$\Delta E = W = F_{\parallel} d$<br><br>c. The component of the net force exerted on an object perpendicular to the direction of the displacement of the object can change the direction of the motion of the object without changing the kinetic energy of the object. This should include uniform circular motion and projectile motion.<br><br>d. The kinetic energy of a rigid system may be translational, rotational, or a combination of both. The change in the rotational kinetic energy of a rigid system is the product of the angular displacement and the net torque.<br><br>*Relevant Equations:*<br><br>$K = \frac{1}{2}mv^2$<br><br>$\Delta E = W = F_{\parallel} d = Fd\cos\theta$ |

| 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.1.1:** The student is able to calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]**<br><br>**4.C.1.2:** The student is able to predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. **[SP 6.4]** | **4.C.1:** The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples include gravitational potential energy, elastic potential energy, and kinetic energy.<br><br>a. A rotating, rigid body may be considered to be a system, and may have both translational and rotational kinetic energy.<br><br>b. Although thermodynamics is not part of Physics 1, included is the idea that during an inelastic collision, some of the mechanical energy dissipates as (converts to) thermal energy.<br><br>*Relevant Equations:*<br><br>$K = \frac{1}{2}mv^2$<br><br>$K = \frac{1}{2}I\omega^2$<br><br>$\Delta U_g = mg\Delta y$<br><br>$U_G = -\frac{Gm_1m_2}{r}$<br><br>$U_S = \frac{1}{2}kx^2$ |
| | **4.C.2.1:** The student is able to make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. **[SP 6.4]**<br><br>**4.C.2.2:** The student is able to apply the concepts of Conservation of Energy and the Work-Energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. **[SP 1.4, 2.2, 7.2]** | **4.C.2:** Mechanical energy (the sum of kinetic and potential energy) is transferred into or out of a system when an external force is exerted on a system such that a component of the force is parallel to its displacement. The process through which the energy is transferred is called work.<br><br>a. If the force is constant during a given displacement, then the work done is the product of the displacement and the component of the force parallel or antiparallel to the displacement.<br><br>*Relevant Equation:*<br><br>$W = F_{\parallel}d$<br><br>b. Work (change in energy) can be found from the area under a graph of the magnitude of the force component parallel to the displacement versus displacement.<br><br>*Relevant Equation:*<br><br>$\Delta E = W = F_{\parallel}d = Fd\cos\theta$ |

| **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.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. | *[While there is no specific learning objective for it, EK 5.A.1 serves as a foundation for other learning objectives in the course.]* | **5.A.1**: A system is an object or a collection of objects. The objects are treated as having no internal structure. |
| | **5.A.2.1:** The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]** | **5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings. |
| | *[While there is no specific learning objective for it, EK 5.A.3 serves as a foundation for other learning objectives in the course.]* | **5.A.3:** An interaction can be either a force exerted by objects outside the system or the transfer of some quantity with objects outside the system. |
| | *[While there is no specific learning objective for it, EK 5.A.4 serves as a foundation for other learning objectives in the course.]* | **5.A.4:** The placement of a boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis. |
| **5.B:** The energy of a system is conserved. | **5.B.1.1:** The student is able to set up a representation or model showing that a single object can only have kinetic energy and use information about that object to calculate its kinetic energy. **[SP 1.4, 2.2]**<br><br>**5.B.1.2:** The student is able to translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies. **[SP 1.5]** | **5.B.1:** Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects.<br><br>*Relevant Equation:*<br><br>$KE = \frac{1}{2}mv^2$<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.B:** The energy of a system is conserved.<br><br>(Continued) | **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 objects in electric fields and examining changes in internal energy with changes in configuration.] |
| | **5.B.3.1:** The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]**<br><br>**5.B.3.2:** The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]**<br><br>**5.B.3.3:** The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]** | **5.B.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces.<br><br>a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system.<br><br>b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators, objects falling in a gravitational field.<br><br>c. The change in electric potential in a circuit is the change in potential energy per unit charge. [Physics 1: only in the context of circuits.]<br><br>*Relevant Equations:*<br><br>$\Delta U_g = mg\Delta y$<br><br>$U_s = \frac{1}{2}kx^2$ |
| | **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. |

| **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. (Continued) | **5.B.5.1:** The student is able to design an experiment and analyze data to examine how a force exerted on an object or system does work on the object or system as it moves through a distance. **[SP 4.2, 5.1]**<br>**5.B.5.2:** The student is able to design an experiment and analyze graphical data in which interpretations of the area under a force-distance curve are needed to determine the work done on or by the object or system. **[SP 4.2, 5.1]**<br>**5.B.5.3:** The student is able to predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance. **[SP 1.4, 2.2, 6.4]**<br>**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>**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]** | **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 part of thermodynamics.]<br>*Relevant Equations:*<br>$\Delta E = W = F_{\parallel} d = Fd\cos\theta$<br>$P = \dfrac{\Delta E}{\Delta t}$ |

| **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.D:** The linear momentum of a system is conserved. | **5.D.1.1:** The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]**<br>**5.D.1.2:** The student is able to apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and only qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]**<br>**5.D.1.3:** The student is able to apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[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>$\vec{p} = m\vec{v}$<br>$K = \frac{1}{2}mv^2$ |

| **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.D:** The linear momentum of a system is conserved. (Continued) | **5.D.1.4:** The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]**<br>**5.D.1.5:** 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.2.1:** The student is able to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]**<br>**5.D.2.3:** 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>a. In a closed system, the linear momentum is constant throughout the collision.<br>b. In a closed system, the kinetic energy after an inelastic collision is different from the kinetic energy before the collision.<br>*Relevant Equations:*<br>$\vec{p} = m\vec{v}$<br>$K = \frac{1}{2}mv^2$ |

# Content Area 5: Momentum

**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) |
|---|---|---|
| **3.D:** A force exerted on an object can change the momentum of the object. | **3.D.1.1:** The student is able to justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. **[SP 4.1]** | **3.D.1:** The change in momentum of an object is a vector in the direction of the net force exerted on the object.<br>*Relevant Equation:*<br>$\Delta\vec{p} = \vec{F}\Delta t$ |
| | **3.D.2.1:** The student is able to justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. **[SP 2.1]**<br>**3.D.2.2:** The student is able to predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 6.4]**<br>**3.D.2.3:** The student is able to analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 5.1]**<br>**3.D.2.4:** The student is able to design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. **[SP 4.2]** | **3.D.2:** The change in momentum of an object occurs over a time interval.<br>a. The force that one object exerts on a second object changes the momentum of the second object (in the absence of other forces on the second object).<br>b. The change in momentum of that object depends on the impulse, which is the product of the average force and the time interval during which the interaction occurred.<br>*Relevant Equation:*<br>$\Delta\vec{p} = \vec{F}\Delta t$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **4.B:** Interactions with other objects or systems can change the total linear momentum of a system. | **4.B.1.1:** The student is able to calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). **[SP 1.4, 2.2]**<br><br>**4.B.1.2:** The student is able to analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. **[SP 5.1]** | **4.B.1:** The change in linear momentum for a constant-mass system is the product of the mass of the system and the change in velocity of the center of mass.<br><br>*Relevant Equation:*<br><br>$\vec{p} = m\vec{v}$ |
| | **4.B.2.1:** The student is able to apply mathematical routines to calculate the change in momentum of a system by analyzing the average force exerted over a certain time on the system. **[SP 2.2]**<br><br>**4.B.2.2:** The student is able to perform analysis on data presented as a force-time graph and predict the change in momentum of a system. **[SP 5.1]** | **4.B.2:** The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted.<br><br>a. The units for momentum are the same as the units of the area under the curve of a force versus time graph.<br><br>b. The change in linear momentum and force are both vectors in the same direction.<br><br>*Relevant Equations:*<br><br>$\vec{p} = m\vec{v}$<br><br>$\Delta\vec{p} = \vec{F}\Delta t$ |
| **5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. | **5.A.2.1:** The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]** | **5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings. |
| **5.D:** The linear momentum of a system is conserved. | **5.D.1.1**: The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]** | **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. |

| **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.1.2:** The student is able to apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and only qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]**<br><br>**5.D.1.3:** The student is able to apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]**<br><br>**5.D.1.4:** The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]** | *Relevant Equations:*<br><br>$\vec{p} = m\vec{v}$<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 Physics 1, 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.*<br><br>*Physics 1 includes only conceptual understanding of center of mass motion of a system without the need for calculation of center of mass.*<br><br>*The Physics 1 course includes topics from Enduring Understanding **5.D** in the context of mechanical systems.* |



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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.D:** The linear momentum of a system is conserved. (Continued) | **5.D.1.5:** 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.2.1:** The student is able to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]**<br><br>**5.D.2.2:** The student is able to plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. **[SP 4.1, 4.2, 5.1]**<br><br>**5.D.2.3:** 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]**<br><br>**5.D.2.4:** The student is able to analyze data that verify conservation of momentum in collisions with and without an external friction force. **[SP 4.1, 4.2, 4.4, 5.1, 5.3]** | **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>$\vec{p} = m\vec{v}$<br><br>$K = \frac{1}{2}mv^2$ |

| 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.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]** | |
| | **5.D.3.1:** The student is able to predict the velocity of the center of mass of a system when there is no interaction outside of the system but there is an interaction within the system (i.e., the student simply recognizes that interactions within a system do not affect the center of mass motion of the system and is able to determine that there is no external force). **[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>c. Included in Physics 1 is the idea that where there is both a heavier and lighter mass, the center of mass is closer to the heavier mass. Only a qualitative understanding of this concept is required. |

# Content Area 6: Simple Harmonic Motion

**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) |
|---|---|---|
| **3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.3.1:** The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. **[SP 6.4, 7.2]**<br><br>**3.B.3.2:** The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. **[SP 4.2]**<br><br>**3.B.3.3:** The student can analyze data to identify qualitative or quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion to use that data to determine the value of an unknown. **[SP 2.2, 5.1]**<br><br>**3.B.3.4:** The student is able to construct a qualitative and/or a quantitative explanation of oscillatory behavior given evidence of a restoring force. **[SP 2.2, 6.2]** | **3.B.3:** Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object will undergo a special type of motion called simple harmonic motion. Examples include gravitational force exerted by the Earth on a simple pendulum and mass-spring oscillator.<br><br>a. For a spring that exerts a linear restoring force, the period of a mass-spring oscillator increases with mass and decreases with spring stiffness.<br><br>b. For a simple pendulum, the period increases with the length of the pendulum and decreases with the magnitude of the gravitational field.<br><br>c. Minima, maxima, and zeros of position, velocity, and acceleration are features of harmonic motion. Students should be able to calculate force and acceleration for any given displacement for an object oscillating on a spring.<br><br>*Relevant Equations:*<br><br>$T_s = 2\pi\sqrt{\frac{l}{g}}$<br><br>$T_p = 2\pi\sqrt{\frac{m}{k}}$ |

| **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.] |
| | **5.B.3.1:** The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]**<br><br>**5.B.3.2:** The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]**<br><br>**5.B.3.3:** The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]** | **5.B.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces.<br><br>a. The work done by a conservative force is independent of the path taken. The work description is used for forces external to the system. Potential energy is used when the forces are internal interactions between parts of the system.<br><br>b. Changes in the internal structure can result in changes in potential energy. Examples include mass-spring oscillators and objects falling in a gravitational field.<br><br>c. The change in electric potential in a circuit is the change in potential energy per unit charge. [Physics 1: only in the context of circuits.]<br><br>*Relevant Equations:*<br><br>$T_s = 2\pi\sqrt{\frac{l}{g}}$<br><br>$T_p = 2\pi\sqrt{\frac{m}{k}}$<br><br>$U_S = \frac{1}{2}kx^2$<br><br>$\Delta U_g = mg\Delta y$ |

| **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.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. |

# Content Area 7: Torque and Rotational Motion

**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) |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. **[SP 1.5, 2.1, 2.2]** | **3.A.1:** An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.<br><br>a. For rotational motion, there are analogous quantities such as angular position, angular velocity, and angular acceleration. The kinematic equations describing angular motion with constant angular acceleration are:<br>$\omega = \omega_0 + \alpha t$<br>$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$<br>$\omega^2 = \omega_0^2 + 2\alpha\theta$<br><br>b. For uniform circular motion of radius $r$, $v$ is proportional to omega (for a given $r$), and proportional to $r$ (for a given omega). Given a radius $r$ and a period of rotation $T$, students derive and apply $v = (2\pi r)/T$. |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **3.F:** A force exerted on an object can cause a torque on that object. | **3.F.1.1:** The student is able to use representations of the relationship between force and torque. **[SP 1.4]**<br><br>**3.F.1.2:** The student is able to compare the torques on an object caused by various forces. **[SP 1.4]**<br><br>**3.F.1.3:** The student is able to estimate the torque on an object caused by various forces in comparison to other situations. **[SP 2.3]**<br><br>**3.F.1.4:** The student is able to design an experiment and analyze data testing a question about torques in a balanced rigid system. **[SP 4.1, 4.2, 5.1]**<br><br>**3.F.1.5:** The student is able to calculate torques on a two-dimensional system in static equilibrium, by examining a representation or model (such as a diagram or physical construction). **[SP 1.4, 2.2]** | **3.F.1:** Only the force component perpendicular to the line connecting the axis of rotation and the point of application of the force results in a torque about that axis.<br><br>a. The lever arm is the perpendicular distance from the axis of rotation or revolution to the line of application of the force.<br><br>b. The magnitude of the torque is the product of the magnitude of the lever arm and the magnitude of the force.<br><br>c. The net torque on a balanced system is zero.<br><br>*Relevant Equation:*<br><br>$\tau = r_{\perp}F = rF\sin\theta$<br><br>**Boundary Statement:** *Quantities such as angular acceleration, velocity, and momentum are defined as vector quantities, but in Physics 1 the determination of "direction" is limited to clockwise and counterclockwise with respect to a given axis of rotation.* |
| | **3.F.2.1:** The student is able to make predictions about the change in the angular velocity about an axis for an object when forces exerted on the object cause a torque about that axis. **[SP 6.4]**<br><br>**3.F.2.2:** The student is able to plan data collection and analysis strategies designed to test the relationship between a torque exerted on an object and the change in angular velocity of that object about an axis. **[SP 4.1, 4.2, 5.1]** | **3.F.2:** The presence of a net torque along any axis will cause a rigid system to change its rotational motion or an object to change its rotational motion about that axis.<br><br>a. Rotational motion can be described in terms of angular displacement, angular velocity, and angular acceleration about a fixed axis.<br><br>b. Rotational motion of a point can be related to linear motion of the point using the distance of the point from the axis of rotation.<br><br>c. The angular acceleration of an object or rigid system can be calculated from the net torque and the rotational inertia of the object or rigid 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) |
|---|---|---|
| **3.F:** A force exerted on an object can cause a torque on that object.<br>(Continued) | | *Relevant Equations:*<br>$\tau = r_{\perp}F = rF\sin\theta$<br>$\alpha = \frac{\sum \tau}{I}$<br>$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$<br>$\omega = \omega_0 + \alpha t$<br>$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$ |
| | **3.F.3.1:** The student is able to predict the behavior of rotational collision situations by the same processes that are used to analyze linear collision situations using an analogy between impulse and change of linear momentum and angular impulse and change of angular momentum. **[SP 6.4, 7.2]**<br>**3.F.3.2:** In an unfamiliar context or using representations beyond equations, the student is able to justify the selection of a mathematical routine to solve for the change in angular momentum of an object caused by torques exerted on the object. **[SP 2.1]**<br>**3.F.3.3:** The student is able to plan data collection and analysis strategies designed to test the relationship between torques exerted on an object and the change in angular momentum of that object. **[SP 4.1, 4.2, 5.1, 5.3]** | **3.F.3:** A torque exerted on an object can change the angular momentum of an object.<br>a. Angular momentum is a vector quantity, with its direction determined by a right-hand rule.<br>b. The magnitude of angular momentum of a point object about an axis can be calculated by multiplying the perpendicular distance from the axis of rotation to the line of motion by the magnitude of linear momentum.<br>c. The magnitude of angular momentum of an extended object can also be found by multiplying the rotational inertia by the angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense of what factors affect rotational inertia, for example why a hoop has more rotational inertia than a puck of the same mass and radius.<br>d. The change in angular momentum of an object is given by the product of the average torque and the time the torque is exerted.<br>*Relevant Equations:*<br>$L = I\omega$<br>$\Delta L = \tau\Delta t$<br>$L = mvr$ |

| **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.D:** A net torque exerted on a system by other objects or systems will change the angular momentum of the system. | **4.D.1.1:** The student is able to describe a representation and use it to analyze a situation in which several forces exerted on a rotating system of rigidly connected objects change the angular velocity and angular momentum of the system. **[SP 1.2, 1.4]**<br><br>**4.D.1.2:** The student is able to plan data collection strategies designed to establish that torque, angular velocity, angular acceleration, and angular momentum can be predicted accurately when the variables are treated as being clockwise or counterclockwise with respect to a well-defined axis of rotation, and refine the research question based on the examination of data. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]** | **4.D.1:** Torque, angular velocity, angular acceleration, and angular momentum are vectors and can be characterized as positive or negative depending upon whether they give rise to or correspond to counterclockwise or clockwise rotation with respect to an axis.<br><br>*Relevant Equations:*<br>$\tau = r_{\perp}F = rF\sin\theta$<br>$\alpha = \frac{\sum \tau}{I}$<br>$L = I\omega$<br>$\Delta L = \tau\Delta t$<br>$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$<br>$\omega = \omega_0 + \alpha t$<br>$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$<br><br>**Boundary Statement:**<br>*Students do not need to know the right hand rule. A full dynamic treatment of rolling without slipping—for instance, using forces and torques to find the linear and angular acceleration of a cylinder rolling down a ramp—is not included 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) |
|---|---|---|
| **4.D:** A net torque exerted on a system by other objects or systems will change the angular momentum of the system.<br><br>(Continued) | **4.D.2.1:** The student is able to describe a model of a rotational system and use that model to analyze a situation in which angular momentum changes due to interaction with other objects or systems. **[SP 1.2, 1.4]**<br><br>**4.D.2.2:** The student is able to plan a data collection and analysis strategy to determine the change in angular momentum of a system and relate it to interactions with other objects and systems. **[SP 4.2]** | **4.D.2:** The angular momentum of a system may change due to interactions with other objects or systems.<br><br>a. The angular momentum of a system with respect to an axis of rotation is the sum of the angular momenta, with respect to that axis, of the objects that make up the system.<br><br>b. The angular momentum of an object about a fixed axis can be found by multiplying the momentum of the particle by the perpendicular distance from the axis to the line of motion of the object.<br><br>c. Alternatively, the angular momentum of a system can be found from the product of the system's rotational inertia and its angular velocity. Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation.<br><br>*Relevant Equations:*<br><br>$L = I\omega$<br>$\Delta L = \tau \Delta t$<br>$\tau = r_{\perp} F = rF\sin\theta$ |
| | **4.D.3.1:** The student is able to use appropriate mathematical routines to calculate values for initial or final angular momentum, or change in angular momentum of a system, or average torque or time during which the torque is exerted in analyzing a situation involving torque and angular momentum. **[SP 2.2]**<br><br>**4.D.3.2:** The student is able to plan a data collection strategy designe d to test the relationship between the change in angular momentum of a system and the product of the average torque applied to the system and the time interval during which the torque is exerted. **[SP 4.1, 4.2]** | **4.D.3:** The change in angular momentum is given by the product of the average torque and the time interval during which the torque is exerted.<br><br>*Relevant Equations:*<br><br>$L = I\omega$<br>$\Delta L = \tau \Delta t$<br>$\tau = r_{\perp} F = rF\sin\theta$ |

| **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.E:** The angular momentum of a system is conserved. | **5.E.1.1:** The student is able to make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. **[SP 6.4, 7.2]**<br><br>**5.E.1.2:** The student is able to make calculations of quantities related to the angular momentum of a system when the net external torque on the system is zero. **[SP 2.1, 2.2]** | **5.E.1:** If the net external torque exerted on the system is zero, the angular momentum of the system does not change.<br><br>*Relevant Equations:*<br>$L = I\omega$<br>$\Delta L = \tau\Delta t$<br>$\tau = r_{\perp}F = rF\sin\theta$ |
| | **5.E.2.1:** The student is able to describe or calculate the angular momentum and rotational inertia of a system in terms of the locations and velocities of objects that make up the system. Students are expected to do qualitative reasoning with compound objects. Students are expected to do calculations with a fixed set of extended objects and point masses. **[SP 2.2]** | **5.E.2:** The angular momentum of a system is determined by the locations and velocities of the objects that make up the system. The rotational inertia of an object or system depends upon the distribution of mass within the object or system. Changes in the radius of a system or in the distribution of mass within the system result in changes in the system's rotational inertia, and hence in its angular velocity and linear speed for a given angular momentum. Examples include elliptical orbits in an Earth-satellite system. Mathematical expressions for the moments of inertia will be provided where needed. Students will not be expected to know the parallel axis theorem.<br><br>Students do not need to know the equation for an object's rotational inertia, as it will be provided at the exam. They should have a qualitative sense that rotational inertia is larger when the mass is farther from the axis of rotation.<br><br>*Relevant Equation:*<br>$I = mr^2$ |

# Content Area 8: Electric Charge and Electric Force

**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.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:**<br>*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. Physics 1 treats gravitational fields only; Physics 2 treats electric and magnetic fields.* |
| | **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]** | **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>*Relevant Equation:*<br><br>$\left\|F_E\right\| = k\left\|\frac{q_1q_2}{r^2}\right\|$ |

| **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.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. |
| **3.C:** 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 (interactions between collections of electric point charges are not covered in Physics 1 and instead are restricted to Physics 2). **[SP 2.2, 6.4]**<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. **[See SP 7.2]** | **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><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><br>b. Electric forces may be attractive or repulsive, depending upon the charges on the objects involved.<br><br>*Relevant Equations:*<br><br>$\left\|F_E\right\| = k\left\|\frac{q_1 q_2}{r^2}\right\|$<br><br>$\left\|\vec{F}_g\right\| = G\frac{m_1 m_2}{r^2}$ |
| **5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. | **5.A.2.1:** The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge and linear momentum to those situations. **[SP 6.4, 7.2]** | **5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings. |

# Content Area 9: DC Circuits

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

**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>$I = \frac{\Delta q}{\Delta t}$ |
| **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><br>a. The resistivity of a material depends on its molecular and atomic structure.<br><br>b. The resistivity depends on the temperature of the material. Resistivity changes with temperature.<br><br>*Relevant Equation:*<br><br>$R = \frac{\rho l}{A}$<br><br>**Boundary Statement:**<br>*Knowledge of what causes temperature to affect resistivity is not part of 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) |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.9.1:** The student is able to construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule). **[SP 1.1, 1.4]**<br><br>**5.B.9.2:** The student is able to apply conservation of energy concepts to the design of an experiment that will demonstrate the validity of Kirchhoff's loop rule ($\Sigma\Delta V=0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches. **[SP 4.2, 6.4, 7.2]**<br><br>**5.B.9.3:** The student is able to apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. **[SP 2.2, 6.4, 7.2]** | **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>The potential difference across an ideal battery is also referred to as the emf of the battery, represented as $\varepsilon$. [Non-ideal batteries are not covered in Physics 1.]<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>*Relevant Equations:*<br><br>$I=\frac{\Delta V}{R}$<br><br>$P=I\Delta V$ |

| **Enduring Understanding** (Core concepts that students should retain) | **Learning Objectives** (What students must be able to do) | **Essential Knowledge** (What students need to know) |
|---|---|---|
| **5.C:** The electric charge of a system is conserved. | **5.C.3.1:** The student is able to apply conservation of electric charge (Kirchhoff's junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if configurations of the circuit are changed. **[SP 6.4, 7.2]**<br><br>**5.C.3.2:** The student is able to design an investigation of an electrical circuit with one or more resistors in which evidence of conservation of electric charge can be collected and analyzed. **[SP 4.1, 4.2, 5.1]**<br><br>**5.C.3.3:** The student is able to use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or 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>$I = \frac{\Delta q}{\Delta t}$<br><br>$I = \frac{\Delta V}{R}$<br><br>$P = I \Delta V$<br><br>$R_S = \sum_i R_i$<br><br>$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$ |

# Content Area 10: Mechanical Waves and Sound

**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.1.1:** The student is able to use a visual representation to construct an explanation of the distinction between transverse and longitudinal waves by focusing on the vibration that generates the wave. **[SP 6.2]**<br><br>**6.A.1.2:** The student is able to describe representations of transverse and longitudinal waves. **[SP 1.2]** | **6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal.<br><br>a. Mechanical waves can be either transverse or longitudinal. Examples include waves on a stretched string and sound waves.<br><br>b. This includes, as part of the mechanism of "propagation," the idea that the speed of a wave depends only on properties of the medium.<br><br>c. The propagation of sound waves included in this EK includes the idea that the traveling disturbance consists of pressure variations coupled to displacement variations.<br><br>d. This applies to both periodic waves and to wave pulses.<br><br>**Boundary Statement:**<br>*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.2.1:** The student is able to describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. **[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.<br><br>**Boundary Statement:**<br>*Electromagnetic waves are not tested in Physics 1. This applies to both periodic waves and wave pulses.* |

| **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.<br><br>(Continued) | **6.A.3.1:** The student is able to use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. **[SP 1.4]** | **6.A.3:** The amplitude is the maximum displacement of a wave from its equilibrium value.<br><br>a. The amplitude is the maximum displacement from equilibrium of the wave. A sound wave may be represented by either the pressure or the displacement of atoms or molecules. This covers both periodic waves and wave pulses.<br><br>b. The pressure amplitude of a sound wave is the maximum difference between local pressure and atmospheric pressure. |
| | **6.A.4.1:** The student is able to explain and/or predict qualitatively how the energy carried by a sound wave relates to the amplitude of the wave, and/or apply this concept to a real-world example. **[SP 6.4]** | **6.A.4:** Classically, the energy carried by a wave depends upon and increases with amplitude. Examples include sound waves.<br><br>a. Higher amplitude refers to both greater pressure variations and greater displacement variations.<br><br>b. Examples include both periodic waves and wave pulses. |
| **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.1.1:** The student is able to use a graphical representation of a periodic mechanical wave (position versus time) to determine the period and frequency of the wave and describe how a change in the frequency would modify features of the representation. **[SP 1.4, 2.2]** | **6.B.1:** For a periodic wave, the period is the repeat time of the wave. The frequency is the number of repetitions of the wave per unit time.<br><br>a. In a periodic sound wave, pressure variations and displacement variations are both present and with the same frequency.<br><br>*Relevant Equation:*<br><br>$T = \frac{1}{f}$ |
| | **6.B.2.1:** The student is able to use a visual representation of a periodic mechanical wave to determine wavelength of the wave. **[SP 1.4]** | **6.B.2:** For a periodic wave, the wavelength is the repeat distance of the wave. |

| **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. (Continued) | **6.B.4.1:** The student is able to design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. **[SP 4.2, 5.1, 7.2]** | **6.B.4:** For a periodic wave, wavelength is the ratio of speed over frequency. *Relevant Equation:* $\lambda = \frac{v}{f}$ |
| | **6.B.5.1:** The student is able to create or use a wave front diagram to demonstrate or interpret qualitatively the observed frequency of a wave, dependent upon relative motions of source and observer. **[SP 1.4]** | **6.B.5:** The observed frequency of a wave depends on the relative motion of source and observer. This is a qualitative treatment only. |
| **6.D:** Interference and superposition lead to standing waves and beats. | **6.D.1.1:** The student is able to use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. **[SP 1.1, 1.4]** <br> **6.D.1.2:** The student is able to design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for wave pulses or standing waves). **[SP 4.2, 5.1]** <br> **6.D.1.3:** The student is able to design a plan for collecting data to quantify the amplitude variations when two or more traveling waves or wave pulses interact in a given medium. **[SP 4.2]** | **6.D.1:** Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition. |

| **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.D:** Interference and superposition lead to standing waves and beats.<br><br>(Continued) | **6.D.2.1:** The student is able to analyze data or observations or evaluate evidence of the interaction of two or more traveling waves in one or two dimensions (i.e., circular wave fronts) to evaluate the variations in resultant amplitudes. **[SP 5.1]** | **6.D.2:** Two or more traveling waves can interact in such a way as to produce amplitude variations in the resultant wave. |
| | **6.D.3.1:** The student is able to refine a scientific question related to standing waves and design a detailed plan for the experiment that can be conducted to examine the phenomenon qualitatively or quantitatively. **[SP 2.1, 3.2, 4.2]**<br><br>**6.D.3.2:** The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. **[SP 6.4]**<br><br>**6.D.3.3:** The student is able to plan data collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared to the prediction, explain any discrepancy and, if necessary, revise the relationship among variables responsible for establishing standing waves on a string or in a column of air. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**<br><br>**6.D.3.4:** The student is able to describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. **[SP 1.2]** | **6.D.3:** Standing waves are the result of the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. Examples include waves on a fixed length of string and sound waves in both closed and open tubes.<br><br>a. Reflection of waves and wave pulses, even if a standing wave is not created, is covered in Physics 1.<br><br>b. For standing sound waves, pressure nodes correspond to displacement antinodes, and vice versa. For example, the open end of a tube is a pressure node because the pressure equalizes with the surrounding air pressure and therefore does not oscillate. The closed end of a tube is a displacement node because the air adjacent to the closed end is blocked from oscillating. |

| **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.D:** Interference and superposition lead to standing waves and beats.<br><br>(Continued) | **6.D.4.1:** The student is able to challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source regardless of the size of the region. **[SP 1.5, 6.1]**<br><br>**6.D.4.2:** The student is able to calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined, and calculate numerical values of wavelengths and frequencies. Examples include musical instruments. **[SP 2.2]** | **6.D.4:** The possible wavelengths of a standing wave are determined by the size of the region to which it is confined.<br><br>a. A standing wave with zero amplitude at both ends can only have certain wavelengths. Examples include fundamental frequencies and harmonics.<br><br>b. Other boundary conditions or other region sizes will result in different sets of possible wavelengths.<br><br>c. The term first harmonic refers to the standing waves corresponding to the fundamental frequency, i.e., the lowest frequency corresponding to a standing wave. The second harmonic is the standing wave corresponding to the second lowest frequency that generates a standing wave in the given scenario.<br><br>d. Resonance is another term for standing sound wave.<br><br>*Relevant Equations:*<br><br>$\lambda = \frac{v}{f}$<br><br>$T = \frac{1}{f}$ |
| | **6.D.5.1:** The student is able to use a visual representation to explain how waves of slightly different frequency give rise to the phenomenon of beats. **[SP 1.2]** | **6.D.5:** Beats arise from the addition of waves of slightly different frequency.<br><br>a. Because of the different frequencies, the two waves are sometimes in phase and sometimes out of phase. The resulting regularly spaced amplitude changes are called beats. Examples include the tuning of an instrument.<br><br>b. The beat frequency is the difference in frequency between the two waves.<br><br>c. In Physics 1, only qualitative understanding of EK 6.D.5 is necessary. |

# 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

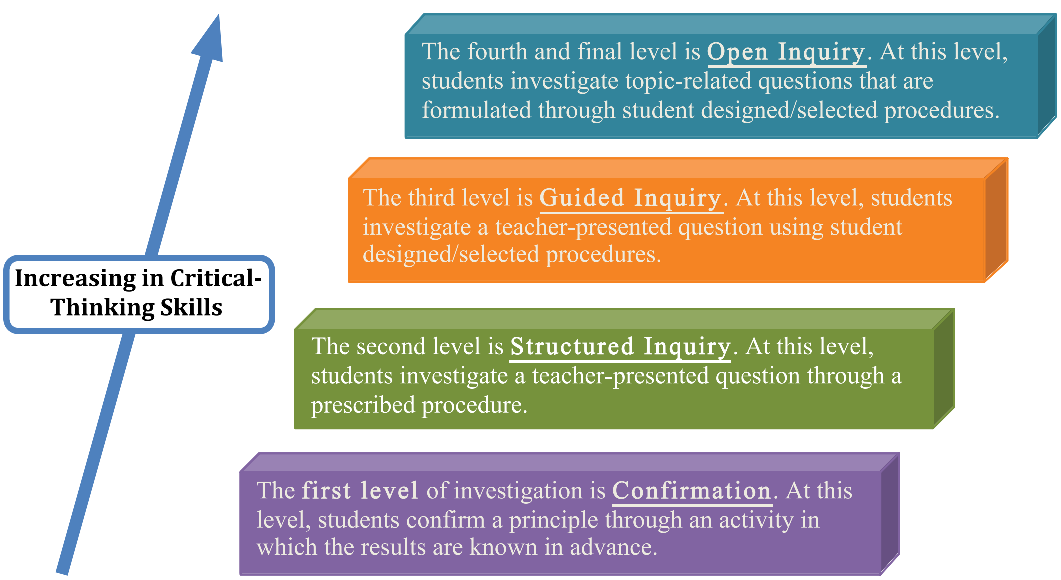
Inquiry-based laboratory experiences support the AP Physics 1 course and AP Course Audit Curricular Requirements by providing opportunities for students to engage in the seven science practices as they design plans for experiments, make predictions, collect and analyze data, apply mathematical routines, develop explanations, and communicate about their work.

The science practices that align to the content 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:



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 1 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 1: Algebra-Based Exam

## Exam Information

The AP Physics 1 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 1 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 1 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 | 3 |
| | | | | Total – 5 |

The sample exam questions in this course and exam description represent the kinds of questions that are included on the AP Physics 1 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 1 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 1 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 1 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.

On the AP Physics 1 exam 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.

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 1 exam, students will not need to calculate uncertainty but will need to demonstrate understanding of the principles of uncertainty. In general, multiple-choice questions on the AP Physics 1 exam 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 1 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 1 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 1 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 1 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

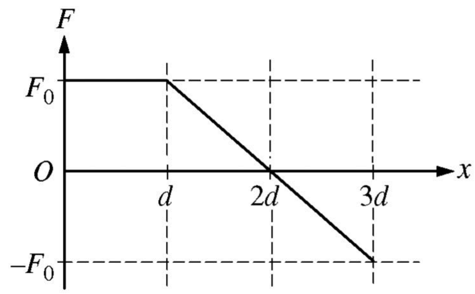
Students need to learn to manage their time to allow them to complete all parts of the exam. Time left is announced by proctors, but students are not forced to move to the next question; thus if they do not properly budget their time, they may not wind up with enough time to complete all the multiple-choice 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 1 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.




1. An object is moving in the positive $x$-direction while a net force directed along the $x$-axis is exerted on the object. The figure above shows the force as a function of position. What is the net work done on the object over the distance shown?

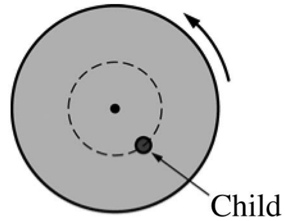
   (A) $F_0d$

   (B) $3F_0d/2$

   (C) $2F_0d$

   (D) $4F_0d$

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.5.3:** The student is able to predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance. | **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. |




Top View

2. The diagram above shows a top view of a child of mass $M$ on a circular platform of mass $2M$ that is rotating counterclockwise. Assume the platform rotates without friction. Which of the following describes an action by the child that will increase the angular speed of the platform-child system and gives the correct reason why?

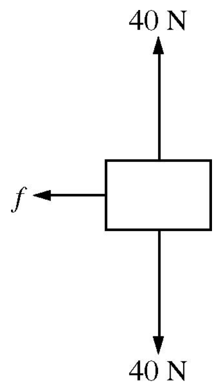
(A) The child moves toward the center of the platform, increasing the total angular momentum of the system.

(B) The child moves toward the center of the platform, decreasing the rotational inertia of the system.

(C) The child moves away from the center of the platform, increasing the total angular momentum of the system.

(D) The child moves away from the center of the platform, decreasing the rotational inertia of the system.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **5.E:** The angular momentum of a system is conserved. | **5.E.1.1:** The student is able to make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |




3. The figure above shows the forces exerted on a block that is sliding on a horizontal surface: the gravitational force of 40 N, the 40 N normal force exerted by the surface, and a frictional force exerted to the left. The coefficient of friction between the block and the surface is 0.20. The acceleration of the block is most nearly

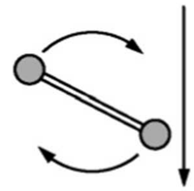
   (A) $1.0\ \mathrm{m/s^2}$ to the right

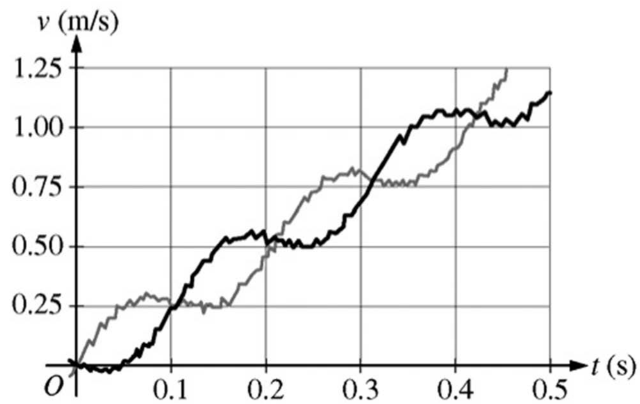
   (B) $1.0\ \mathrm{m/s^2}$ to the left

   (C) $2.0\ \mathrm{m/s^2}$ to the right

   (D) $2.0\ \mathrm{m/s^2}$ to the left

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **2.B:** A gravitational field is caused by an object with mass.<br><br>**3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br><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.B.1.1:** The student is able to apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass $m$ in a gravitational field of strength $g$ in the context of the effects of a net force on objects and systems.<br><br>**3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations.<br><br>**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.<br><br>**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. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br><br>**1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain.<br><br>**2.2:** The student c an *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. |






4. A student on another planet has two identical spheres, each of mass 0.6 kg, attached to the ends of a rod of negligible mass. The student gives the assembly a rotation in the vertical plane and then releases it so it falls, as shown in the top figure above. Sensors record the vertical velocity of the two spheres, and the data is shown in the graph of velocity $v$ as a function of time $t$. Another student wants to calculate the assembly's angular speed and the change in the linear momentum of the center of mass of the assembly between 0 s and 0.3 s. Which of these quantities can be determined using the graph?

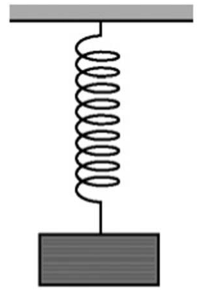
(A) Angular speed only

(B) Change in linear momentum only

(C) Angular speed and change in linear momentum

(D) Neither of these quantities can be determined using the graph.

| Enduring Understandings | Learning Objectives | Science Practice |
|---|---|---|
| **3.F:** A force exerted on an object can cause a torque on that object.<br><br>**4.B:** Interactions with other objects or systems can change the total linear momentum of a system. | **3.F.2.2:** The student is able to plan data collection and analysis strategies designed to test the relationship between a torque exerted on an object and the change in angular velocity of that object about an axis.<br><br>**4.B.1.2:** The student is able to analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. | **5.1:** The student can *analyze data* to identify patterns or relationships. |



5. A block of known mass hanging from an ideal spring of known spring constant is oscillating vertically. A motion detector records the position, velocity, and acceleration of the block as a function of time. Which of the following indicates the measured quantities that are sufficient to determine whether the net force exerted on the block equals the vector sum of the individual forces?

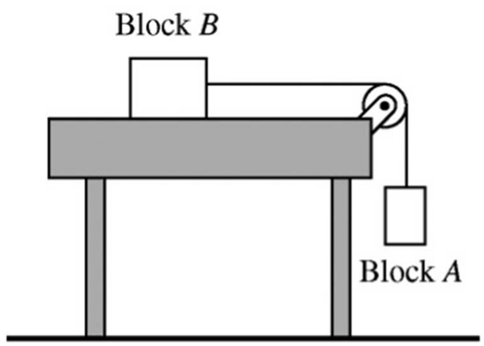
(A) Acceleration only

(B) Acceleration and position only

(C) Acceleration and velocity only

(D) Acceleration, position, and velocity

| Enduring Understanding | Learning Objectives | Science Practice |
|---|---|---|
| **3.B:** Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\sum \vec{F}}{m}$. | **3.B.1.2:** The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces.<br><br>**3.B.3.3:** The student can analyze data to identify qualitative or quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion to use that data to determine the value of an unknown. | **5.1:** The student can *analyze data* to identify patterns or relationships. |




6. Block $A$ hangs from a light string that passes over a light pulley and is attached to block $B$, which is on a level horizontal frictionless table, as shown above. Students are to determine the mass of block $B$ from the motion of the two-block system after it is released from rest. They plan to measure the time block $A$ takes to reach the floor. The students must also take which of the following measurements to determine the mass of block $B$?

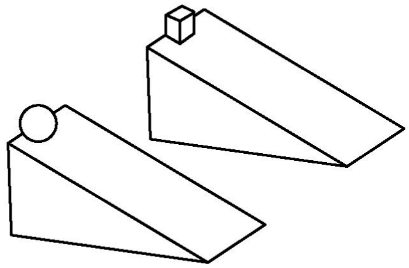
   (A) Only the mass of block $A$

   (B) Only the distance block $A$ falls to reach the floor

   (C) Only the mass of block $A$ and the distance block $A$ falls to reach the floor

   (D) The mass of block $A$, the distance block $A$ falls to reach the floor, and the radius of the pulley

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.2:** The student is able to design an experimental investigation of the motion of an object. | **4.2:** The student can *design a plan* for collecting *data* to answer a particular scientific question. |
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **4.A.2.1:** The student is able to make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |



7. Two objects are released from rest at the top of ramps with the same dimensions, as shown in the figure above. The sphere rolls down one ramp without slipping. The small block slides down the other ramp without friction. Which object reaches the bottom of its ramp first, and why?

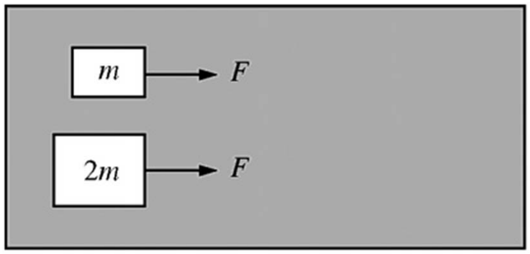
(A) The sphere, because it gains rotational kinetic energy, but the block does not

(B) The sphere, because it gains mechanical energy due to the torque exerted on it, but the block does not

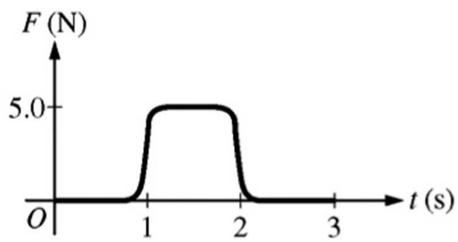
(C) The block, because it does not lose mechanical energy due to friction, but the sphere does

(D) The block, because it does not gain rotational kinetic energy, but the sphere does

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




Top View




8. Two blocks, of mass $m$ and $2m$, are initially at rest on a horizontal frictionless surface. A force $F$ is exerted individually on each block, as shown above. The graph shows how $F$ varies with time $t$. Which block has the greatest average power provided to it between $t = 0$ s and $t = 3$ s?

(A) The block of mass $m$

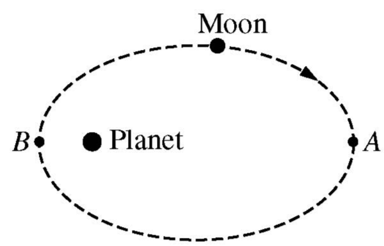
(B) The block of mass $2m$

(C) Both blocks have the same power provided to them.

(D) It cannot be determined without knowing the ratio of the maximum force to the mass $m$.

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br><br>**3.E:** A force exerted on an object can change the kinetic energy of the object. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations.<br><br>**3.E.1.4:** The student is able to apply mathematical routines to determine the change in kinetic energy of an object given the forces on the object and the displacement of the object. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br><br>**1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain. |

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **5.B:** The energy of a system is conserved. | **5.B.5.3:** The student is able to predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance.<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. | **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. |




9. A moon is in an elliptical orbit about a planet as shown above. At point $A$ the moon has speed $u_A$ and is at distance $R_A$ from the planet. At point $B$ the moon has speed $u_B$. Which of the following explains a correct method for determining the distance of the moon from the planet at point $B$ in terms of the given quantities?

(A) Conservation of angular momentum, because the gravitational force exerted by the moon on the planet is the same as that exerted by the planet on the moon

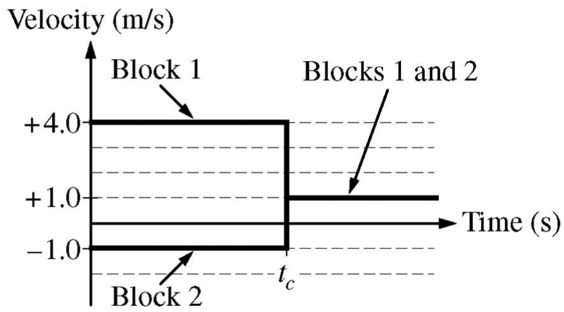
(B) Conservation of angular momentum, because the gravitational force exerted on the moon is always directed toward the planet

(C) Conservation of energy, because the gravitational force exerted on the moon is always directed toward the planet

(D) Conservation of energy, because the gravitational force exerted by the moon on the planet is the same as that exerted by the planet on the moon

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **5.B:** The energy of a system is conserved.<br><br>**5.E:** The angular momentum of a system is conserved. | **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).<br><br>**5.E.1.1:** The student is able to make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. | **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. |

**Questions 10–12 refer to the following material.**




Block 1 of mass $m_1$ and block 2 of mass $m_2$ are sliding along the same line on a horizontal frictionless surface when they collide at time $t_c$. The graph above shows the velocities of the blocks as a function of time.

10. Which block has the greater mass, and what information indicates this?
    (A) Block 1, because it had a greater speed before the collision.
    (B) Block 1, because the velocity after the collision is in the same direction as its velocity before the collision.
    (C) Block 2, because it had a smaller speed before the collision.
    (D) Block 2, because the final velocity is closer to the initial velocity of block 2 than it is to the initial velocity of block 1.

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$.<br>**5.D:** The linear momentum of a system is conserved. | **4.A.2.3:** The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system.<br>**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. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

11. How does the kinetic energy of the two-block system after the collision compare with its kinetic energy before the collision, and why?

    (A) It is less, because the blocks have the same velocity after the collision, so some of their kinetic energy was transformed into internal energy.

    (B) It is less, because the blocks have velocities in opposite directions before the collision, so some of their kinetic energy cancels.

    (C) It is the same, because the collision was instantaneous, so the effect of external forces during the collision is negligible.

    (D) It is the same, because the blocks have the same velocity after the collision, and there is no friction acting on them.

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **5.D:** The linear momentum of a system is conserved. | **5.D.2.3:** 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. | **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. |

12. Which of the following is true of the motion of the center of mass of the two-block system during the time shown?

(A) The center of mass does not move because the blocks are moving in opposite directions before the collision.

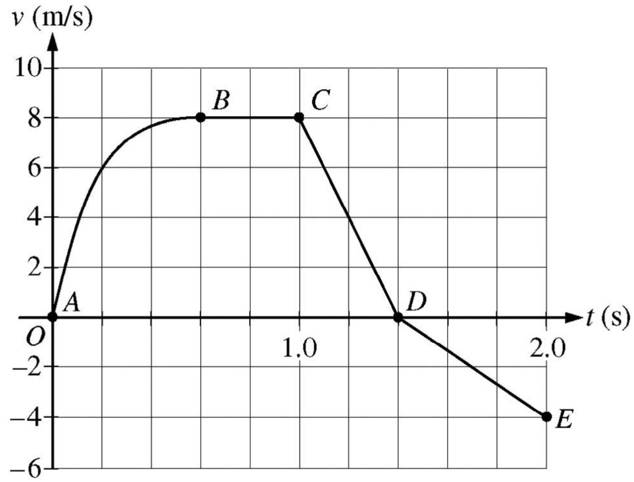
(B) The center of mass moves at a constant velocity of +1.0 m/s because there is no friction acting on the system.

(C) The center-of-mass velocity starts out greater than +1.0 m/s but decreases to +1.0 m/s during the collision because the collision is inelastic.

(D) The center-of-mass velocity increases as the blocks get closer together, and then becomes constant after the collision.

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **4.A.2.3:** The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a 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. |

**Questions 13–15 refer to the following information.**




A cart is constrained to move along a straight line. A varying net force along the direction of motion is exerted on the cart. The cart's velocity $v$ as a function of time $t$ is shown in the graph above. The five labeled points divide the graph into four sections.

13. Which of the following correctly ranks the magnitude of the average acceleration of the cart during the four sections of the graph?

(A) $a_{CD} > a_{AB} > a_{BC} > a_{DE}$

(B) $a_{BC} > a_{AB} > a_{CD} > a_{DE}$

(C) $a_{AB} > a_{BC} > a_{DE} > a_{CD}$

(D) $a_{CD} > a_{AB} > a_{DE} > a_{BC}$

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. | **1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain. |
| | **3.A.1.3:** The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

14. For which segment does the cart move the greatest distance?
    (A) *AB*
    (B) *BC*
    (C) *CD*
    (D) *DE*

| Enduring Understanding | Learning Objective | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. | **1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain.<br><br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

15. During some part of the motion, the work done on the cart is negative. What feature of the motion indicates this?

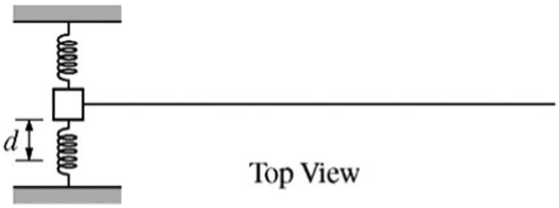
    (A) The speed is increasing.

    (B) The speed is decreasing.

    (C) The acceleration is positive.

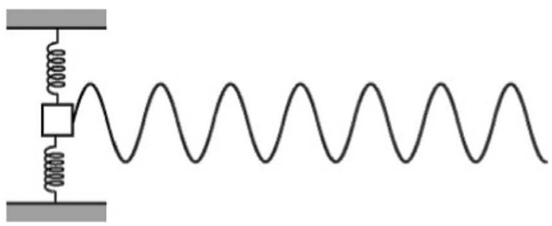
    (D) The acceleration is negative.

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.E:** A force exerted on an object can change the kinetic energy of the object.<br>**5.B:** The energy of a system is conserved. | **3.E.1.3:** The student is able to use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether kinetic energy of that object would increase, decrease, or remain unchanged.<br>**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). | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<br>**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. |



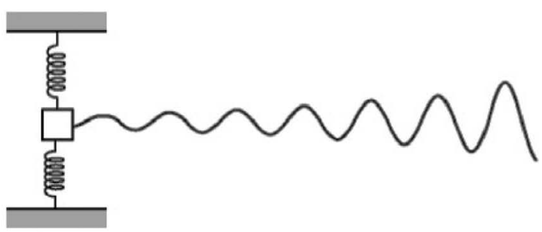

16. The figure above shows a block on a horizontal surface attached to two springs whose other ends are fixed to walls. A light string attached to one side of the block initially lies straight across the surface, as shown. The other end of the string is free to move. There is significant friction between the block and the surface but negligible friction between the string and the surface. The block is displaced a distance $d$ and released from rest. Which of the following best represents the shape of the string a short time later?

(A)

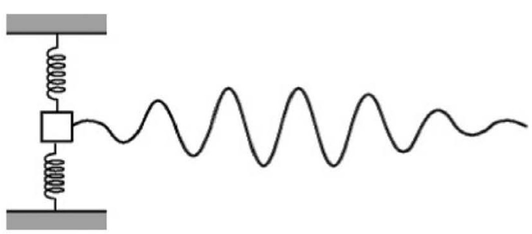


(B)

(C)



(D)



| 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>**4.C:** Interactions with other objects or systems can change the total energy of a system.<br><br>**6.A:** A wave is a traveling disturbance that transfers energy and momentum. | **3.B.3.1:** The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties.<br><br>**4.C.2.1:** The student is able to make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass.<br><br>**6.A.3.1:** The student is able to use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. | **1.4:** The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.<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. |

17. Two massive, positively charged particles are initially held a fixed distance apart. When they are moved farther apart, the magnitude of their mutual gravitational force changes by a factor of $n$. Which of the following indicates the factor by which the magnitude of their mutual electrostatic force changes?

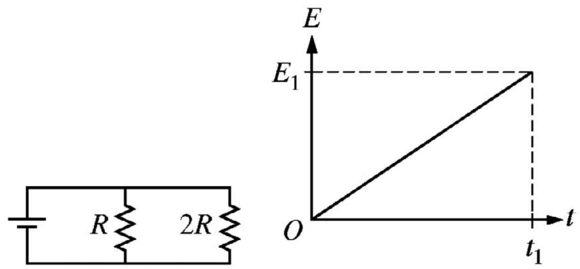
(A) $1/n^2$

(B) $1/n$

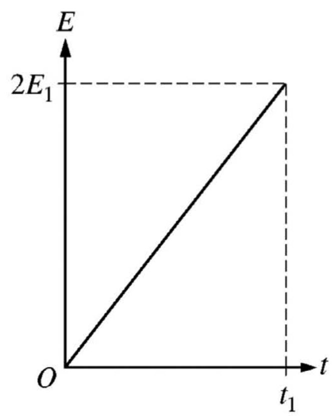
(C) $n$

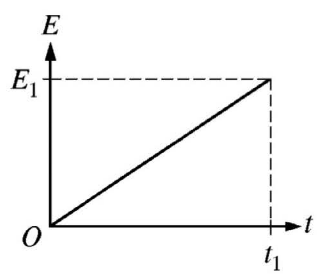
(D) $n^2$

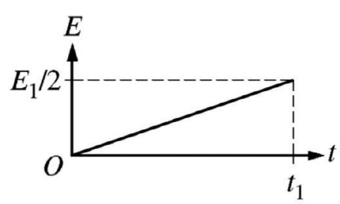
| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **3.C:** At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces. | **3.C.2.1:** The student is able to use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges (interactions between collections of electric point charges are not covered in Physics 1 and instead are restricted to Physics 2).<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>**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. |

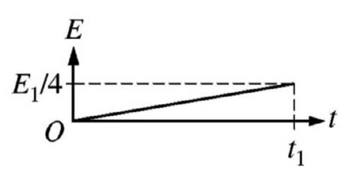



18. The circuit shown above contains two resistors of resistance $R$ and $2R$. The graph shows the total energy $E$ dissipated by the smaller resistance as a function of time. Which of the following shows the corresponding graph for the larger resistance?

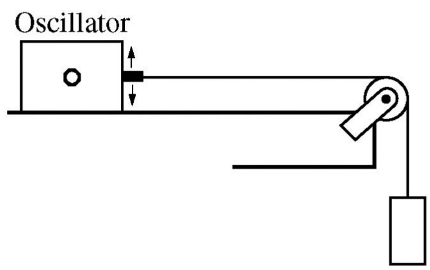
(A)



(B)



(C)



(D)


| Enduring Understanding | Learning Objectives | Science Practices |
| --- | --- | --- |
| **5.B:** The energy of a system is conserved. | **5.B.9.1:** The student is able to construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule).<br><br>**5.B.9.3:** The student is able to apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. | **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>**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. |




19. A student connects one end of a string with negligible mass to an oscillator. The other end of the string is passed over a pulley and attached to a suspended weight, as shown above. The student finds that a standing wave with one antinode is formed on the string when the frequency of the oscillator is $f_0$. The student then moves the oscillator to shorten the horizontal segment of string to half its original length. At what frequency will a standing wave with one antinode now be formed on the string?

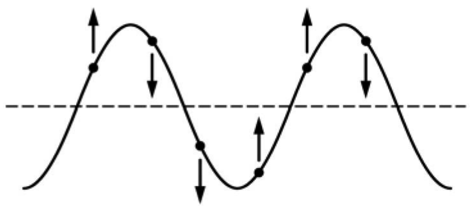
(A) $f_0 / 2$

(B) $f_0$

(C) $2f_0$

(D) There is no frequency at which a standing wave will be formed.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **6.D:** Interference and superposition lead to standing waves and beats. | **6.D.4.2:** The student is able to calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined, and calculate numerical values of wavelengths and frequencies. Examples include musical instruments. | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |



20. The figure above shows a portion of a periodic wave on a string at a particular moment in time. The vertical arrows indicate the direction of the velocity of some points on the string. Is the wave moving to the right or to the left?

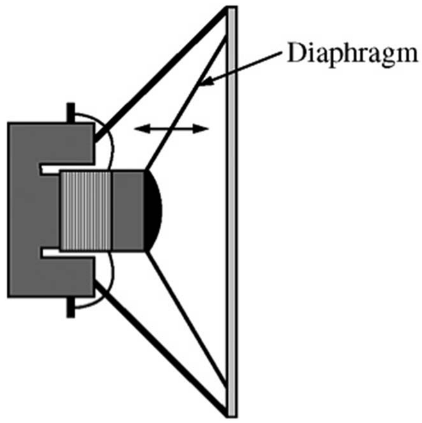
(A) To the right

(B) To the left

(C) Neither direction; the wave is a standing wave, so it is not moving.

(D) Either direction; the figure is consistent with wave motion to the right or to the left.

| Enduring Understanding | Learning Objective | Science Practice |
|---|---|---|
| **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. | **1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain. |




21. A radio speaker produces sound when a membrane called a diaphragm vibrates, as shown above. A person turns up the volume on the radio. Which of the following aspects of the motion of a point on the diaphragm must increase?

    (A) The maximum displacement only

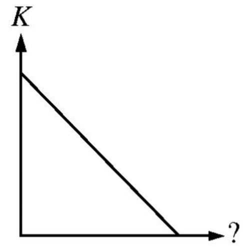
    (B) The average speed only

    **(C)** Both the maximum displacement and the average speed

    (D) Neither the maximum displacement nor the average speed

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | 3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations. | **1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain. |
| **6.A:** A wave is a traveling disturbance that transfers energy and momentum. | 6.A.2.1: The student is able to describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. | **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. |

**Directions:** For each of 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. A block is given a short push and then slides with constant friction across a horizontal floor. The graph above shows the kinetic energy of the block after the push ends as a function of an unidentified quantity. The quantity could be which of the following? Select two answers.

(A) Time elapsed since the push

(B) Distance traveled by the block

(C) Speed of the block

(D) Magnitude of the net work done on the block

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. | **1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain. |
| **3.E:** A force exerted on an object can change the kinetic energy of the object. | **3.E.1.1:** The student is able to make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. | **2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |
| | | **6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |
| | | **7.2:** The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas. |

23. A musician stands outside in a field and plucks a string on an acoustic guitar. Standing waves will most likely occur in which of the following media? Select two answers.
    (A) The guitar string
    (B) The air inside the guitar
    (C) The air surrounding the guitar
    (D) The ground beneath the musician

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **6.D:** Interference and superposition lead to standing waves and beats. | **6.D.3.2:** The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes.<br><br>**6.D.3.4:** The student is able to describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. | **1.2:** The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.<br><br>**6.4:** The student can *make claims and predictions about natural phenomena* based on scientific theories and models. |

24. A 0.2 kg rock is dropped into a lake from a few meters above the surface of the water. The rock reaches terminal velocity in the lake after 5 s in the water. During the final 3 s of its descent to the lake bottom, the rock moves at a constant speed of 4 m/s. Which of the following can be determined from the information given? Select two answers.

    (A) The speed of the rock as it enters the lake

    (B) The distance the rock travels in the first 5 s of its descent in the water

    (C) The acceleration of the rock 2 s before it reaches the lake bottom

    (D) The change in potential energy of the rock-Earth-water system during the final 3 s of the rock's descent

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations. | **1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain. |
| **4.C:** Interactions with other objects or systems can change the total energy of a system. | **4.C.1.2:** The student is able to predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. | **6.4:** The student can *make claims and predictions* about natural phenomena based on scientific theories and models. |

25. In an experiment, three microscopic latex spheres are sprayed into a chamber and become charged with $+3e$, $+5e$, and $-3e$, respectively. Later, all three spheres collide simultaneously and then separate. Which of the following are possible values for the final charges on the spheres? Select two answers.

| | $X$ | $Y$ | $Z$ |
|---|---|---|---|
| (A) | $+4e$ | $-4e$ | $+5e$ |
| (B) | $+4e$ | $+4.5e$ | $+4.5e$ |
| (C) | $+5e$ | $-8e$ | $+7e$ |
| (D) | $+6e$ | $+6e$ | $-7e$ |

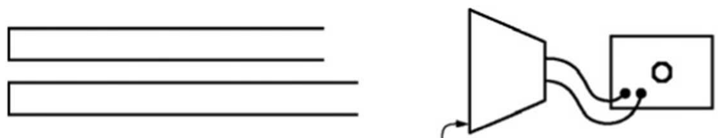
| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **1.B:** Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge. | **1.B.1.2:** The student is able to make predictions, using the conservation 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.<br>**1.B.3.1:** The student is able to challenge the claim that an electric charge smaller than the elementary charge has been isolated. | **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. |

# Answers to Multiple-Choice Questions

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

## Free-Response Questions

**Directions:** Question 1 is a short free-response question that requires about 12 minutes to answer and is worth 7 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. The figure above shows two tubes that are identical except for their slightly different lengths. Both tubes have one open end and one closed end. A speaker connected to a variable frequency generator is placed in front of the tubes, as shown. The speaker is set to produce a note of very low frequency and then turned on. The frequency is then slowly increased to produce resonances in the tubes. Students observe that at first only one of the tubes resonates at a time. Later, as the frequency gets very high, there are times when both tubes resonate.

   In a clear, coherent, paragraph-length answer, explain why there are some high frequencies, but no low frequencies, at which both tubes resonate. You may include diagrams and/or equations as part of your explanation.

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **6.D:** Interference and superposition lead to standing waves and beats. | **6.D.3.2:** The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes.<br>**6.D.3.4:** The student is able to describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region.<br>**6.D.4.1:** The student is able to challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source regardless of the size of the region. | **1.2:** The student can describe representations and models of natural or man–made phenomena and systems in the domain.<br>**6.1:** The student can justify claims with evidence.<br>**6.4:** The student can make claims and predictions about natural phenomena based on scientific theories and models. |

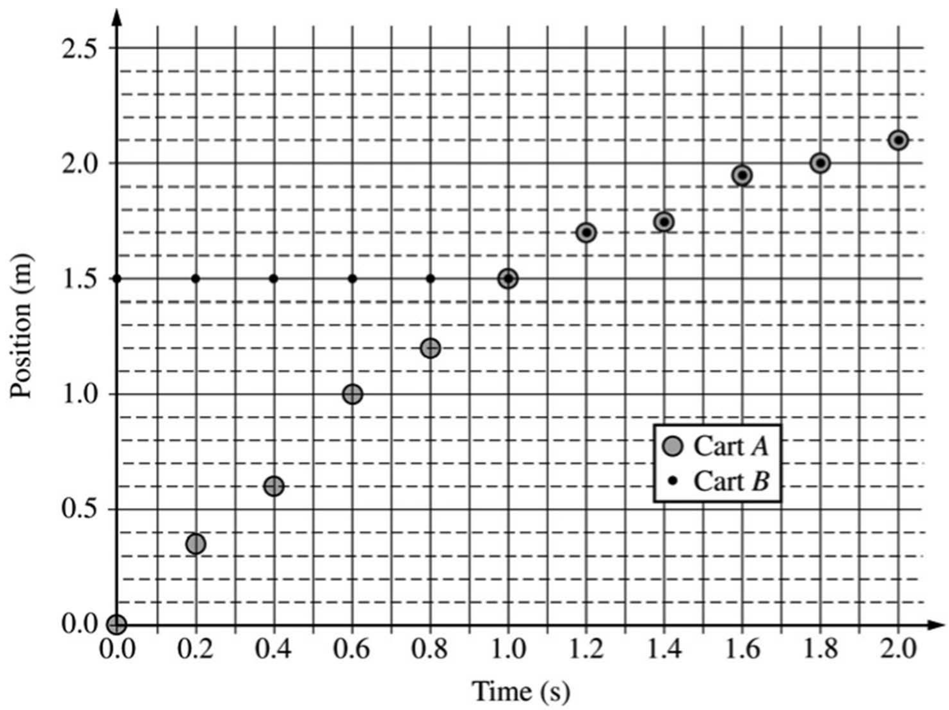
Sample Questions


2. A group of students has two carts, *A* and *B*, with wheels that turn with negligible friction. The carts can travel along a straight horizontal track. Cart *A* has known mass $m_A$. The students are asked to use a one-dimensional collision between the carts to determine the mass of cart *B*. Before the collision, cart *A* travels to the right and cart *B* is initially at rest, as shown above. After the collision, the carts stick together.

   (a) Describe an experimental procedure to determine the velocities of the carts before and after a collision, including all the additional equipment you would need. You may include a labeled diagram of your setup to help in your description. Indicate what measurements you would take and how you would take them. Include enough detail so that another student could carry out your procedure.

   (b) There will be sources of error in the measurements taken in the experiment, both before and after the collision. For your experimental procedure, will the uncertainty in the calculated value of the mass of cart *B* be affected more by the error in the measurements taken before the collision or by those taken after the collision, or will it be equally affected by both sets of measurements? Justify your answer.

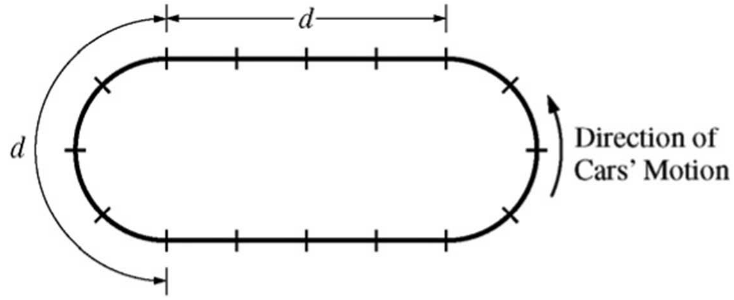
   A group of students took measurements for one collision. A graph of the students' data is shown below.




   (c) Given $m_A = 0.50$ kg, use the graph to calculate the mass of cart *B*. Explicitly indicate the principles used in your calculations.

(d) The students are now asked to consider the kinetic energy changes in an inelastic collision, specifically whether the initial values of one of the physical quantities affect the fraction of mechanical energy dissipated in the collision. How could you modify the experiment to investigate this question? Be sure to explicitly describe the calculations you would make, specifying all equations you would use (but do not actually do any algebra or arithmetic).

| Enduring Understandings | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames.<br><br>**5.D:** The linear momentum of a system is conserved. | **3.A.1.2:** The student is able to design an experimental investigation of the motion of an object.<br><br>**5.D.1.4:** The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome.<br><br>**5.D.2.2:** The student is able to plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. | **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>**5.3:** The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question. |




3. The figure above represents a racetrack with semicircular sections connected by straight sections. Each section has length $d$, and markers along the track are spaced $d/4$ apart. Two people drive cars counterclockwise around the track, as shown. Car $X$ goes around the curves at constant speed $v_c$, increases speed at constant acceleration for half of each straight section to reach a maximum speed of $2v_c$, then brakes at constant acceleration for the other half of each straight section to return to speed $v_c$. Car $Y$ also goes around the curves at constant speed $v_c$, increases speed at constant acceleration for one-fourth of each straight section to reach the same maximum speed $2v_c$, stays at that speed for half of each straight section, then brakes at constant acceleration for the remaining fourth of each straight section to return to speed $v_c$.

   (a) On the figures below, draw an arrow showing the direction of the net force on each of the cars at the positions noted by the dots. If the net force is zero at any position, label the dot with 0.


   (b) i. Indicate which car, if either, completes one trip around the track in less time, and justify your answer qualitatively without using equations.

   ii. Justify your answer about which car, if either, completes one trip around the track in less time quantitatively with appropriate equations.

   (c) Explain how your equations in part (b) ii reexpress your reasoning in part (b) i. Do not simply refer to any final results of your calculations, but instead indicate how terms in your equations correspond to concepts in your qualitative explanation.

| Enduring Understanding | Learning Objectives | Science Practices |
|---|---|---|
| **3.A:** All forces share certain common characteristics when considered by observers in inertial reference frames. | **3.A.1.1:** The student is able to express the motion of an object using narrative, mathematical, and graphical representations.<br><br>**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. | **1.1:** The student can *create representations and models* of natural or man-made phenomena and systems in the domain.<br><br>**1.5:** The student can *reexpress key elements of natural phenomena across multiple representations* in the domain.<br><br>**2.2:** The student can *apply mathematical routines* to quantities that describe natural phenomena. |

# Scoring Guidelines

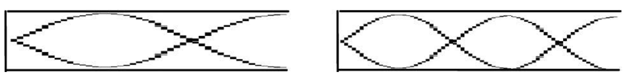
## Scoring Guidelines for Free-Response Question 1 (7 points)

Explanations can include figures to support or clarify the meaning of prose, but figures alone are not sufficient.

| | |
|---|---|
| For explaining the condition for resonance in a tube closed at one end | 2 points |
| For comparing wavelengths at low frequency to the tube lengths | 1 point |
| For linking the above two ideas (conditions of resonance and comparing wavelengths at low frequency) to explain why only one resonance occurs at a time | 1 point |
| For indicating that as frequency goes up, wavelength goes down | 1 point |
| For indicating how smaller wavelengths relate to differences in tube length, explaining how both tubes can now meet boundary conditions | 2 points |

Example:

In order to resonate, the length of a tube must be an odd multiple of a quarter wavelength of the sound, as shown below.



For resonance at low frequencies, the wavelength of the sound is of the order of the length of the tubes. So the match can occur for only one tube at a time — the difference in tube lengths is much smaller than a half wavelength. As the frequency increases, the wavelength decreases and many more wavelengths fit inside a tube. When half the wavelength becomes of the order of the difference in tube lengths, the tubes can contain an odd multiple of quarter wavelengths for the same wavelength at the same time — for instance, one tube might contain 17 quarter wavelengths while the other contains 19 quarter wavelengths.

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

(a) (3 points)

| | |
|---|---|
| For a reasonable setup that would allow useful measurements | 1 point |
| For indicating all the measurements needed to determine the velocities | 1 point |
| For having no obviously extraneous equipment or measurements | 1 point |

Examples:

- Use tape to mark off two distances on the track — one for cart *A* before the collision and one for the combined carts after the collision. Push cart *A* to give it an initial speed. Use a stopwatch to measure the time it takes for the cart(s) to cross the marked distances. The speeds are the distances divided by the times.
- Place a motion detector at the left end of the track. Push cart *A* to give it an initial speed. Record position as a function of time, first for cart *A* and then for the combined carts *A* and *B*.

(b) (2 points)

| | |
|---|---|
| For indicating a reasonable assumption about the relative size of the measurement errors before and after the collision | 1 point |
| For correctly using the assumption in comparing the effect on the calculated value of the mass of cart *B* | 1 point |

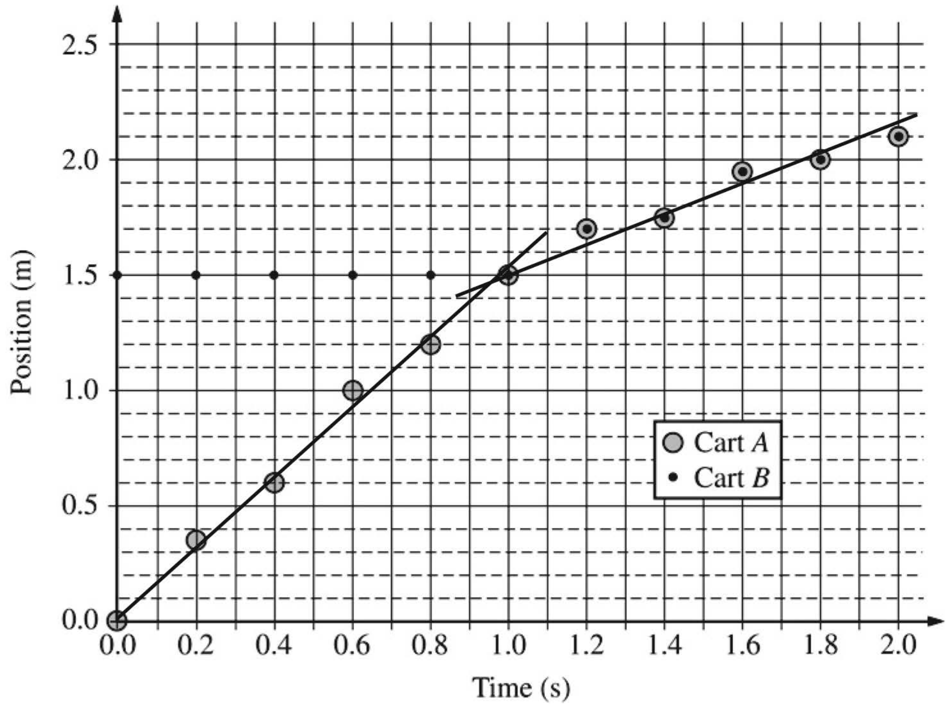
Example:

If the measurement errors are of the same magnitude, they will have a greater effect after the collision. The speed of the combined carts will be less than the initial speed of cart A, so errors of the same magnitude will be a greater percentage of the actual value after the collision. So the values after the collision will have a greater effect on the value of the mass of cart B.

A response could also argue any of the following:

- Measurement error could be greater before the collision (it could be harder to measure with the same accuracy at the greater speed). So percent error could be the same or greater.
- Measurement error could be greater before the collision (it could be harder to measure with the same accuracy at the greater speed). So the magnitude of the reported uncertainty could be the same.
- Measurement error could be the same before and after the collision if the same motion detector is used throughout.

(c) (4 points)




| | |
|---|---|
| For providing sufficient description of the principles used in the calculation (in either a single explanation or dispersed throughout the calculations) | 1 point |

Conservation of momentum can be used to determine the mass of cart $B$:
$m_A v_i = (m_A + m_B) v_f$

| | |
|---|---|
| For correctly recognizing the two regions on the graph corresponding to before and after the collision | 1 point |
| For using data from the graph to attempt calculation of speed from slope | 1 point |
| For indicating use of the slope of one or two drawn lines to determine one or more speeds (This point cannot be earned if calculations use data points not on the line[s].) | 1 point |

The speed $v_i$ before the collision is the slope of the best-fit line for the data from 0 to 1 s.

The speed $v_f$ after the collision is the slope of the best-fit line for the data from 1 s to 2 s.

Using the example lines drawn above:

$$v_i = \frac{(1.4-0)\text{m}}{(0.9-0)\text{s}} = \frac{14}{9}\frac{\text{m}}{\text{s}}$$

$$v_f = \frac{(2.1-1.5)\text{m}}{(1.9-1.0)\text{s}} = \frac{0.6\text{m}}{0.9\text{s}} = \frac{2}{3}\frac{\text{m}}{\text{s}}$$

Applying conservation of momentum:

$$(0.5\,\text{kg})\left(\frac{14}{9}\frac{\text{m}}{\text{s}}\right) = (0.5\,\text{kg}+m_B)\left(\frac{2}{3}\frac{\text{m}}{\text{s}}\right)$$

$$(0.5\,\text{kg})\left(\frac{14}{9}\right)\left(\frac{3}{2}\right) = (0.5\,\text{kg}+m_B)$$

$$(0.5\,\text{kg})\left(\frac{7}{3}\right) = (0.5\,\text{kg}+m_B)$$

$$m_B = (0.5\,\text{kg})\left(\frac{7}{3}-1\right) = (0.5\,\text{kg})\left(\frac{4}{3}\right) = \frac{2}{3}\,\text{kg}$$

(d) (3 points)

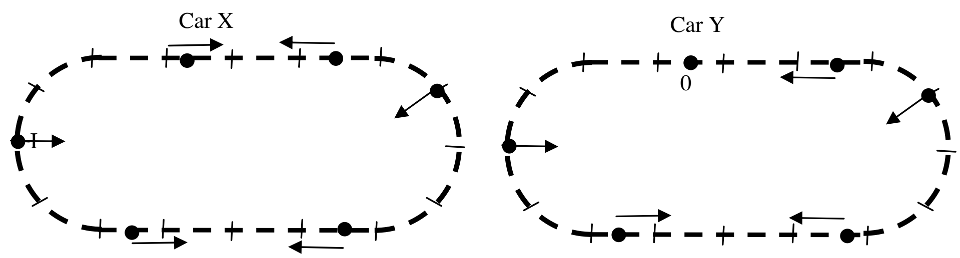
| | |
|---|---|
| For an answer consistent with previous responses that indicates a modification of the procedure to accomplish varying the initial speed of cart $A$ or one of the cart masses OR that indicates that the previously described procedure would provide appropriate data, so it does not need modification | 1 point |
| For indicating that the data can be used to calculate the kinetic energy $K$ before and after the collision | 1 point |
| For indicating that the fraction of $K$ lost in the various collisions should be compared | 1 point |

Example:

You could vary the initial speed of cart A. From the data, calculate values of kinetic energy before and after the collision using $K = (1/2)mv^2$. Then analyze $((K_i - K_f)/K_i)$ to see if the changes in initial speed give different values.

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

(a) (3 points)




| | |
|---|---|
| For correct directions of the net forces at all the locations on the semicircular sections (i.e., all directed generally toward the center of the circle) | 1 point |
| For correct directions of the net forces at all the locations on the bottom straightaways (i.e., directed toward the center of the segment) | 1 point |
| For correct directions of the net forces at all locations on the top straightaway (i.e., both rightmost arrows directed toward the left, the left one for car $X$ directed toward the right, and the left one for car $Y$ equal to zero) | 1 point |

(b) (7 points total)

i) (2 points)

| | |
|---|---|
| For realizing that the difference in time is only on the straightaways | 1 point |
| For correct reasoning leading to Car $Y$ taking a shorter time on the straightaways | 1 point |

Example:

Car $X$ takes longer to accelerate and does not spend any time traveling at top speed. Car $Y$ accelerates over a shorter time and spends time going at top speed. So car $Y$ must cover the straightaways in a shorter time. Curves take the same time, so car $Y$ must overall take a shorter time.

ii) (5 points)

The time to travel each curve is $d/v_c$. Answers can be expressed in terms of $d/v_c$ or $t_c = d/v_c$ or some other defined unit of time. The calculations below will use $t_c = d/v_c$.

| | |
|---|---|
| For stating that the time to travel each curve is $d/v_c$ | 1 point |
| For correct kinematics expressions that allow determination of the time it takes for one segment of acceleration on the straightaways | 1 point |

Example: $D = v_c t_1 + \frac{1}{2} a t_1^2, a = (2v_c - v_c)/t_1 = v_c/t_1,$

| | |
|---|---|
| For work that shows an understanding of how to determine the time that car $X$ and car $Y$ each spend accelerating | 1 point |
| For work that shows an understanding of how to determine the time that car $Y$ spends at constant speed | 1 point |
| For correctly determining the total straightaway times for each car | 1 point |

Calculating the time for car $X$ to travel one straightaway:

$$\frac{d}{2} = v_c t_1 + \frac{1}{2} a t_1^2, a = (2v_c - v_c)/t_1 = v_c/t_1$$

$$t_1 = \frac{d}{3v_c} = \frac{t_c}{3}, \text{total time is } \frac{2t_c}{3}$$

Calculating the time for car Y to travel one straightaway:

Doing the calculation shown above using the distance of acceleration $d/4$ gives the result that one section of acceleration takes a time $t_c/6$.

The time for car Y to travel one constant speed section on the straightaway is $(d/2)/2v_c = (t_c/4)$.

Adding three segments to get the total time for one straightaway gives $7t_c/12$.

The calculations show that car $Y$ takes less time on a straightaway, and both cars take the same time on the curves, so car $Y$ overall takes less time.

(c) (2 points)

| | |
|---|---|
| For linking math to one aspect of qualitative reasoning that explains the difference in times | 1 point |
| For linking math to all other qualitative reasoning that explains the difference in times | 1 point |

Examples:

The only difference in the calculations for the time of one segment of linear acceleration is the difference in distances. That shows that car *X* takes longer to accelerate. The equation $(d/2)/2v_c = (t_c/4)$ corresponds to car *Y* traveling for a time at top speed.

Substituting $a = v_c/t_1$ into the displacement equation in part (b) ii gives $D = (3/2)v_c t_1$. This shows that a car takes less time to reach its maximum speed when it accelerates over a shorter distance. This means car *Y* reaches its maximum speed more quickly and therefore spends more time at its maximum speed than car *X* does, as argued in part (b) i.

# Appendix A: The Big Ideas in AP Physics 1

## 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.1:** A system is an object or a collection of objects. Objects are treated as having no internal structure.<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.1:** Inertial mass is the property of an object or a system that determines how its motion changes when it interacts with other objects or systems.<br><br>**Essential Knowledge 1.C.2:** Gravitational mass is the property of an object or a system that determines the strength of the gravitational interaction with other objects, systems, or gravitational fields.<br><br>**Essential Knowledge 1.C.3:** Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles. |
| **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.2:** Matter has a property called resistivity. |

## 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. |
| **Enduring Understanding 2.B:** A gravitational field is caused by an object with mass. | **Essential Knowledge 2.B.1:** A gravitational field $\vec{g}$ at the location of an object with mass $m$ causes a gravitational force of magnitude $mg$ to be exerted on the object in the direction of the field.<br><br>**Essential Knowledge 2.B.2:** The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object. |

## 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.1:** An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration.<br><br>**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.<br><br>**Essential Knowledge 3.B.3:** Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object will undergo a special type of motion called simple harmonic motion. Examples include gravitational force exerted by the Earth on a simple pendulum and mass-spring oscillator. |

| | |
|---|---|
| **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.1:** Gravitational force describes the interaction of one object that has mass with another object that has mass.<br><br>**Essential Knowledge 3.C.2:** Electric force results from theinteraction of one object that has an electric charge with another object that has an electric charge.<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). |
| **Enduring Understanding 3.D:** A force exerted on an object can change the momentum of the object. | **Essential Knowledge 3.D.1:** The change in momentum of an object is a vector in the direction of the net force exerted on the object.<br><br>**Essential Knowledge 3.D.2:** The change in momentum of an object occurs over a time interval. |
| **Enduring Understanding 3.E:** A force exerted on an object can change the kinetic energy of the object. | **Essential Knowledge 3.E.1:** The change in the kinetic energy of an object depends on the force exerted on the object and on the displacement of the object during the time interval that the force is exerted. |
| **Enduring Understanding 3.F:** A force exerted on an object can cause a torque on that object. | **Essential Knowledge 3.F.1:** Only the force component perpendicular to the line connecting the axis of rotation and the point of application of the force results in a torque about that axis.<br><br>**Essential Knowledge 3.F.2:** The presence of a net torque along any axis will cause a rigid system to change its rotational motion or an object to change its rotational motion about that axis.<br><br>**Essential Knowledge 3.F.3:** A torque exerted on an object can change the angular momentum of an 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. |

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

| | |
|---|---|
| **Enduring Understanding 4.A:** The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\sum \vec{F}}{m}$. | **Essential Knowledge 4.A.1:** The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.<br><br>**Essential Knowledge 4.A.2:** Acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.<br><br>**Essential Knowledge 4.A.3:** Forces that systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system. |

| | |
|---|---|
| **Enduring Understanding 4.B:** Interactions with other objects or systems can change the total linear momentum of a system. | **Essential Knowledge 4.B.1:** The change in linear momentum for a constant-mass system is the product of the mass of the system and the change in velocity of the center of mass.<br><br>**Essential Knowledge 4.B.2:** The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted. |
| **Enduring Understanding 4.C:** Interactions with other objects or systems can change the total energy of a system. | **Essential Knowledge 4.C.1:** The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples include gravitational potential energy, elastic potential energy, and kinetic energy.<br><br>**Essential Knowledge 4.C.2:** Mechanical energy (the sum of kinetic and potential energy) is transferred into or out of a system when an external force is exerted on a system such that a component of the force is parallel to its displacement. The process through which the energy is transferred is called work. |
| **Enduring Understanding 4.D:** A net torque exerted on a system by other objects or systems will change the angular momentum of the system. | **Essential Knowledge 4.D.1:** Torque, angular velocity, angular acceleration, and angular momentum are vectors and can be characterized as positive or negative depending upon whether they give rise to or correspond to counterclockwise or clockwise rotation with respect to an axis.<br><br>**Essential Knowledge 4.D.2:** The angular momentum of a system may change due to interactions with other objects or systems.<br><br>**Essential Knowledge 4.D.3:** The change in angular momentum is given by the product of the average torque and the time interval during which the torque is exerted. |

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

| | |
|---|---|
| **Enduring Understanding 5.A:** Certain quantities are conserved, in the sense that the changes of those quantities in a given system are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. | **Essential Knowledge 5.A.1:** A system is an object or a collection of objects. The objects are treated as having no internal structure.<br><br>**Essential Knowledge 5.A.2:** For all systems under all circumstances, energy, charge, linear momentum, and angular momentum are conserved. For an isolated or a closed system, conserved quantities are constant. An open system is one that exchanges any conserved quantity with its surroundings.<br><br>**Essential Knowledge 5.A.3:** An interaction can be either a force exerted by objects outside the system or the transfer of some quantity with objects outside the system.<br><br>**Essential Knowledge 5.A.4:** The boundary between a system and its environment is a decision made by the person considering the situation in order to simplify or otherwise assist in analysis. |

| | |
|---|---|
| **Enduring Understanding 5.B:** The energy of a system is conserved. | **Essential Knowledge 5.B.1:** Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects.<br><br>**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.3:** A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces.<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.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.] |
| **Enduring Understanding 5.C:** The electric charge of a system is conserved. | **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. [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.] |
| **Enduring Understanding 5.E:** The angular momentum of a system is conserved. | **Essential Knowledge 5.E.1:** If the net external torque exerted on the system is zero, the angular momentum of the system does not change.<br><br>**Essential Knowledge 5.E.2:** The angular momentum of a system is determined by the locations and velocities of the objects that make up the system. The rotational inertia of an object or system depends upon the distribution of mass within the object or system. Changes in the radius of a system or in the distribution of mass within the system result in changes in the system's rotational inertia, and hence in its angular velocity and linear speed for a given angular momentum. Examples include elliptical orbits in an Earth-satellite system. Mathematical expressions for the moments of inertia should be provided where needed. Students will not be expected to know the parallel axis theorem. |

## 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:** 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><br>**Essential Knowledge 6.A.2:** For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples include light traveling through a vacuum and sound not traveling through a vacuum.<br><br>**Essential Knowledge 6.A.3:** The amplitude is the maximum displacement of a wave from its equilibrium value.<br><br>**Essential Knowledge 6.A.4:** Classically, the energy carried by a wave depends upon and increases with amplitude. Examples include sound waves. |

| | |
|---|---|
| **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.1:** For a periodic wave, the period is the repeat time of the wave. The frequency is the number of repetitions of the wave per unit time.<br>**Essential Knowledge 6.B.2:** For a periodic wave, the wavelength is the repeat distance of the wave.<br>**Essential Knowledge 6.B.4:** For a periodic wave, wavelength is the ratio of speed over frequency.<br>**Essential Knowledge 6.B.5:** The observed frequency of a wave depends on the relative motion of source and observer. This is a qualitative treatment only. |
| **Enduring Understanding 6.D:** Interference and superposition lead to standing waves and beats. | **Essential Knowledge 6.D.1:** Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition.<br>**Essential Knowledge 6.D.2:** Two or more traveling waves can interact in such a way as to produce amplitude variations in the resultant wave.<br>**Essential Knowledge 6.D.3:** Standing waves are the result of the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. Examples include waves on a fixed length of string and sound waves in both closed and open tubes.<br>**Essential Knowledge 6.D.4:** The possible wavelengths of a standing wave are determined by the size of the region to which it is confined.<br>**Essential Knowledge 6.D.5:** Beats arise from the addition of waves of slightly different frequency. |

# 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 1 Principles | Big Ideas |
|---|---|
| Kinematics (1D and 2D) | 3 |
| Dynamics: Newton's Laws | 1, 2, 3, 4 |
| Circular Motion and Universal Law of Gravitation | 1, 2, 3, 4 |
| Simple Harmonic Motion: Simple Pendulum and Mass-Spring Systems | 3, 5 |
| Impulse, Linear Momentum, and Conservation of Linear Momentum: Collisions | 3, 4, 5 |
| Work, Energy, and Conservation of Energy | 3, 4, 5 |
| Rotational Motion: Torque, Rotational Kinematics and Energy, Rotational Dynamics, and Conservation of Angular Momentum | 3, 4, 5 |
| Electrostatics: Electric Charge and Electric Force | 1, 3, 5 |
| DC Circuits: Resistors Only | 1, 5 |
| Mechanical Waves and Sound | 6 |

# Appendix C: AP Physics 1 Equations and Constants

**Table of Information and Equation Tables for the AP Physics 1 Exam**

The accompanying table of information and equation tables will be provided to students when they take the AP Physics 1 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 1 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 1 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 | Coulomb's law constant, | $k = 1/4\pi\varepsilon_0 = 9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2}$ |
| Electron mass, | $m_e = 9.11 \times 10^{-31}$ kg | Universal gravitational constant, | $G = 6.67 \times 10^{-11}\ \mathrm{m^3/kg{\cdot}s^2}$ |
| Speed of light, | $c = 3.00 \times 10^8$ m/s | Acceleration due to gravity at Earth's surface, | $g = 9.8\ \mathrm{m/s^2}$ |

| UNIT SYMBOLS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | meter, | m | kelvin, | K | watt, | W | degree Celsius, | °C |
| | kilogram, | kg | hertz, | Hz | coulomb, | C | | |
| | second, | s | newton, | N | volt, | V | | |
| | ampere, | A | joule, | J | ohm, | Ω | | |

| 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

| $\theta$ | $0^\circ$ | $30^\circ$ | $37^\circ$ | $45^\circ$ | $53^\circ$ | $60^\circ$ | $90^\circ$ |
|---|---|---|---|---|---|---|---|
| $\sin\theta$ | 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 | $4/3$ | $\sqrt{3}$ | $\infty$ |

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. Assume air resistance is negligible unless otherwise stated.
III. In all situations, positive work is defined as work done <u>on</u> a system.
IV. The direction of current is conventional current: the direction in which positive charge would drift.
V. Assume all batteries and meters are ideal unless otherwise stated.

## ADVANCED PLACEMENT PHYSICS 1 EQUATIONS

### MECHANICS

$$v_x = v_{x0} + a_x t$$

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

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

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

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

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

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

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

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

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

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

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

$$\omega = \omega_0 + \alpha t$$

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

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

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

$$L = I\omega$$

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

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

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

$$U_s = \frac{1}{2}kx^2$$

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

- $a$ = acceleration
- $A$ = amplitude
- $d$ = distance
- $E$ = energy
- $f$ = frequency
- $F$ = force
- $I$ = 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
- $V$ = volume
- $v$ = speed
- $W$ = work done on a system
- $x$ = position
- $y$ = height
- $\alpha$ = angular acceleration
- $\mu$ = coefficient of friction
- $\theta$ = angle
- $\rho$ = density
- $\tau$ = torque
- $\omega$ = angular speed

$$\Delta U_g = mg\,\Delta y$$

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

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

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

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

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

$$U_G = -\frac{Gm_1 m_2}{r}$$

### ELECTRICITY

$$\left|\vec{F}_E\right| = k\left|\frac{q_1 q_2}{r^2}\right|$$

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

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

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

$$P = I\,\Delta V$$

$$R_s = \sum_i R_i$$

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

- $A$ = area
- $F$ = force
- $I$ = current
- $\ell$ = length
- $P$ = power
- $q$ = charge
- $R$ = resistance
- $r$ = separation
- $t$ = time
- $V$ = electric potential
- $\rho$ = resistivity

### WAVES

$$\lambda = \frac{v}{f}$$

- $f$ = frequency
- $v$ = speed
- $\lambda$ = wavelength

### GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

Triangle
$A = \frac{1}{2}bh$

Circle
$A = \pi r^2$
$C = 2\pi r$

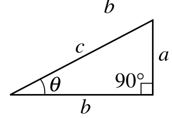
Rectangular solid
$V = \ell wh$

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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