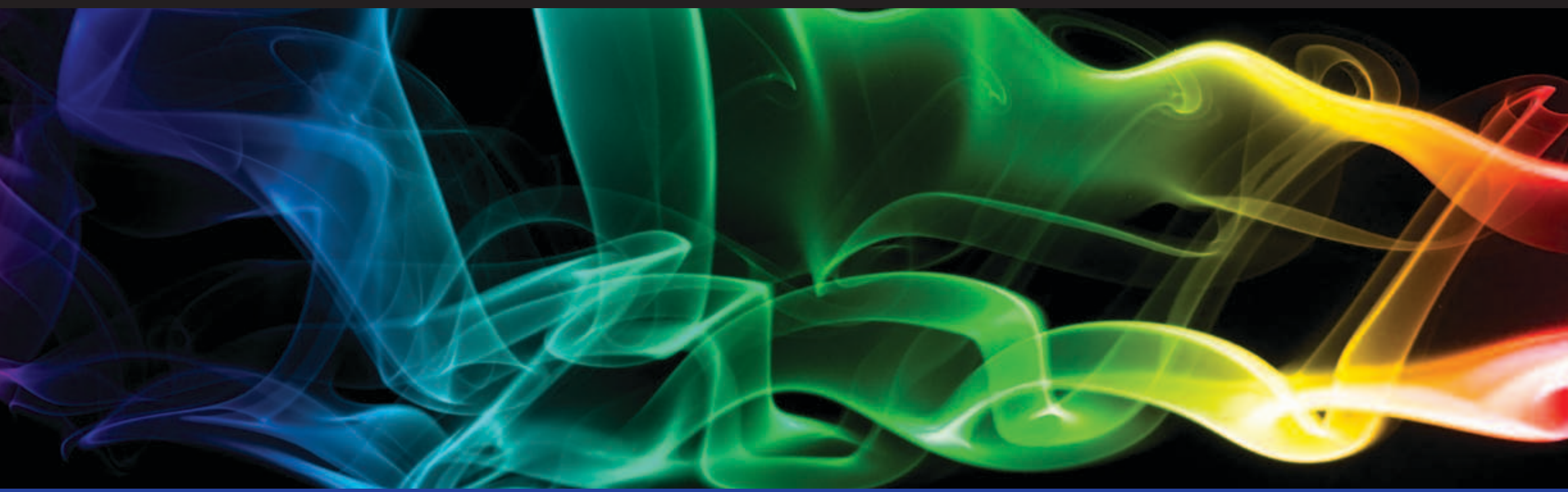
CollegeBoard

AP® PHYSICS 1: ALGEBRA-BASED AND AP® PHYSICS 2: ALGEBRA-BASED

Curriculum Framework

2014–2015



AP® Physics 1: Algebra-Based and AP Physics 2: Algebra-Based

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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.

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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.

The AP Physics 1: Algebra-based and AP Physics 2: Algebra-based Curriculum Framework is designed to provide educators with a first look at essential information needed to understand the design and intent of the revised AP Physics course in advance of its implementation in schools in the 2014-15 academic year. Please be advised that the information contained in this document is subject to change. The final course and exam information will be available in the *AP Physics 1: Algebra-Based and AP Physics 2: Algebra-Based Course and Exam Description*, which will be published in early 2014.

Contents

Introduction

AP® Physics 1: Algebra-based and AP Physics 2: Algebra-based is a two-year sequence equivalent to the first and second semesters of a typical introductory, algebra-based, college physics course. This two-year sequence gives teachers the time needed to foster greater depth of conceptual understanding through the use of student-centered, inquiry-based instructional practices. This sequence also gives teachers time to cover the concepts and skills students will need to demonstrate in order to earn credit for the introductory algebra-based college physics course.

This framework shifts away from a traditional "content coverage" model of instruction to one that focuses on the big ideas in an introductory college-level physics sequence and provides students with enduring, conceptual understandings of foundational physics principles. This approach will enable students to spend less time on mathematical routines and more time engaged in inquiry-based learning of essential concepts, and it will help them develop the critical thinking and reasoning skills necessary to engage in the science practices used throughout their study of algebra-based AP Physics and subsequent course work in science disciplines.

Having a deep understanding of physics principles implies the ability to reason about physical phenomena using important science process skills such as explaining causal relationships, applying and justifying the use of mathematical routines, designing experiments, analyzing data and making connections across multiple topics within the course. Therefore, the Curriculum Framework for AP Physics 1: Algebra-based and AP Physics 2: Algebra-based pairs the core essential knowledge with the fundamental scientific reasoning skills necessary for authentic scientific inquiry and engages students at an academic level equivalent to two semesters of a typical college or university algebra-based, introductory physics course sequence. The result will be readiness for the study of advanced topics in subsequent college courses — a goal of every AP course.

The Emphasis on Science Practices

A practice is a way to coordinate knowledge and skills in order to accomplish a goal or task. The science practices enable students to establish lines of evidence and use them to develop and refine testable explanations and predictions of natural phenomena. Because content, inquiry and reasoning are equally important in AP Physics, each learning objective described in the concept outline combines content with inquiry and reasoning skills described in the science practices.

The science practices that follow the concept outline of this framework 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.

Overview of the Concept Outline

The AP Physics 1: Algebra-based and AP Physics 2: Algebra-based concepts are articulated together in one concept outline, providing the full scope of conceptual understandings a student should acquire by the end of an introductory sequence in college-level algebra-based physics.

The key concepts and related content that define the AP Physics 1: Algebra-based and AP Physics 2: Algebra-based courses and exams are organized around seven underlying principles called the big ideas, which encompass the core scientific principles, theories and processes of physics that cut across traditional content boundaries and provide students a broad way of thinking about the physical world. For each big idea, *enduring understandings*, which incorporate the core concepts that students should retain from the learning experience, are also identified.

Each enduring understanding is followed by statements of the *essential knowledge* necessary to support that understanding. Unless otherwise specified, all the details in the outline are required elements of the course and may be needed to successfully meet the learning objectives tested by the AP Physics 1: Algebra-based or AP Physics 2: Algebra-based exams (unless otherwise specified) as outlined in the Curriculum Framework. The corresponding *learning objectives*, which pair the essential knowledge to the appropriate science practice(s), articulate specifically what students should know and be able to do.

Learning objectives provide clear and detailed articulation of what students should know and be able to do. Each learning objective is designed to help teachers integrate science practices with specific content, and to provide them with clear information about how students will be expected to demonstrate their knowledge and abilities. These learning objectives fully define what will be assessed on the AP Physics 1 and AP Physics 2 exams; questions that do not correspond to one or more learning objectives will not appear on the exam. Learning objectives are numbered to correspond with each Big Idea, Enduring Understanding, and Essential Knowledge. Alignment of the learning objectives to the science practices is denoted in brackets, as shown in this example:

Learning Objective (1.A.2.1):
The student is able to construct representations of the differences between a fundamental particle and a system composed of fundamental particles and to relate this to the properties and scales of the systems being investigated.
[See Science Practices 1.1 and 7.1]

There are instances where the essential knowledge does not have stated learning objectives; this essential knowledge serves as a necessary foundation that will be applied in other learning objectives found either within that same enduring understanding or in multiple enduring understandings throughout the Curriculum Framework. Where these instances occur, a statement will appear as follows:

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

Boundary 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 are denoted as in the example shown below:

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

Boundary Statement: AP Physics 2 has learning objectives under this enduring understanding 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.

Reading the Concept Outline

Each essential knowledge (EK) statement references the big idea, enduring understanding. This EK statement is under Big Idea 1, Enduring Understanding A and is the fifth EK statement under that enduring understanding.

PHYSICS 1 | PHYSICS 2

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*.

Learning Objective (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. **[See Science Practices 1.1 and 7.1]**

PHYSICS 2

Learning Objective (1.A.5.2):
The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. **[See Science Practices 1.1, 1.4, and 7.1]**

Each learning objective integrates the essential knowledge with the science practice(s) and clearly defines what a student should know and be able to do.

Course division of content is indicated by text borders for both essential knowledge statements and learning objectives.

The Concept Outline

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

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures. A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

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

In a problem of interest, this enduring understanding distinguishes *systems,* where internal structure exists and may need to be taken into account, from *objects,* where internal structure is not present or can be ignored.

Matter builds from fundamental particles, which are objects that have no internal structure, up to systems such as nuclei, atoms, molecules, and macroscopic objects that do have internal structure. The number and arrangements of atomic constituents cause substances to have different properties. There is much contact with chemistry in this enduring understanding in terms of atomic structure, chemical properties of elements, and the incorporation of concepts leading to the quantum model of the atom: energy states, quantized parameters, and transitions.

PHYSICS 1

Essential Knowledge 1.A.1: A system is an object or a collection of objects. Objects are treated as having no internal structure.

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.

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.

c. The electric charges on neutrons and protons result from their quark compositions.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 2

Essential Knowledge 1.A.2: Fundamental particles have no internal structure.

a. Electrons, neutrinos, photons, and quarks are examples of fundamental particles.

b. Neutrons and protons are composed of quarks.

c. All quarks have electric charges, which are fractions of the elementary charge of the electron. Students will not be expected to know specifics of quark charge or quark composition of nucleons.

Learning Objective (1.A.2.1):
The student is able to construct representations of the differences between a fundamental particle and a system composed of fundamental particles and to relate this to the properties and scales of the systems being investigated.
[See Science Practices 1.1 and 7.1]

Essential Knowledge 1.A.3: Nuclei have internal structures that determine their properties.

a. The number of protons identifies the element.

b. The number of neutrons together with the number of protons identifies the isotope.

c. There are different types of radioactive emissions from the nucleus.

d. The rate of decay of any radioactive isotope is specified by its half-life.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 2

Essential Knowledge 1.A.4: Atoms have internal structures that determine their properties.

a. The number of protons in the nucleus determines the number of electrons in a neutral atom.

b. The number and arrangements of electrons cause elements to have different properties.

c. The Bohr model based on classical foundations was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states (represented in energy diagrams by discrete energy levels).

d. Discrete energy state transitions lead to spectra.

Learning Objective (1.A.4.1):
The student is able to construct representations of the energy-level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated.
[See Science Practices 1.1 and 7.1]

PHYSICS 2

PHYSICS 1 | PHYSICS 2

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*.

PHYSICS 1

Learning Objective (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.
[**See Science Practices 1.1 and 7.1**]

PHYSICS 2

Learning Objective (1.A.5.2):
The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures.
[**See Science Practices 1.1, 1.4, and 7.1**]

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.

Electric charge is the fundamental property of an object that determines how the object interacts with other electrically charged objects. The interaction of a charged object with a distribution of other charged objects is simplified by the field model, where a distribution of charged objects creates a field at every point and the charged object interacts with the field. There are two types of electric charge, positive and negative. Protons are examples of positively charged objects, and electrons are examples of negatively charged objects. Neutral objects and systems are ones whose net charge is zero. The magnitudes of the charge of a proton and of an electron are equal, and this is the smallest unit of charge that is found in an isolated object. Electric charge is conserved in all known processes and interactions.

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

PHYSICS 1 | PHYSICS 2

Essential Knowledge 1.B.1: Electric charge is conserved. The net charge of a system is equal to the sum of the charges of all the objects in the system.

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

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

Learning Objective (1.B.1.1):
The student is able to make claims about natural phenomena based on conservation of electric charge.
[See Science Practice 6.4]

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

PHYSICS 1 PHYSICS 2

Essential Knowledge 1.B.2: There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge.

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

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

PHYSICS 1

Learning Objective (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.
[See Science Practice 6.2]

Learning Objective (1.B.2.2):
The student is able to make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes.
[See Science Practices 6.4 and 7.2]

Learning Objective (1.B.2.3):
The student is able to challenge claims that polarization of electric charge or separation of charge must result in a net charge on the object.
[See Science Practice 6.1]

PHYSICS 1

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.

a. The magnitude of the elementary charge is equal to 1.6×10^{-19} coulombs.

b. Electrons have a negative elementary charge; protons have a positive elementary charge of equal magnitude, although the mass of a proton is much larger than the mass of an electron.

Learning Objective (1.B.3.1):
The student is able to challenge the claim that an electric charge smaller than the elementary charge has been isolated.
[**See Science Practices 1.5, 6.1, and 7.2**]

PHYSICS 2

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.

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. Gravitational mass is the property of an object or a system that determines the magnitude of its gravitational interaction with other objects, systems, or gravitational fields. From these definitions, classically, there is no expectation that these quantities would be identical. Einstein's assumption that these two quantities, experimentally verified to be equivalent, are in fact the same, is fundamental to the general theory of relativity (which is not part of this course).

Mass is conserved in any process, such as change of shape, change of state, or dissolution, when it is not converted to energy or when energy is not converted to mass. Mass is a central concept in this course; further discussions of mass are found throughout.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 4.2]

PHYSICS 1

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.

a. The gravitational mass of an object determines the amount of force exerted on the object by a gravitational field.

b. Near the Earth's surface, all objects fall (in a vacuum) with the same acceleration, regardless of their inertial mass.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 4.2]

PHYSICS 2

Essential Knowledge 1.C.4: In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.

Learning Objective (1.C.4.1):
The student is able to articulate the reasons that the theory of conservation of mass was replaced by the theory of conservation of mass-energy.
[See Science Practice 6.3]

Enduring Understanding 1.D: Classical mechanics cannot describe all properties of objects.

Physicists developed classical mechanics from the intuitive partition of behavior of nature at the human scale into objects that behaved like particles (e.g., rocks) and systems that behaved like waves (e.g., sound waves). Similarly, in classical mechanics they recognized from experience that the motion of objects would appear differently to observers moving relative to each other, but assumed that measurements of elapsed time would not be affected by motion. As physicists in the late 19th and early 20th centuries probed the structure of matter at smaller and smaller scales, they discovered that models of atomic and subatomic behavior based on classical intuitions could not explain the experimental results. Ultimately, new mathematical theories were developed that could predict the outcome of experiments, but lacked the intuitive underpinning of the classical view. The mathematics gives unambiguous results, but has no single intuitive reference or analogy that can be described in ordinary language. As a result, the best we can do is to describe certain results of experiments as analogous to classical particle behavior and others as analogous to classical wavelike behavior, while recognizing that the underlying nature of the object has no precise analogy in human-scale experience.

During the same period, experimental results and theoretical predictions of results in the study of electromagnetic radiation came into conflict with the classical assumption of a common time for all observers. At relative velocities that are large compared with common experience, the special theory of relativity correctly predicts changes in the observed momentum, length, and elapsed time for objects in relative motion. Because humans have no experience of relative motion at such velocities, we have no intuitive underpinnings to explain this behavior. The physics of large relative velocities will only be treated qualitatively in this course.

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PHYSICS 2

Essential Knowledge 1.D.1: Objects classically thought of as particles can exhibit properties of waves.

a. This wavelike behavior of particles has been observed, e.g., in a double-slit experiment using elementary particles.

b. The classical models of objects do not describe their wave nature. These models break down when observing objects in small dimensions.

Learning Objective (1.D.1.1):
The student is able to explain why classical mechanics cannot describe all properties of objects by articulating the reasons that classical mechanics must be refined and an alternative explanation developed when classical particles display wave properties.
[See Science Practice 6.3]

PHYSICS 2

Essential Knowledge 1.D.2: Certain phenomena classically thought of as waves can exhibit properties of particles.

a. The classical models of waves do not describe the nature of a photon.

b. Momentum and energy of a photon can be related to its frequency and wavelength.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

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PHYSICS 2

Essential Knowledge 1.D.3: Properties of space and time cannot always be treated as absolute.

a. Relativistic mass–energy equivalence is a reconceptualization of matter and energy as two manifestations of the same underlying entity, fully interconvertible, thereby rendering invalid the classically separate laws of conservation of mass and conservation of energy. Students will not be expected to know apparent mass or rest mass.

b. Measurements of length and time depend on speed. (Qualitative treatment only.)

Learning Objective (1.D.3.1):
The student is able to articulate the reasons that classical mechanics must be replaced by special relativity to describe the experimental results and theoretical predictions that show that the properties of space and time are not absolute. [Students will be expected to recognize situations in which nonrelativistic classical physics breaks down and to explain how relativity addresses that breakdown, but students will not be expected to know in which of two reference frames a given series of events corresponds to a greater or lesser time interval, or a greater or lesser spatial distance; they will just need to know that observers in the two reference frames can "disagree" about some time and distance intervals.]
[**See Science Practices 6.3 and 7.1**]

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.

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material. Some of the most important fundamental characteristics of matter and space are identified here and employed in other big ideas.

Matter has properties called density, resistivity, and thermal conductivity that are used when discussing thermodynamics, fluids, electric current, and transfer of thermal energy. The values of these quantities depend upon the molecular and atomic structure of the material. Matter and space also have properties called electric permittivity and magnetic permeability. The permittivity and the permeability of free space are constants that appear in physical relationships and in the relationship for the speed of electromagnetic radiation in a vacuum. The electric permittivity and the magnetic permeability of materials both depend upon the material's structure at the atomic level.

Electric dipole moments (as treated in Enduring Understanding 2C) and magnetic dipole moments are other properties of matter. A separated pair of positively and negatively charged objects is an example of an electric dipole. A current loop is an example of a magnetic dipole.

PHYSICS 2

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

Learning Objective (1.E.1.1):
The student is able to predict the densities, differences in densities, or changes in densities under different conditions for natural phenomena and design an investigation to verify the prediction.
[See Science Practices 4.2 and 6.4]

Learning Objective (1.E.1.2):
The student is able to select from experimental data the information necessary to determine the density of an object and/or compare densities of several objects.
[See Science Practices 4.1 and 6.4]

PHYSICS 1 PHYSICS 2

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

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

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

Learning Objective (1.E.2.1):
The student is able to choose and justify the selection of data needed to determine resistivity for a given material.
[See Science Practice 4.1]

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

a. The thermal conductivity is the measure of a material's ability to transfer thermal energy.

PHYSICS 2

Learning Objective (1.E.3.1):
The student is able to design an experiment and analyze data from it to examine thermal conductivity.
[**See Science Practices 4.1, 4.2, and 5.1**]

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

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

PHYSICS 2

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

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

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

PHYSICS 2

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 2

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

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

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

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

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

All of the fundamental forces, including the gravitational force and the electric and magnetic forces, are exerted "at a distance"; the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields, which associate a value of some quantity with every point in space. Forces are vectors and so the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, for instance, temperature and pressure, vary with position. In general, a field created by an array of "sources" can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition. For a gravitational field the source is an object with mass. For an electric field the source is an object with electric charge. For a magnetic field the source is a magnet or a moving object with electric charge. Visual representations are extensively used by physicists in the analysis of many situations. A broadly used example across many applications involving fields is a map of isolines connecting points of equal value for some quantity related to a field, such as topographical maps that display lines of approximately equal gravitational potential.

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.

All fundamental forces, including gravitational force, electric force, and magnetic force, are exerted by one object on another object "at a distance"; this means that the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields. Forces are vectors and the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, such as temperature and pressure, vary with position. In general, the field created by an array of "sources," such as objects with electric charge, can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition.

Boundary Statement: Physics 1 treats gravitational fields; Physics 2 treats electric and magnetic fields.

PHYSICS 1 | PHYSICS 2

Essential Knowledge 2.A.1: A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.

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

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

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

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 2

Essential Knowledge 2.A.2: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential.

a. Scalar fields are represented by field values.

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

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

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

Enduring Understanding 2.B: A gravitational field is caused by an object with mass.

The gravitational field is the field most accessible to students. The effect of a gravitational field $\vec{g}$ on an object with mass m positioned in the field is a force of magnitude mg that points in the direction of the field. The gravitational field can be represented mathematically. The gravitational field at a point in space due to a spherical object with mass M is a vector whose magnitude is equal to the gravitational force per unit of mass placed at that point. The direction of the field at the point is toward the center of mass of the source object. The magnitude of the field outside the object is equal to $G\frac{M}{r^2}$, where r is the distance between the center of mass of the object and the point of interest and G is a constant. As with any vector field, a gravitational field can be represented by a drawing that shows arrows at points that are uniformly distributed in space.

PHYSICS 1

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.

a. On the Earth, this gravitational force is called weight.

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.

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.

Learning Objective (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. **[See Science Practices 2.2 and 7.2]**

PHYSICS 1

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.

a. The gravitational field caused by a spherically symmetric object is a vector whose magnitude outside the object is equal to $G\frac{M}{r^2}$.

b. Only spherically symmetric objects will be considered as sources of the gravitational field.

Learning Objective (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.
[See Science Practice 2.2]

Learning Objective (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.
[See Science Practice 2.2]

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

Coulomb's law of electric force describes the interaction at a distance between two electrically charged objects. By contrast, the electric field serves as the intermediary in the interaction of two objects or systems that have the property of electric charge. In the field view, charged source objects create an electric field. The magnitude and direction of the electric field at a given location are due to the vector sum of the fields created by each of the charged objects that are the source of the field. Another charged object placed at a given location in the field experiences an electric force. The force depends on the charge of the object and the magnitude and direction of the electric field at that location. The concept of the electric field greatly facilitates the description of electrical interactions between multiple-point charges or continuous distributions of charge. In this course, students should be familiar with graphical and mathematical representations of the electric field due to one or more point charges including the field of an electric dipole, the field outside a spherically symmetric charged object, and the uniform field between the plates when far from the edges of oppositely charged parallel plates. Students should be able to use these representations to calculate the direction and magnitude of the force on a small charged object due to such electric fields. Electric field representations are to be vectors and not lines.

PHYSICS 2

Essential Knowledge 2.C.1: The magnitude of the electric force F exerted on an object with electric charge q by an electric field $\vec{E}$ is $\vec{F} = q\vec{E}$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distribution, and uniformly charged parallel plates.

Learning Objective (2.C.1.1):
The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $\vec{F} = q\vec{E}$; a vector relation.
[See Science Practices 6.4 and 7.2]

Learning Objective (2.C.1.2):
The student is able to calculate any one of the variables — electric force, electric charge, and electric field — at a point given the values and sign or direction of the other two quantities.
[See Science Practice 2.2]

PHYSICS 2

Essential Knowledge 2.C.2: The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

Learning Objective (2.C.2.1):
The student is able to qualitatively and semi-quantitatively apply the vector relationship between the electric field and the net electric charge creating that field.
[See Science Practices 2.2 and 6.4]

PHYSICS 2

Essential Knowledge 2.C.3: The electric field outside a spherically symmetric charged object is radial and its magnitude varies as the inverse square of the radial distance from the center of that object. Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.

a. The inverse square relation known as Coulomb's law gives the magnitude of the electric field at a distance r from the center of a source object of electric charge Q as $|E| = \frac{1}{4\pi\varepsilon_0}\frac{|Q|}{r^2}$.

b. This relation is based on a model of the space surrounding a charged source object by considering the radial dependence of the area of the surface of a sphere centered on the source object.

Learning Objective (2.C.3.1):
The student is able to explain the inverse square dependence of the electric field surrounding a spherically symmetric electrically charged object.
[See Science Practice 6.2]

PHYSICS 2

Essential Knowledge 2.C.4: The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

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

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

Learning Objective (2.C.4.1):
The student is able to distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semi-quantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field.
[See Science Practices 2.2, 6.4, and 7.2]

Learning Objective (2.C.4.2):
The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points.
[See Science Practices 1.4 and 2.2]

PHYSICS 2

Essential Knowledge 2.C.5: Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.

Learning Objective (2.C.5.1):
The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates.
[See Science Practices 1.1 and 2.2]

Learning Objective (2.C.5.2):
The student is able to calculate the magnitude and determine the direction of the electric field between two electrically charged parallel plates, given the charge of each plate, or the electric potential difference and plate separation.
[See Science Practice 2.2]

Learning Objective (2.C.5.3):
The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field.
[See Science Practices 1.1, 2.2, and 7.1]

Enduring Understanding 2.D: A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

Knowledge of the properties and sources of magnetic fields is necessary in other big ideas dealing with magnetism. This knowledge is critical to student understanding of areas such as geophysical processes and medical applications. Students also should know that magnetic fields observed in nature always seem to be caused by dipoles or combinations of dipoles and never by single poles. A magnetic dipole can be modeled as a current in a loop. A single magnetic pole (a magnetic monopole like an isolated north pole of a magnet) has never been observed in nature.

Representations of these fields are important to the skills that students need to develop in the course. The pattern of magnetic field vectors tangent to concentric circles around a current-carrying wire and the dipole pattern of field vectors around a bar magnet are needed representations.

Magnetic materials contain magnetic domains that are themselves little magnets. Representations can be drawn of the atomic-scale structure of ferromagnetic materials, such as arrows or smaller bar magnets, which indicate the directional nature of magnets even at these small scales. These magnetic moments lead to discussions of important modern applications such as magnetic storage media.

PHYSICS 2

Essential Knowledge 2.D.1: The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity and the magnitude of the magnetic field. It also depends on the angle between the velocity, and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles.

Learning Objective (2.D.1.1):
The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. **[See Science Practice 2.2]**

PHYSICS 2

Essential Knowledge 2.D.2: The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.

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

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

Learning Objective (2.D.2.1):
The student is able to create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires.
[See Science Practice 1.1]

PHYSICS 2

Essential Knowledge 2.D.3: A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.

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

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

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

d. The Earth has a magnetic field.

Learning Objective (2.D.3.1):
The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet.
[See Science Practice 1.2]

PHYSICS 2

Essential Knowledge 2.D.4: Ferromagnetic materials contain magnetic domains that are themselves magnets.

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

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

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

Learning Objective (2.D.4.1):
The student is able to use the representation of magnetic domains to qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material.
[See Science Practice 1.4]

Enduring Understanding 2.E: Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.

When visualizing a scalar field, it is useful to construct a set of contour lines connecting points at which the field has the same (constant) value. A good example is the set of contour lines (gravitational equipotentials) on which the gravitational potential energy per unit mass has a constant value. Such equipotential lines can be constructed using the electric potential and can also be associated with temperature and other scalar fields. When considering equipotential lines, the associated vector field (such as the electric field) is always perpendicular to the equipotential lines. When not provided with a diagram of field vectors, students will be expected to draw accurate equipotential lines ONLY for spherically symmetric sources and for sources that create approximately uniform fields.

PHYSICS 2

Essential Knowledge 2.E.1: Isolines on a topographic (elevation) map describe lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential). As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational and electrical potential and potential differences.]

Learning Objective (2.E.1.1):
The student is able to construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential.
[See Science Practices 1.4, 6.4, and 7.2]

PHYSICS 2

Essential Knowledge 2.E.2: Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as equipotential lines.

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

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

Learning Objective (2.E.2.1):
The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field.
[See Science Practices 6.4 and 7.2]

Learning Objective (2.E.2.2):
The student is able to predict the structure of isolines of electric potential by constructing them in a given electric field and make connections between these isolines and those found in a gravitational field.
[See Science Practices 6.4 and 7.2]

Learning Objective (2.E.2.3):
The student is able to qualitatively use the concept of isolines to construct isolines of electric potential in an electric field and determine the effect of that field on electrically charged objects.
[See Science Practice 1.4]

PHYSICS 2

Essential Knowledge 2.E.3: The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

Learning Objective (2.E.3.1):
The student is able to apply mathematical routines to calculate the average value of the magnitude of the electric field in a region from a description of the electric potential in that region using the displacement along the line on which the difference in potential is evaluated.
[**See Science Practice 2.2**]

Learning Objective (2.E.3.2):
The student is able to apply the concept of the isoline representation of electric potential for a given electric charge distribution to predict the average value of the electric field in the region.
[**See Science Practices 1.4 and 6.4**]

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

An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

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

The description of motion, including such quantities as position, velocity, or acceleration, depends on the observer, specifically on the reference frame. When the interactions of objects are considered, we only consider the observers in inertial reference frames. In such reference frames, an object that does not interact with any other objects moves at constant velocity. 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. If a component of the acceleration is observed to be zero, then the sum of the corresponding force components must be zero. If one object exerts a force on a second object, the second object always exerts a force of equal magnitude but opposite direction on the first object. These two forces are known as an action-reaction pair.

Boundary Statement: AP Physics 2 has learning objectives under this enduring understanding 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.

PHYSICS 1

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.

a. Displacement, velocity, and acceleration are all vector quantities.

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.

c. A choice of reference frame determines the direction and the magnitude of each of these quantities.

Learning Objective (3.A.1.1):
The student is able to express the motion of an object using narrative, mathematical, and graphical representations.
[See Science Practices 1.5, 2.1, and 2.2]

Learning Objective (3.A.1.2):
The student is able to design an experimental investigation of the motion of an object.
[See Science Practice 4.2]

Learning Objective (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.
[See Science Practice 5.1]

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PHYSICS 1 | PHYSICS 2

Essential Knowledge 3.A.2: Forces are described by vectors.

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

b. Forces have magnitude and direction.

Learning Objective (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. [**See Science Practice 1.1**]

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PHYSICS 1 PHYSICS 2

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

a. An object cannot exert a force on itself.

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

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

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Learning Objective (3.A.3.2):
The student is able to challenge a claim that an object can exert a force on itself.
[See Science Practice 6.1]

Learning Objective (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.
[See Science Practice 1.4]

Learning Objective (3.A.3.4):
The student is able to make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge.
[See Science Practices 6.1 and 6.4]

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PHYSICS 1 | PHYSICS 2

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.

Learning Objective (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.
[See Science Practices 1.4 and 6.2]

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practice 1.4]

Enduring Understanding 3.B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\Sigma \vec{F}}{m}$.

Newton's second law describes the acceleration when one or more forces are exerted on the object. The object's acceleration also depends on the inertial mass. Newton's second law is easier to appreciate when the law is written as $\vec{a} = \frac{\Sigma \vec{F}}{m}$, which underscores the cause–effect relationship. In a free-body diagram, the choice of appropriate axes (usually one axis parallel to the direction in which the object will accelerate) and the resolution of forces into components along the chosen set of axes are essential parts of the process of analysis. The set of component forces along an axis corresponds to the list of forces that are combined to cause acceleration along that axis. Constant forces will yield a constant acceleration, but restoring forces, proportional to the displacement of an object, cause oscillatory motion. In this course the oscillatory solution of the law should be the result of an experiment, rather than the solution of the differential equation.

Boundary Statement: AP Physics 2 contains learning objectives under this enduring understanding 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.

PHYSICS 1 PHYSICS 2

Essential Knowledge 3.B.1: If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 4.2 and 5.1]

PHYSICS 2

Learning Objective (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.
[See Science Practices 1.5 and 2.2]

Learning Objective (3.B.1.4):
The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations.
[See Science Practices 6.4 and 7.2]

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PHYSICS 1

PHYSICS 2

Essential Knowledge 3.B.2: Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.

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

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

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

Learning Objective (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.
[See Science Practices 1.1, 1.4, and 2.2]

PHYSICS 1

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 should include gravitational force exerted by the Earth on a simple pendulum, mass-spring oscillator.

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.

b. For a simple pendulum oscillating the period increases with the length of the pendulum.

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.

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practice 4.2]

Learning Objective (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.
[See Science Practices 2.2 and 5.1]

Learning Objective (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.
[See Science Practices 2.2 and 6.2]

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

In Big Idea 3, the behavior of an object is analyzed without reference to the internal structure of the object. Internal structure is included in Big Idea 4. There are a small number of forces that occur in nature and the macroscopic ones are considered here. The identification of forces is a key step in the analysis of mechanical systems.

Gravitational forces, electric forces, and magnetic forces between objects are all evident on the macroscopic scale. The gravitational force is a weaker force than the electric or magnetic force. However, on the larger scale, the gravitational force dominates. Electric forces are dominant in determining the properties of the objects in our everyday experience. However, the many electrically charged particles that interact make the treatment of this everyday force very complex. Introducing new concepts such as the frictional force as averages over the many particles reduces the complexity. Contact forces (e.g., frictional force, buoyant force) result from the interaction of one object touching another object and are ultimately due to microscopic electric forces. The frictional force is due to the interaction between surfaces at rest or in relative motion. Buoyant force is caused by the difference in pressure, or force per unit area, exerted on the different surfaces of the object. It is important for students to study each of these forces and to use free-body diagrams to analyze the interactions between objects.

PHYSICS 1

Essential Knowledge 3.C.1: Gravitational force describes the interaction of one object that has mass with another object that has mass.

a. The gravitational force is always attractive.

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.

c. In a narrow range of heights above the Earth's surface, the local gravitational field, g, is approximately constant.

Learning Objective (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.
[See Science Practice 2.2]

Learning Objective (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).
[See Science Practice 2.2]

PHYSICS 1

PHYSICS 2

Essential Knowledge 3.C.2: Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.

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

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

Learning Objective (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).
[**See Science Practices 2.2 and 6.4**]

Learning Objective (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 Science Practice 7.2**]

Learning Objective (3.C.2.3):
The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry).
[**See Science Practice 2.2**]

PHYSICS 2

Essential Knowledge 3.C.3: A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.

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

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

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

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

Learning Objective (3.C.3.1):
The student is able to use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor.
[See Science Practice 1.4]

Learning Objective (3.C.3.2):
The student is able to plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion.
[See Science Practices 4.2 and 5.1]

PHYSICS 1 | PHYSICS 2

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

Learning Objective (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.
[See Science Practice 6.1]

Learning Objective (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.
[See Science Practice 6.2]

Enduring Understanding 3.D: A force exerted on an object can change the momentum of the object.

The momentum of an object can only change if there is a net force exerted on the object by other objects. Classically, the change in momentum of the object is the product of the average net force on the object and the time interval during which the force is exerted. This product is a vector, called the impulse, and the direction of the impulse is the direction of the change in momentum. The magnitude of the impulse is the area under the force-time curve, which reduces to the product of force and time in the case of a constant force.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 4.1]

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PHYSICS 1

Essential Knowledge 3.D.2: The change in momentum of an object occurs over a time interval.

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).

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.

Learning Objective (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.
[See Science Practice 2.1]

Learning Objective (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.
[See Science Practice 6.4]

Learning Objective (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.
[See Science Practice 5.1]

Learning Objective (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.
[See Science Practice 4.2]

Enduring Understanding 3.E: A force exerted on an object can change the kinetic energy of the object.

A net force exerted on an object causes an acceleration of the object, which produces a change in the component of the velocity in the direction of the force. If there is a component of the force in the direction of the object's displacement, the kinetic energy of the object will change. The interaction transfers kinetic energy to or from the object. Only the component of the velocity in the direction of the force is involved in this transfer of kinetic energy. Thus, only the force component in the direction of the object's motion transfers kinetic energy. The amount of energy transferred during a given displacement depends on the magnitude of the force, the magnitude of the displacement, and the relative direction of force and displacement of the object. Since objects have no internal structure, an isolated object can only have kinetic energy.

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PHYSICS 1

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 interval that the force is exerted.

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.

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.

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.

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practice 1.4]

Learning Objective (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.
[See Science Practice 1.4 and 2.2]

Learning Objective (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.
[See Science Practice 2.2]

Enduring Understanding 3.F: A force exerted on an object can cause a torque on that object.

An object or a rigid system, which can revolve or rotate about a fixed axis, will change its rotational motion when an external force exerts a torque on the object. The magnitude of the torque due to a given force is the product of the perpendicular distance from the axis to the line of application of the force (the lever arm) and the magnitude of the force. The rate of change of the rotational motion is most simply expressed by defining the rotational kinematic quantities of angular displacement, angular velocity, and angular acceleration, analogous to the corresponding linear quantities, and defining the rotational dynamic quantities of torque, rotational inertia, and angular momentum, analogous to force, mass, and momentum. The behaviors of the angular displacement, angular velocity, and angular acceleration can be understood by analogy with Newton's second law for linear motion.

Boundary Statement: Quantities such as angular acceleration, velocity, and momentum are defined as vector quantities, but in this course the determination of "direction" is limited to clockwise and counterclockwise with respect to a given axis of rotation.

PHYSICS 1

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.

a. The lever arm is the perpendicular distance from the axis of rotation or revolution to the line of application of the force.

b. The magnitude of the torque is the product of the magnitude of the lever arm and the magnitude of the force.

c. The net torque on a balanced system is zero.

Learning Objective (3.F.1.1):
The student is able to use representations of the relationship between force and torque.
[See Science Practice 1.4]

Learning Objective (3.F.1.2):
The student is able to compare the torques on an object caused by various forces.
[See Science Practice 1.4]

Learning Objective (3.F.1.3):
The student is able to estimate the torque on an object caused by various forces in comparison to other situations.
[See Science Practice 2.3]

Learning Objective (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.
[See Science Practices 4.1, 4.2, and 5.1]

Learning Objective (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).
[See Science Practices 1.4 and 2.2]

PHYSICS 1

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.

a. Rotational motion can be described in terms of angular displacement, angular velocity, and angular acceleration about a fixed axis.

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.

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.

Learning Objective (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.
[See Science Practice 6.4]

Learning Objective (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.
[See Science Practices 4.1, 4.2, and 5.1]

PHYSICS 1

Essential Knowledge 3.F.3: A torque exerted on an object can change the angular momentum of an object.

a. Angular momentum is a vector quantity, with its direction determined by a right-hand rule.

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.

c. The magnitude of angular momentum of an extended object can also be found by multiplying the rotational inertia by the angular velocity.

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.

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practice 2.1]

Learning Objective (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.
[See Science Practices 4.1, 4.2, 5.1, and 5.3]

Enduring Understanding 3.G: Certain types of forces are considered fundamental.

There are different types of fundamental forces, and these forces can be characterized by their actions at different scales. The fundamental forces discussed in these courses include the electroweak force, the gravitational force, and the strong (nuclear) force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. All other forces can be thought of as secondary forces and are ultimately derived from the fundamental forces.

On the scale appropriate to the secondary forces we deal with every day, the electromagnetic aspect of the electroweak force dominates. There are two kinds of electric charge that can produce both attractive and repulsive interactions. While there are two kinds of electric charge, there appears to be only a single type of mass. Consequently, gravitational forces are only attractive. Since there are no repulsive contributions to the net force exerted at a very large distance the gravitational force dominates at large scales. The weak aspect of the electroweak force is important at very large stellar scales and at very small nuclear scales, and the strong force dominates inside the nucleus. (Students will not be required to know interactions involving the weak force.)

PHYSICS 1 | PHYSICS 2

Essential Knowledge 3.G.1: Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales.

PHYSICS 1

Learning Objective (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.
[See Science Practice 7.1]

PHYSICS 2

Learning Objective (3.G.1.2):
The student is able to connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces.
[See Science Practice 7.1]

Essential Knowledge 3.G.2: Electromagnetic forces are exerted at all scales and can dominate at the human scale.

PHYSICS 2

Learning Objective (3.G.2.1):
The student is able to connect the strength of electromagnetic forces with the spatial scale of the situation, the magnitude of the electric charges, and the motion of the electrically charged objects involved.
[See Science Practice 7.1]

Essential Knowledge 3.G.3: The strong force is exerted at nuclear scales and dominates the interactions of nucleons.

PHYSICS 2

Learning Objective (3.G.3.1):
The student is able to identify the strong force as the force that is responsible for holding the nucleus together.
[See Science Practice 7.2]

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

A system is a collection of objects, and the interactions of such systems are an important aspect of understanding the physical world. The concepts and applications in Big Idea 3, which concerned only objects, can be extended to discussions of such systems. The behavior of a system of objects may require a specification of their distribution, which can be described using the center of mass. The motion of the system is then described by Newton's second law as applied to the center of mass. When external forces or torques are exerted on a system, changes in linear momentum, angular momentum, and/or kinetic, potential, or internal energy of the system can occur. Energy transfers, particularly, are at the heart of almost every process that is investigated in the AP sciences. The behavior of electrically charged and magnetic systems can be changed through electromagnetic interactions with other 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 $\vec{a} = \frac{\Sigma\vec{F}}{m}$.

The concept of center of mass allows one to analyze and predict the motion of a system using an approach very similar to the way one can analyze and predict the motion of an object. When dealing with a system of objects, it is useful to first identify the forces that are "internal" and "external" to the system. The internal forces are forces that are exerted between objects in the system, while the external forces are those that are exerted between the system's objects and objects outside the system. Internal forces do not affect the motion of the center of mass of the system. Since all the internal forces will be action-reaction pairs, they cancel one another. Thus, $\vec{F}_{net}$ will be equivalent to the sum of all the external forces, so the acceleration of the center of mass of the system can be calculated using $\vec{a} = \frac{\Sigma\vec{F}}{m}$. Hence, many of the results for the motion of an object can be applied to the motion of the center of mass of a system.

Boundary Statement: 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.

PHYSICS 1	
	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.
	Learning Objective (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. **[See Science Practices 1.2, 1.4, 2.3, and 6.4]**

PHYSICS 1

Essential Knowledge 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.

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.

b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.

Learning Objective (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.
[See Science Practice 6.4]

Learning Objective (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.
[See Science Practice 5.3]

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 2.2]

Learning Objective (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.
[See Science Practice 1.4]

Enduring Understanding 4.B: Interactions with other objects or systems can change the total linear momentum of a system.

When a net external force is exerted on a system, linear momentum is transferred to parts of the system in the direction of the external force. Qualitative comparisons of the change in momentum in different scenarios are important. The change in momentum for a constant-mass system is the product of the mass and the change in velocity. The momentum transferred in an interaction is the product of the average net force and the time interval during which the force is exerted, whether or not the mass is constant. Graphs of force versus time can therefore be used to determine the change in momentum.

PHYSICS 1

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.

Learning Objective (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.).
[See Science Practices 1.4 and 2.2]

Learning Objective (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.
[See Science Practice 5.1]

PHYSICS 1

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.

a. The units for momentum are the same as the units of the area under the curve of a force versus time graph.

b. The changes in linear momentum and force are both vectors in the same direction.

Learning Objective (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.
[See Science Practice 2.2]

Learning Objective (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.
[See Science Practice 5.1]

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Enduring Understanding 4.C: Interactions with other objects or systems can change the total energy of a system.

A system of objects can be characterized by its total energy, a scalar that is the sum of the kinetic energy (due to large-scale relative motion of parts of the system), its potential energy (due to the relative position of interacting parts of the system), and its microscopic internal energy (due to relative motion and interactions at the molecular and atomic levels of the parts of the system). A single object does not possess potential energy. Rather, the system of which the object is a part has potential energy due to the interactions and relative positions of its constituent objects. In general, kinetic, potential, and internal energies can be changed by interactions with other objects or other systems that transfer energy into or out of the system under study. An external force exerted on an object parallel to the displacement of the object transfers energy into or out of the system. For a force that is constant in magnitude and direction, the product of the magnitude of the parallel force component and the magnitude of the displacement is called the work. For a constant or variable force, the work can be calculated by finding the area under the force versus displacement graph. The force component parallel to the displacement gives the rate of transfer of energy with respect to displacement. Work can result in a change in kinetic energy, potential energy, or internal energy of a system. Positive work transfers energy into the system, while negative work transfers energy out of the system. There are two mechanisms by which energy transfers into (or out of) a system. One is when the environment does work on the system (defined as positive work on the system), or the system does work on its environment (defined as negative work on the system). The other is when energy is exchanged between two systems at different temperatures, with no work involved. The latter mechanism of energy transfer is called heat. Both work and heat are not "kinds" of energy (like kinetic or potential) but are processes through which energy can be transferred. Summing work and heat gives the change in a system's energy.

Classically, mass conservation and energy conservation are separate laws, but in modern physics we recognize that the mass of a system changes when its energy changes, so that a transfer of energy into a system entails an increase in the mass of that system as well, although in most processes the change in mass is small enough to be ignored. The relationship between the mass and energy of a system is described by Einstein's famous equation, $E = mc^2$. The large energies produced during nuclear fission and fusion processes correspond to small reductions in the mass of a system.

Boundary Statement: Thermodynamics is treated in Physics 2 only.

PHYSICS 1

Essential Knowledge 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.

Learning Objective (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.
[See Science Practices 1.4, 2.1, and 2.2]

Learning Objective (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.
[See Science Practice 6.4]

PHYSICS 1

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.

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.

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.

Learning Objective (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.
[See Science Practice 6.4]

Learning Objective (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.
[See Science Practices 1.4, 2.2, and 7.2]

PHYSICS 2

Essential Knowledge 4.C.3: Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process through which energy is transferred between systems at different temperatures is called heat.

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

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

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

Learning Objective (4.C.3.1):
The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level.
[See Science Practice 6.4]

PHYSICS 2

Essential Knowledge 4.C.4: Mass can be converted into energy and energy can be converted into mass.

a. Mass and energy are interrelated by $E = mc^2$.

b. Significant amounts of energy can be released in nuclear processes.

Learning Objective (4.C.4.1):
The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale.
[See Science Practices 2.2, 2.3, and 7.2]

Enduring Understanding 4.D: A net torque exerted on a system by other objects or systems will change the angular momentum of the system.

Systems not only translate, they can also rotate. The behavior of such a system of objects requires a specification of their distribution in terms of a rotational inertia and an analysis relative to an appropriate axis. The existence of a net torque with respect to an axis will cause the object to change its rate of rotation with respect to that axis. Many everyday phenomena involve rotating systems. Understanding the effects of a nonzero net torque on a system in terms of the angular momentum leads to a better understanding of systems that roll or rotate. The angular momentum is a quantity that is conserved if the net torque on an object is zero, and this leads to one of the conservation laws discussed in Big Idea 5. Students will be provided with the value for rotational inertia or formula to calculate rotational inertia where necessary.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practices 1.2 and 1.4]

Learning Objective (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.
[See Science Practices 3.2, 4.1, 4.2, 5.1, and 5.3]

PHYSICS 1

Essential Knowledge 4.D.2: The angular momentum of a system may change due to interactions with other objects or systems.

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.

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.

c. Alternatively, the angular momentum of a system can be found from the product of the system's rotational inertia and its angular velocity.

Learning Objective (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.
[See Science Practices 1.2 and 1.4]

Learning Objective (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.
[See Science Practice 4.2]

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 2.2]

Learning Objective (4.D.3.2):
The student is able to plan a data collection strategy designed 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.
[See Science Practices 4.1 and 4.2]

Enduring Understanding 4.E: The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.

Electric and magnetic forces may be exerted on objects that possess an electric charge. These forces affect the motion of electrically charged objects. If a charged object is part of a system, electric and magnetic forces and fields can affect the properties of the system. One such example involves the behavior of moving charged objects (i.e., an electric current) in a circuit. The electric current in a circuit can be affected by an applied potential difference or by changing the magnetic flux through the circuit. The behavior of individual circuit elements, such as resistors and capacitors, can be understood in terms of how an applied electric or magnetic field affects charge motion within the circuit element.

PHYSICS 2

Essential Knowledge 4.E.1: The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.

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

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

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

Learning Objective (4.E.1.1):
The student is able to use representations and models to qualitatively describe the magnetic properties of some materials that can be affected by magnetic properties of other objects in the system.
[See Science Practices 1.1, 1.4, and 2.2]

PHYSICS 2

Essential Knowledge 4.E.2: Changing magnetic flux induces an electric field that can establish an induced emf in a system.

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

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

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

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

Learning Objective (4.E.2.1):
The student is able to construct an explanation of the function of a simple electromagnetic device in which an induced emf is produced by a changing magnetic flux through an area defined by a current loop (i.e., a simple microphone or generator) or of the effect on behavior of a device in which an induced emf is produced by a constant magnetic field through a changing area. **[See Science Practice 6.4]**

PHYSICS 2

Essential Knowledge 4.E.3: The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.

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

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

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

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

Learning Objective (4.E.3.1):
The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction.
[See Science Practice 6.4]

Learning Objective (4.E.3.2):
The student is able to make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects.
[See Science Practices 6.4 and 7.2]

Learning Objective (4.E.3.3):
The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors.
[See Science Practices 1.1, 1.4, and 6.4]

Learning Objective (4.E.3.4):
The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction.
[See Science Practices 1.1, 1.4, and 6.4]

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PHYSICS 2

Learning Objective (4.E.3.5):
The student is able to plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure.
[See Science Practices 3.2, 4.1, 4.2, 5.1, and 5.3]

PHYSICS 2

Essential Knowledge 4.E.4: The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.

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

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

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

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

Learning Objective (4.E.4.1):
The student is able to make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships.
[See Science Practices 2.2 and 6.4]

Learning Objective (4.E.4.2):
The student is able to design a plan for the collection of data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors.
[See Science Practices 4.1 and 4.2]

Learning Objective (4.E.4.3):
The student is able to analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors.
[See Science Practice 5.1]

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PHYSICS 2

Essential Knowledge 4.E.5: The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors.

Learning Objective (4.E.5.1):
The student is able to make and justify a quantitative prediction of the effect of a change in values or arrangements of one or two circuit elements on the currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel.
[**See Science Practices 2.2 and 6.4**]

Learning Objective (4.E.5.2):
The student is able to make and justify a qualitative prediction of the effect of a change in values or arrangements of one or two circuit elements on currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel.
[**See Science Practices 6.1 and 6.4**]

Learning Objective (4.E.5.3):
The student is able to plan data collection strategies and perform data analysis to examine the values of currents and potential differences in an electric circuit that is modified by changing or rearranging circuit elements, including sources of emf, resistors, and capacitors.
[**See Science Practices 2.2, 4.2, and 5.1**]

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

Conservation laws constrain the possible behaviors of the objects in a system of any size, or the outcome of an interaction or a process. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, conservation laws constrain the possible configurations of a system. Among many conservation laws, several apply across all scales. Conservation of energy is pervasive across all areas of physics and across all the sciences. All processes in nature conserve the net electric charge. Whether interactions are elastic or inelastic, linear momentum and angular momentum are conserved. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

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.

Conservation laws constrain the possible motions of the objects in a system of any size, or the outcome of an interaction or a process. For example, thinking about physical systems from the perspective of Newton's second law, each object changes its motion at any instant in response to external forces and torques, its response constrained only by its inertial mass and the distribution of that mass. However, with even a few objects in a system, tracking the motions becomes very complex. Associated with every conservation law is a physical quantity, a scalar or a vector, which characterizes a system. In a closed system, that quantity has a constant value, independent of interactions between objects in the system for all configurations of the system. In an open system, the changes of that quantity are always equal to the transfer of that quantity to or from the system by all possible interactions with other systems. Thus, the conservation law constrains the possible configurations of a system. When analyzing a physical situation, the choice of a system and the expression of the conservation laws provide a quick and powerful set of tools to express mathematical constraints relating the variables in the system.

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PHYSICS 1

Essential Knowledge 5.A.1: A system is an object or a collection of objects. The objects are treated as having no internal structure.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 1

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.

Learning Objective (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.
[**See Science Practices 6.4 and 7.2**]

PHYSICS 1

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.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 1

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.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

Enduring Understanding 5.B: The energy of a system is conserved.

Of all the conservation laws, the conservation of energy is the most pervasive across all areas of physics and across all the sciences. Conservation of energy occurs in all physical, chemical, biological, and environmental processes, and these isolated ideas are connected by this enduring understanding. Several of the concepts included under this enduring understanding are statements about the conservation of energy: Kirchhoff's loop rule for electric circuits, Bernoulli's equation for fluids, and the change in internal energy of a thermodynamic system due to heat or work. In nuclear processes, interconversion of energy and mass occurs, and the conservation principle is extended.

Energy is conserved in any system, whether that system is physical, biological, or chemical. An object can have kinetic energy; systems can have kinetic energy; but, if they have internal structure, changes in that internal structure can result in changes in internal energy and potential energy. If a closed system's potential energy or internal energy changes, that energy change can result in changes to the system's kinetic energy. In systems that are open to energy transfer, changes in the total energy can be due to external forces (work is done), thermal contact processes (heating occurs), or to emission or absorption of photons (radiative processes). Energy transferred into or out of a system can change kinetic, potential, and internal energies of the system. These exchanges provide information about properties of the system. If photons are emitted or absorbed, then there is a change in the energy states for atoms in the system.

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

PHYSICS 1

Essential Knowledge 5.B.1: Classically, an object can only have kinetic energy since potential energy requires an interaction between two or more objects.

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

Learning Objective (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.
[See Science Practice 1.5]

PHYSICS 1 PHYSICS 2

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.]

Learning Objective (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.
[See Science Practices 1.4 and 2.1]

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PHYSICS 1

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.

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.

b. Changes in the internal structure can result in changes in potential energy. Examples should include mass-spring oscillators, objects falling in a gravitational field.

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.]

Learning Objective (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.
[See Science Practices 2.2, 6.4, and 7.2]

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

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PHYSICS 1 | PHYSICS 2

Essential Knowledge 5.B.4: The internal energy of a system includes the kinetic energy of the objects that make up the system and the potential energy of the configuration of the objects that make up the system.

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

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

Learning Objective (5.B.4.1):
The student is able to describe and make predictions about the internal energy of systems.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 1.4, 2.1, and 2.2]

PHYSICS 1 | PHYSICS 2

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.]

Learning Objective (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.
[See Science Practices 4.2 and 5.1]

PHYSICS 1

Learning Objective (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.
[See Science Practices 4.2 and 5.1]

Learning Objective (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.
[See Science Practices 1.4, 2.2, and 6.4]

PHYSICS 2

Learning Objective (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).
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 2.2 and 6.4]

Learning Objective (5.B.5.6):
The student is able to design an experiment and analyze graphical data in which interpretations of the area under a pressure-volume curve are needed to determine the work done on or by the object or system.
[See Science Practices 4.2 and 5.1]

PHYSICS 2

Essential Knowledge 5.B.6: Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.

Learning Objective (5.B.6.1):
The student is able to describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation.
[See Science Practice 1.2]

PHYSICS 2

Essential Knowledge 5.B.7: The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples should include P-V diagrams — isovolumetric process, isothermal process, isobaric process, adiabatic process. No calculations of heat or internal energy from temperature change; and in this course, examples of these relationships are qualitative and/or semi-quantitative.

Learning Objective (5.B.7.1):
The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles.
[See Science Practices 6.4 and 7.2]

Learning Objective (5.B.7.2):
The student is able to create a plot of pressure versus volume for a thermodynamic process from given data.
[See Science Practice 1.1]

Learning Objective (5.B.7.3):
The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics).
[See Science Practices 1.1, 1.4, and 2.2]

PHYSICS 2

Essential Knowledge 5.B.8: Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei.

a. Transitions between two given energy states of an atom correspond to the absorption or emission of a photon of a given frequency (and hence, a given wavelength).

b. An emission spectrum can be used to determine the elements in a source of light.

Learning Objective (5.B.8.1):
The student is able to describe emission or absorption spectra associated with electronic or nuclear transitions as transitions between allowed energy states of the atom in terms of the principle of energy conservation, including characterization of the frequency of radiation emitted or absorbed.
[See Science Practices 1.2 and 7.2]

PHYSICS 1 PHYSICS 2

Essential Knowledge 5.B.9: Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.

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

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

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

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

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

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PHYSICS 1

Learning Objective (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).
[See Science Practices 1.1 and 1.4]

Learning Objective (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 ($\sum \Delta V = 0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches.
[See Science Practices 4.2, 6.4, and 7.2]

Learning Objective (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.
[See Science Practices 2.2, 6.4, and 7.2]

PHYSICS 2

Learning Objective (5.B.9.4):
The student is able to analyze experimental data including an analysis of experimental uncertainty that will demonstrate the validity of Kirchhoff's loop rule ($\sum \Delta V = 0$).
[See Science Practice 5.1]

Learning Objective (5.B.9.5):
The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors.
[See Science Practice 6.4]

Learning Objective (5.B.9.6):
The student is able to mathematically express the changes in electric potential energy of a loop in a multiloop electrical circuit and justify this expression using the principle of the conservation of energy.
[See Science Practices 2.1 and 2.2]

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PHYSICS 2

Learning Objective (5.B.9.7):
The student is able to refine and analyze a scientific question for an experiment using Kirchhoff's Loop rule for circuits that includes determination of internal resistance of the battery and analysis of a non-ohmic resistor.
[See Science Practices 4.1, 4.2, 5.1, and 5.3]

Learning Objective (5.B.9.8):
The student is able to translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor.
[See Science Practice 1.5]

PHYSICS 2

Essential Knowledge 5.B.10: Bernoulli's equation describes the conservation of energy in fluid flow.

Learning Objective (5.B.10.1):
The student is able to use Bernoulli's equation to make calculations related to a moving fluid.
[See Science Practice 2.2]

Learning Objective (5.B.10.2):
The student is able to use Bernoulli's equation and/or the relationship between force and pressure to make calculations related to a moving fluid.
[See Science Practice 2.2]

Learning Objective (5.B.10.3):
The student is able to use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid.
[See Science Practice 2.2]

Learning Objective (5.B.10.4):
The student is able to construct an explanation of Bernoulli's equation in terms of the conservation of energy.
[See Science Practice 6.2]

PHYSICS 2

Essential Knowledge 5.B.11: Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.

a. $E = mc^2$ can be used to calculate the mass equivalent for a given amount of energy transfer or an energy equivalent for a given amount of mass change (e.g., fission and fusion reactions).

Learning Objective (5.B.11.1):
The student is able to apply conservation of mass and conservation of energy concepts to a natural phenomenon and use the equation $E = mc^2$ to make a related calculation.
[See Science Practices 2.2 and 7.2]

Enduring Understanding 5.C: The electric charge of a system is conserved.

Conservation of electric charge is a fundamental conservation principle in physics. All processes in nature conserve the net electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves around a circuit or from place to place within a circuit. Any increase or decrease in the net charge in one region is compensated for by a corresponding decrease or increase in the net charge in other regions. In electrostatics, it is common for electrons to move from one object to another, and the number of electrons that leave one object is always equal to the number of electrons that move onto other objects. In some reactions such as radioactive decay or interactions involving elementary particles, it is possible for the number of electrically charged particles after a reaction or decay to be different from the number before. However, the *net* charge before and after is always equal. So, if a process produces a "new" electron that was not present before the reaction, then a "new" positive charge must also be created so that the net charge is the same before and after the process.

Essential Knowledge 5.C.1: Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples should include equations representing nuclear decay.

PHYSICS 2

Learning Objective (5.C.1.1):
The student is able to analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge.
[See Science Practices 6.4 and 7.2]

Essential Knowledge 5.C.2: The exchange of electric charges among a set of objects in a system conserves electric charge.

a. Charging by conduction between objects in a system conserves the electric charge of the entire system.
b. Charge separation in a neutral system can be induced by an external charged object placed close to the neutral system.
c. Grounding involves the transfer of excess charge to another larger system (e.g., the earth).

PHYSICS 2

Learning Objective (5.C.2.1):
The student is able to predict electric charges on objects within a system by application of the principle of charge conservation within a system.
[See Science Practice 6.4]

Learning Objective (5.C.2.2):
The student is able to design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data.
[See Science Practices 4.2 and 5.1]

Learning Objective (5.C.2.3):
The student is able to justify the selection of data relevant to an investigation of the electrical charging of objects and electric charge induction on neutral objects.
[See Science Practice 4.1]

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PHYSICS 1

PHYSICS 2

Essential Knowledge 5.C.3: Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Since charge is conserved, current must be conserved at each junction in the circuit. Examples should 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.]

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 4.1, 4.2, and 5.1]

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

PHYSICS 2

Learning Objective (5.C.3.4):
The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Learning Objective (5.C.3.5):
The student is able to determine missing values and direction of electric current in branches of a circuit with resistors and NO capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule.
[See Science Practices 1.4 and 2.2]

Learning Objective (5.C.3.6):
The student is able to determine missing values and direction of electric current in branches of a circuit with both resistors and capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule.
[See Science Practices 1.4 and 2.2]

Learning Objective (5.C.3.7):
The student is able to determine missing values, direction of electric current, charge of capacitors at steady state, and potential differences within a circuit with resistors and capacitors from values and directions of current in other branches of the circuit.
[See Science Practices 1.4 and 2.2]

Enduring Understanding 5.D: The linear momentum of a system is conserved.

Conservation of linear momentum is another of the important conservation laws. This law holds at all scales from the subatomic scale to the galactic scale. Linear momentum in a system isolated from external forces is constant. Interactions with other objects or systems can change the total linear momentum of a system. Such changes are discussed in Enduring Understandings 3.D and 4.B.

When objects collide, the collisions can be elastic or inelastic. In both types of collisions linear momentum is conserved. The elastic collision of non-rotating objects describes those cases in which the linear momentum stays constant and the kinetic and internal energies of the system are the same before and after the collision. The inelastic collision of objects describes those cases in which the linear momentum stays constant and the kinetic and internal energies of the objects are different before and after the collision.

The velocity of the center of mass of the system cannot be changed by an interaction within the system. In an isolated system that is initially stationary, the location of the center of mass is fixed. When two objects collide, the velocity of their center of mass will not change.

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

PHYSICS 1

PHYSICS 2

Essential Knowledge 5.D.1: In a collision between objects, linear momentum is conserved. In an elastic collision, kinetic energy is the same before and after.

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

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

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 2.2, 3.2, 5.1, and 5.3]

Learning Objective (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.
[See Science Practices 2.1 and 2.2]

Learning Objective (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.
[See Science Practices 4.2, 5.1, 5.3, and 6.4]

PHYSICS 1

Learning Objective (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.
[See Science Practices 2.1 and 2.2]

PHYSICS 2

Learning Objective (5.D.1.6):
The student is able to make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed.
[See Science Practice 6.4]

Learning Objective (5.D.1.7):
The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values.
[See Science Practices 2.1 and 2.2]

PHYSICS 1

PHYSICS 2

Essential Knowledge 5.D.2: In a collision between objects, linear momentum is conserved. In an inelastic collision, kinetic energy is not the same before and after the collision.

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

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

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 4.1, 4.2, and 5.1]

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 4.1, 4.2, 4.4, 5.1, and 5.3]

PHYSICS 2

Learning Objective (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.
[See Science Practices 2.1 and 2.2]

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PHYSICS 2

Learning Objective (5.D.2.6):
The student is able to apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy.
[See Science Practices 6.4 and 7.2]

PHYSICS 1 PHYSICS 2

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.]

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.

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.

Learning Objective (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).
[See Science Practice 6.4]

PHYSICS 2

Learning Objective (5.D.3.2):
The student is able to make predictions about the velocity of the center of mass for interactions within a defined one-dimensional system.
[See Science Practice 6.4]

Learning Objective (5.D.3.3):
The student is able to make predictions about the velocity of the center of mass for interactions within a defined two-dimensional system.
[See Science Practice 6.4]

Enduring Understanding 5.E: The angular momentum of a system is conserved.

The conservation of angular momentum is a consequence of the symmetry of physical laws under rotation, which means that if everything relevant to an experiment is turned through some angle, the results of the experiment will be the same. In nature, conservation of angular momentum helps to explain the vortex of the bathtub drain; the rotation of ocean currents; the changing spin of a dancer, a skater, a gymnast, and a diver; the direction of rotation of cyclonic weather systems; and the roughly planar arrangement of planetary systems and galaxies. The angular momentum of a rigid system of objects allows us to describe the linked trajectories of the many objects in the system with a single number, which is unchanging when no external torques are applied. Choosing such a closed system for analyzing a rotational situation allows many problems to be solved by equating the total angular momentum in two configurations of the system. Students will be provided with the value for rotational inertia or formula to calculate rotational inertia where necessary.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

Learning Objective (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.
[See Science Practices 2.1 and 2.2]

PHYSICS 1

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 should 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.

Learning Objective (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.
[See Science Practice 2.2]

Enduring Understanding 5.F: Classically, the mass of a system is conserved.

The conservation of mass is an important principle that holds up to a certain energy scale where the concepts of mass and energy need to be combined. In this course, conservation of mass is assumed in most problems. Thus, when using $\vec{a} = \frac{\Sigma\vec{F}}{m}$, etc., conservation of mass is assumed.

An ideal example of this conservation law is found in the continuity equation, which describes conservation of mass flow rate in fluids. If no mass is entering or leaving a system, then the mass must be constant. If an enclosed fluid flow is uniform and the fluid is also incompressible, then the mass entering an area must be equal to the mass leaving an area. Fluid flow in engineering and in biological systems can be modeled starting with this enduring understanding but requires the addition of fluid viscosity for a complete treatment, which is not a part of this course.

Essential Knowledge 5.F.1: The continuity equation describes conservation of mass flow rate in fluids. Examples should include volume rate of flow, mass flow rate.

Learning Objective (5.F.1.1):
The student is able to make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation).
[See Science Practices 2.1, 2.2, and 7.2]

PHYSICS 2

Enduring Understanding 5.G: Nucleon number is conserved.

The conservation of nucleon number, according to which the number of nucleons (protons and neutrons) doesn't change, applies to nuclear reactions and decays including fission, fusion, alpha decay, beta decay, and gamma decay. This conservation law, along with conservation of electric charge, is the basis for balancing nuclear equations.

Essential Knowledge 5.G.1: The possible nuclear reactions are constrained by the law of conservation of nucleon number.

Learning Objective (5.G.1.1):
The student is able to apply conservation of nucleon number and conservation of electric charge to make predictions about nuclear reactions and decays such as fission, fusion, alpha decay, beta decay, or gamma decay.
[See Science Practice 6.4]

PHYSICS 2

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.

Classically, waves are a "disturbance" that propagates through space. Mechanical waves are a disturbance of a mechanical medium such as a string, a solid, or a gas, and they carry energy and momentum from one place to another without any net motion of the medium. Electromagnetic waves are a different type of wave; in this case, the disturbance is in the electromagnetic field itself, and therefore requires no medium. Electromagnetic waves also carry energy and momentum. In most cases, multiple waves can propagate through a medium independently of each other. Two waves do not "collide" as would objects traveling through the same region of space. Waves "pass through" each other, according to the principle of superposition and a phenomenon called interference. Important examples of wave motion are sound (a mechanical wave that can propagate in gases, liquids, and solids), and light (which can be modeled as electromagnetic waves to which our eyes are sensitive). In the quantum regime, all particles can be modeled as waves, although the wavelike behavior is only observable under certain conditions — for example, an electron in an atom behaves in some ways like a classical particle and in other ways like a classical wave.

Boundary Statement: Physics 1 will treat 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.

Enduring Understanding 6.A: A wave is a traveling disturbance that transfers energy and momentum.

When an object moves as a projectile from one place to another, it possesses kinetic energy and momentum. Such a process thus transfers energy and momentum, and also mass, from place to place. A wave is a disturbance that carries energy and momentum from one place to another without the transfer of mass. Some waves are mechanical in nature — this means that they are a disturbance of a mechanical system such as a solid, a liquid, or a gas; this system is called the medium through which the wave travels. Mechanical waves are then described in terms of the way they disturb or displace their medium. The propagation properties of the mechanical wave, such as the wave speed, also depend on the properties of the medium. Electromagnetic waves do not require a mechanical medium. They are instead associated with oscillating electric and magnetic fields. Electromagnetic waves can travel through a mechanical medium, such as a solid, but they can also travel through a vacuum.

PHYSICS 1 | PHYSICS 2

Essential Knowledge 6.A.1: Waves can propagate via different oscillation modes such as transverse and longitudinal.

PHYSICS 1

a. Mechanical waves can be either transverse or longitudinal. Examples should include waves on a stretched string and sound waves.

PHYSICS 2

b. Electromagnetic waves are transverse waves.

c. Transverse waves may be polarized.

PHYSICS 1

Learning Objective (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.
[See Science Practice 6.2]

PHYSICS 1 | PHYSICS 2

Learning Objective (6.A.1.2):
The student is able to describe representations of transverse and longitudinal waves.
[See Science Practice 1.2]

PHYSICS 2

Learning Objective (6.A.1.3):
The student is able to analyze data (or a visual representation) to identify patterns that indicate that a particular mechanical wave is polarized and construct an explanation of the fact that the wave must have a vibration perpendicular to the direction of energy propagation.
[See Science Practices 5.1 and 6.2]

PHYSICS 1 PHYSICS 2

Essential Knowledge 6.A.2: For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples should include light traveling through a vacuum and sound not traveling through a vacuum.

PHYSICS 1

Learning Objective (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.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Learning Objective (6.A.2.2):
The student is able to contrast mechanical and electromagnetic waves in terms of the need for a medium in wave propagation.
[See Science Practices 6.4 and 7.2]

PHYSICS 1

Essential Knowledge 6.A.3: The amplitude is the maximum displacement of a wave from its equilibrium value.

Learning Objective (6.A.3.1):
The student is able to use graphical representation of a periodic mechanical wave to determine the amplitude of the wave.
[See Science Practice 1.4]

PHYSICS 1

Essential Knowledge 6.A.4: Classically, the energy carried by a wave depends upon and increases with amplitude. Examples should include sound waves.

Learning Objective (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.
[See Science Practice 6.4]

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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.

The properties of periodic waves are important to understanding wave phenomena in the world around us. These properties are amplitude, frequency, period, speed of the wave in a particular medium, wavelength, and energy. A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave. Wave speeds depend upon the properties of the medium, but the speed of a wave is generally independent of the frequency and wavelength of the wave. The speed of an electromagnetic wave in a vacuum is a constant, usually referred to as *c*. In other materials, the apparent speed of an electromagnetic wave depends on properties of the material.

The frequency of a wave, as perceived by observers, depends upon the relative motion of the source and the observer. If the relative motions of the source and observer are away from each other, the perceived frequency decreases. If the relative motions of the source and observer are toward each other, the perceived frequency increases. This change in observed frequency or wavelength is known as the Doppler effect and finds uses from astronomy to medicine to radar speed traps.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practices 1.4 and 2.2]

PHYSICS 1

Essential Knowledge 6.B.2: For a periodic wave, the wavelength is the repeat distance of the wave.

Learning Objective (6.B.2.1):
The student is able to use a visual representation of a periodic mechanical wave to determine wavelength of the wave.
[See Science Practice 1.4]

PHYSICS 2

Essential Knowledge 6.B.3: A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave.

Learning Objective (6.B.3.1):
The student is able to construct an equation relating the wavelength and amplitude of a wave from a graphical representation of the electric or magnetic field value as a function of position at a given time instant and vice versa, or construct an equation relating the frequency or period and amplitude of a wave from a graphical representation of the electric or magnetic field value at a given position as a function of time and vice versa.
[See Science Practice 1.5]

PHYSICS 1

Essential Knowledge 6.B.4: For a periodic wave, wavelength is the ratio of speed over frequency.

Learning Objective (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.
[See Science Practices 4.2, 5.1, and 7.2]

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 1.4]

Enduring Understanding 6.C: Only waves exhibit interference and diffraction.

When two or more waves move through the same space, the displacement at a particular point is a result of the superposition or sum of the displacements due to each of the waves. Depending on the direction of propagation of the waves from the various sources and their phase or

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time relationship to each other, this principle explains a large variety of phenomena, including standing waves in a musical instrument, rogue waves at sea, and the colors seen in soap bubbles. Where the crest of one wave coincides with the crest of another wave, constructive interference occurs, producing large amplitude oscillations. Where crest meets trough, cancellation or destructive interference occurs. Since the oscillation at a particular point can be treated as a source of waves spreading from that point (Huygens's principle), as waves pass through openings or around objects that are of sizes comparable to the wavelength, we observe that waves can spread or diffract out into the space beyond the edge or obstacle, which accounts, among other things, for our ability to hear around corners, but not see around them.

PHYSICS 2

Essential Knowledge 6.C.1: When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called superposition.

Learning Objective (6.C.1.1):
The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples should include standing waves.
[**See Science Practices 6.4 and 7.2**]

Learning Objective (6.C.1.2):
The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition.
[**See Science Practice 1.4**]

PHYSICS 2

Essential Knowledge 6.C.2: When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.

Learning Objective (6.C.2.1):
The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening, and to qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave. [**See Science Practices 1.4, 6.4, and 7.2**]

Essential Knowledge 6.C.3: When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples should include monochromatic double-slit interference.

PHYSICS 2

Learning Objective (6.C.3.1):
The student is able to qualitatively apply the wave model to quantities that describe the generation of interference patterns to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small compared to the wavelength of the waves.
[See Science Practices 1.4 and 6.4]

Essential Knowledge 6.C.4: When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples should include hearing around corners, but not seeing around them, and water waves bending around obstacles.

PHYSICS 2

Learning Objective (6.C.4.1):
The student is able to predict and explain, using representations and models, the ability or inability of waves to transfer energy around corners and behind obstacles in terms of the diffraction property of waves in situations involving various kinds of wave phenomena, including sound and light.
[See Science Practices 6.4 and 7.2]

Enduring Understanding 6.D: Interference and superposition lead to standing waves and beats.

Interference and superposition of waves find application in many areas. These include musical instruments, lasers, medical imaging, and the search for gravitational waves. Two wave pulses can overlap to produce amplitude variations in the resultant wave. At the moment of overlap, the displacement at each point can be determined by superposition, adding the displacements at each point due to the individual pulses. This principle applies to all waves from pulses to traveling periodic waves.

When incident and reflected traveling waves are confined to a region, their superposition or addition can result in standing waves with constructive and destructive interference at different points in space. Examples include waves on a fixed length of string, and sound waves in a tube. When two waves of slightly different frequency superimpose, their superposition or addition can result in beats with constructive and destructive interference at different points in time. Standing waves and beats are important phenomena in music.

PHYSICS 1

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.

Learning Objective (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.
[See Science Practices 1.1 and 1.4]

Learning Objective (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).
[See Science Practices 4.2 and 5.1]

Learning Objective (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.
[See Science Practice 4.2]

PHYSICS 1

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.

Learning Objective (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.
[See Science Practice 5.1]

PHYSICS 1

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 should include waves on a fixed length of string, and sound waves in both closed and open tubes.

Learning Objective (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.
[**See Science Practices 2.1, 3.2, and 4.2**]

Learning Objective (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.
[**See Science Practice 6.4**]

Learning Objective (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.
[**See Science Practices 3.2, 4.1, 5.1, 5.2, and 5.3**]

Learning Objective (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.
[**See Science Practice 1.2**]

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PHYSICS 1

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.

a. A standing wave with zero amplitude at both ends can only have certain wavelengths. Examples should include fundamental frequencies and harmonics.

b. Other boundary conditions or other region sizes will result in different sets of possible wavelengths.

Learning Objective (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.
[See Science Practices 1.5 and 6.1]

Learning Objective (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 should include musical instruments.
[See Science Practice 2.2]

PHYSICS 1

Essential Knowledge 6.D.5: Beats arise from the addition of waves of slightly different frequency.

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 should include the tuning of an instrument.

b. The beat frequency is the difference in frequency between the two waves.

Learning Objective (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.
[See Science Practice 1.2]

Enduring Understanding 6.E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.

The propagation of a wave depends on the properties of the medium or region through which the wave travels. The speed of a wave, including electromagnetic waves such as light, depends on the material through which it travels. When light (or any other type of wave) travels from one material to another, the frequency remains the same, but the change in wave speed causes a change in the propagation direction, described by Snell's law. This change in direction is termed refraction when light passes through an interface. Reflection occurs when part or all of a wave bounces back from the interface. Both reflection and refraction can be used to form images. The study of image formation with light is called geometrical optics and involves the properties of images formed with mirrors and lenses.

PHYSICS 2

Essential Knowledge 6.E.1: When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed. (Qualitative understanding only.)

Learning Objective (6.E.1.1):
The student is able to make claims using connections across concepts about the behavior of light as the wave travels from one medium into another, as some is transmitted, some is reflected, and some is absorbed.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Essential Knowledge 6.E.2: When light hits a smooth reflecting surface at an angle, it reflects at the same angle on the other side of the line perpendicular to the surface (specular reflection); and this law of reflection accounts for the size and location of images seen in plane mirrors.

Learning Objective (6.E.2.1):
The student is able to make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Essential Knowledge 6.E.3: When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.

a. Snell's law relates the angles of incidence and refraction to the indices of refraction, with the ratio of the indices of refraction inversely proportional to the ratio of the speeds of propagation in the two media.

b. When light travels from an optically slower substance into an optically faster substance, it bends away from the perpendicular.

c. At the critical angle, the light bends far enough away from the perpendicular that it skims the surface of the material.

d. Beyond the critical angle, all of the light is internally reflected.

Learning Objective (6.E.3.1):
The student is able to describe models of light traveling across a boundary from one transparent material to another when the speed of propagation changes, causing a change in the path of the light ray at the boundary of the two media.
[See Science Practices 1.1 and 1.4]

Learning Objective (6.E.3.2):
The student is able to plan data collection strategies as well as perform data analysis and evaluation of the evidence for finding the relationship between the angle of incidence and the angle of refraction for light crossing boundaries from one transparent material to another (Snell's law).
[See Science Practices 4.1, 5.1, 5.2, and 5.3]

Learning Objective (6.E.3.3):
The student is able to make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation.
[See Science Practices 6.4 and 7.2]

PHYSICS 2

Essential Knowledge 6.E.4: The reflection of light from surfaces can be used to form images.

a. Ray diagrams are very useful for showing how and where images of objects are formed for different mirrors, and how this depends upon the placement of the object. Concave and convex mirror examples should be included.

b. They are also useful for determining the size of the resulting image compared to the size of the object.

c. Plane mirrors, convex spherical mirrors, and concave spherical mirrors are part of this course. The construction of these ray diagrams and comparison with direct experiences are necessary.

Learning Objective (6.E.4.1):
The student is able to plan data collection strategies, and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors. [**See Science Practices 3.2, 4.1, 5.1, 5.2, and 5.3**]

Learning Objective (6.E.4.2):
The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces. [**See Science Practices 1.4 and 2.2**]

PHYSICS 2

Essential Knowledge 6.E.5: The refraction of light as it travels from one transparent medium to another can be used to form images.

a. Ray diagrams are used to determine the relative size of object and image, the location of object and image relative to the lens, the focal length, and the real or virtual nature of the image. Converging and diverging lenses should be included as examples.

Learning Objective (6.E.5.1):
The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses.
[See Science Practices 1.4 and 2.2]

Learning Objective (6.E.5.2):
The student is able to plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses.
[See Science Practices 3.2, 4.1, 5.1, 5.2, and 5.3]

Enduring Understanding 6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.

One of the great discoveries of modern physics is that electromagnetic radiation, modeled in the 19th century as a classical wave, also has particle-like properties that are best captured by a hybrid model in which light is neither waves nor particles. In this hybrid, quantum model of electromagnetic spectra, photons are individual energy packets of electromagnetic waves. The discrete spectra of atoms are evidence that supports the quantum model of electromagnetic spectra. The nature of light requires that a different model of light is most appropriate at different scales. Interference is a property of waves, and radio waves traveling different paths can interfere with each other causing “dead spots” — areas of limited reception. The behavior of waves through a slit or set of slits is discussed in 6.C. Wavelengths of electromagnetic radiation range from extremely small to extremely large.

PHYSICS 2

Essential Knowledge 6.F.1: Types of electromagnetic radiation are characterized by their wavelengths, and certain ranges of wavelength have been given specific names. These include (in order of increasing wavelength spanning a range from picometers to kilometers) gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.

Learning Objective (6.F.1.1):
The student is able to make qualitative comparisons of the wavelengths of types of electromagnetic radiation.
[**See Science Practices 6.4 and 7.2**]

PHYSICS 2

Essential Knowledge 6.F.2: Electromagnetic waves can transmit energy through a medium and through a vacuum.

a. Electromagnetic waves are transverse waves composed of mutually perpendicular electric and magnetic fields that can propagate through a vacuum.

b. The planes of these transverse waves are both perpendicular to the direction of propagation.

Learning Objective (6.F.2.1):
The student is able to describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present.
[**See Science Practices 1.1**]

Essential Knowledge 6.F.3: Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck's constant and f is the frequency of the associated light wave.

a. In the quantum model of electromagnetic radiation, the energy is emitted or absorbed in discrete energy packets called photons. Discrete spectral lines should be included as an example.

b. For the short-wavelength portion of the electromagnetic spectrum, the energy per photon can be observed by direct measurement when electron emissions from matter result from the absorption of radiant energy.

c. Evidence for discrete energy packets is provided by a frequency threshold for electron emission. Above the threshold, emission increases with the frequency and not the intensity of absorbed radiation. The photoelectric effect should be included as an example.

PHYSICS 2

Learning Objective (6.F.3.1)
The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect.
[See Science Practice 6.4]

Essential Knowledge 6.F.4: The nature of light requires that different models of light are most appropriate at different scales.

a. The particle-like properties of electromagnetic radiation are more readily observed when the energy transported during the time of the measurement is comparable to E_{photon}.

b. The wavelike properties of electromagnetic radiation are more readily observed when the scale of the objects it interacts with is comparable to or larger than the wavelength of the radiation.

PHYSICS 2

Learning Objective (6.F.4.1)
The student is able to select a model of radiant energy that is appropriate to the spatial or temporal scale of an interaction with matter.
[See Science Practices 6.4 and 7.1]

Enduring Understanding 6.G: All matter can be modeled as waves or as particles.

At the human scale, a thrown rock moves through space on a well-defined path. The moving object carries momentum and energy that are transferred on impact to another object or system. A splash in a pond creates a disturbance in the water, spreading in all directions and transferring energy and momentum without transferring mass. These two different forms of interaction have historically served as the metaphors that we attempt to use to explain the physical phenomena we observe. Abstracted into sophisticated mathematical models, they give highly precise predictions at the human scale. However, at other vastly different scales of size and energy, we find that neither model is an exact fit for the phenomena. Instead, we find that each of the metaphors works well to model some aspects of a situation while failing to model other aspects. The successful mathematical treatment of quantum mechanics combining mathematics derived from both metaphors goes beyond either to accurately describe phenomena at the quantum scale but leaves us without any simple visual metaphor from our everyday experience. The wave representing a particle indicates the probability of locating that particle at a particular place in space and time. This course treats these wave representations in a qualitative fashion.

PHYSICS 2

Essential Knowledge 6.G.1: Under certain regimes of energy or distance, matter can be modeled as a classical particle.

Learning Objective (6.G.1.1)
The student is able to make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate.
[See Science Practices 6.4 and 7.1]

Essential Knowledge 6.G.2: Under certain regimes of energy or distance, matter can be modeled as a wave. The behavior in these regimes is described by quantum mechanics.

a. A wave model of matter is quantified by the de Broglie wavelength that increases as the momentum of the particle decreases.

b. The wave property of matter was experimentally confirmed by the diffraction of electrons in the experiments of Clinton Joseph Davisson, Lester Germer, and George Paget Thomson.

Physics 2

Learning Objective (6.G.2.1)
The student is able to articulate the evidence supporting the claim that a wave model of matter is appropriate to explain the diffraction of matter interacting with a crystal, given conditions where a particle of matter has momentum corresponding to a de Broglie wavelength smaller than the separation between adjacent atoms in the crystal.
[See Science Practice 6.1]

Learning Objective (6.G.2.2)
The student is able to predict the dependence of major features of a diffraction pattern (e.g., spacing between interference maxima), based upon the particle speed and de Broglie wavelength of electrons in an electron beam interacting with a crystal. (de Broglie wavelength need not be given, so students may need to obtain it.)
[See Science Practice 6.4]

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

As developed by Newton, classical mechanics uses mathematics to deterministically calculate the motions of objects as a result of their interactions. Newton and his followers envisioned a universe in which the future could be calculated from the past. In practice, physicists soon found that only a small number of objects and interactions could be dealt with in such calculations. When a system includes many objects, such as the molecules in a gas, the mathematics of probability must be used to describe the system. Using probability, the properties of an ideal gas can be explained in terms of a small number of variables such as temperature and pressure. Furthermore, the evolution of isolated systems toward states of higher disorder can be explained using probability, giving one account of the "arrow of time."

When the physical size of a system is scaled down to atomic size, the mathematics of probability can be used to interpret the meaning of the wave model of matter. At this scale, we find that interactions between objects are fundamentally not deterministic as Newton envisioned, but can only be described by probabilities, which are calculated from a mathematical description of the wave called a wave function. This accounts for the observed wavelike properties. Although quantum physics is far from intuitive, the probabilistic description of matter at this scale has been fantastically successful in explaining the behavior of atoms and is now being applied at the frontiers of modern technology.

Enduring Understanding 7.A: The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure.

In a gas, all of the molecules are in constant motion, and there is a distribution of speeds. Individual speeds may be influenced by collisions with other molecules and with the walls of the container. In an ideal gas, this complicated behavior can be characterized by just a few variables: pressure (P), the combined result of the impacts of molecules; temperature (T), the average kinetic energy of the molecules; and volume (V). Statistical methods are used to relate the state variables of pressure and temperature to the distribution of velocities of the molecules. For the ideal gas model the equation $PV = nRT$ describes the relationship between the state variables.

In Maxwell's description of the connection between thermodynamic properties and atomic-scale motion, the rate of change of momentum at any surface, including that of the container that holds the gas, increases as temperature increases. Newton's second law expresses the rate of change of momentum as a force. Pressure is expressed as force per unit area.

The average kinetic energy of the gas molecules in the system is an average over a distribution of different speeds for individual molecules. The root mean square of the velocity is related to the temperature.

PHYSICS 2

Essential Knowledge 7.A.1: The pressure of a system determines the force that the system exerts on the walls of its container and is a measure of the average change in the momentum or impulse of the molecules colliding with the walls of the container. The pressure also exists inside the system itself, not just at the walls of the container.

Learning Objective (7.A.1.1):
The student is able to make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container, and how changes in pressure affect the thermal equilibrium of the system.
[See Science Practices 6.4 and 7.2]

Learning Objective (7.A.1.2):
Treating a gas molecule as an object (i.e., ignoring its internal structure), the student is able to analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, to quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables.
[See Science Practices 1.4 and 2.2]

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PHYSICS 2

Essential Knowledge 7.A.2: The temperature of a system characterizes the average kinetic energy of its molecules.

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

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

Learning Objective (7.A.2.1):
The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system.
[See Science Practice 7.1]

Learning Objective (7.A.2.2):
The student is able to connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and to relate this to thermodynamic processes.
[See Science Practice 7.1]

PHYSICS 2

Essential Knowledge 7.A.3: In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation $PV = nRT$.

Learning Objective (7.A.3.1):
The student is able to extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero.
[See Science Practices 6.4 and 7.2]

Learning Objective (7.A.3.2):
The student is able to design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables.
[See Science Practices 3.2 and 4.2]

Learning Objective (7.A.3.3):
The student is able to analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$.
[See Science Practice 5.1]

Enduring Understanding 7.B: The tendency of isolated systems to move toward states with higher disorder is described by probability.

The transfers of energy that occur in thermal processes depend on a very large number of very small-scale (molecular and atomic) interactions, and thus these energy transfers are best described by the mathematics of probability. When parts of an isolated system initially at different temperatures interact, higher momentum particles are more likely to be involved in more collisions. Consequently, conservation of momentum makes it more likely that kinetic energy will be transferred from higher energy to lower energy particles, reducing both the number of high energy particles and the number of low energy particles until, after many collisions, all interacting parts of a system will arrive at the same temperature. The amount of thermal energy needed to change the temperature of a given part of a system will depend on the total mass of that part of the system and on the difference between its initial and final temperatures. Neither energy conservation nor momentum conservation laws have any preferred direction in time, yet large-scale processes always tend toward equilibrium, and not toward disequilibrium. The second law of thermodynamics describes the tendency of large systems to move toward states with higher disorder. A new state function, entropy, can be defined, and it depends only on the configuration of the system and not on how the system arrived in that configuration. Unlike energy, entropy is not conserved but instead always increases for irreversible processes in closed systems.

PHYSICS 2

Essential Knowledge 7.B.1: The approach to thermal equilibrium is a probability process.

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

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

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

Learning Objective (7.B.1.1):
The student is able to construct an explanation, based on atomic-scale interactions and probability, of how a system approaches thermal equilibrium when energy is transferred to it or from it in a thermal process.
[See Science Practice 6.2]

PHYSICS 2

Essential Knowledge 7.B.2: The second law of thermodynamics describes the change in entropy for reversible and irreversible processes. Only a qualitative treatment is considered in this course.

a. Entropy, like temperature, pressure, and internal energy, is a state function, whose value depends only on the configuration of the system at a particular instant and not on how the system arrived at that configuration.

b. Entropy can be described as a measure of the disorder of a system, or of the unavailability of some system energy to do work.

c. The entropy of a closed system never decreases, i.e., it can stay the same or increase.

d. The total entropy of the universe is always increasing.

Learning Objective (7.B.2.1):
The student is able to connect qualitatively the second law of thermodynamics in terms of the state function called entropy and how it (entropy) behaves in reversible and irreversible processes. **[See Science Practice 7.1]**

Enduring Understanding 7.C: At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.

This enduring understanding follows on the heels of Enduring Understandings 1.D and 6.G. Students need to be aware that classical physics cannot describe everything and that there are new, nonclassical ideas that must be addressed for a more complete understanding of the physical world.

The dynamic properties of quantum mechanical systems are expressed in terms of probability distributions. At this scale, we find that interactions between objects are fundamentally not deterministic as Newton envisioned, but can only be described by probabilities, which are calculated from the wave function. This gives rise to observed wave properties of matter. One such property is that an electron in an atom has a discrete set of possible energy states. The energy states of the atom can be described in terms of allowable energy transitions due to emission or absorption of photons, processes that are determined by probability. These phenomena are the basis of lasers. The spontaneous radioactive decay of an individual nucleus is described by probability as well. Balancing of mass and charge in nuclear equations can be used to determine missing species in the equation, and to explain pair production and annihilation. These ideas can also be used to understand fission and fusion, one current and one possible future source of energy.

PHYSICS 2

Essential Knowledge 7.C.1: The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region. (Qualitative treatment only, using graphical analysis.)

Learning Objective (7.C.1.1):
The student is able to use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region.
[See Science Practice 1.4]

PHYSICS 2

Essential Knowledge 7.C.2: The allowed states for an electron in an atom can be calculated from the wave model of an electron.

a. The allowed electron energy states of an atom are modeled as standing waves. Transitions between these levels, due to emission or absorption of photons, are observable as discrete spectral lines.

b. The de Broglie wavelength of an electron can be calculated from its momentum, and a wave representation can be used to model discrete transitions between energy states as transitions between standing waves.

Learning Objective (7.C.2.1):
The student is able to use a standing wave model in which an electron orbit circumference is an integer multiple of the de Broglie wavelength to give a qualitative explanation that accounts for the existence of specific allowed energy states of an electron in an atom.
[See Science Practice 1.4]

PHYSICS 2

Essential Knowledge 7.C.3: The spontaneous radioactive decay of an individual nucleus is described by probability.

a. In radioactive decay processes, we cannot predict when any one nucleus will undergo a change; we can only predict what happens on the average to a large number of identical nuclei.

b. In radioactive decay, mass and energy are interrelated, and energy is released in nuclear processes as kinetic energy of the products or as electromagnetic energy.

c. The time for half of a given number of radioactive nuclei to decay is called the half-life.

d. Different unstable elements and isotopes have vastly different half-lives, ranging from small fractions of a second to billions of years.

Learning Objective (7.C.3.1):
The student is able to predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay.
[See Science Practice 6.4]

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PHYSICS 2

Essential Knowledge 7.C.4: Photon emission and absorption processes are described by probability.

a. An atom in a given energy state may absorb a photon of the right energy and move to a higher energy state (stimulated absorption).

b. An atom in an excited energy state may jump spontaneously to a lower energy state with the emission of a photon (spontaneous emission).

c. Spontaneous transitions to higher energy states have a very low probability but can be stimulated to occur. Spontaneous transitions to lower energy states are highly probable.

d. When a photon of the right energy interacts with an atom in an excited energy state, it may stimulate the atom to make a transition to a lower energy state with the emission of a photon (stimulated emission). In this case, both photons have the same energy and are in phase and moving in the same direction.

Learning Objective (7.C.4.1):
The student is able to construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that since the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.] **[See Science Practices 1.1 and 1.2]**

Science Practices for AP Physics 1 and 2

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.

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Science Practice 3: The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.

Research scientists pose and answer meaningful questions. Students may easily miss this point since, depending on how a science class is taught, it may seem that science is about compiling and passing down a large body of known facts (e.g., the acceleration of free-falling objects is 9.8 m/s^2; $\vec{a} = \frac{\Sigma\vec{F}}{m}$). At the opposite end of the spectrum, some students may believe that science can solve every important societal problem. Thus, helping students learn how to pose, refine, and evaluate scientific questions is an important instructional and cognitive goal, albeit a difficult skill to learn. Even within a simple physics topic, posing a scientific question can be difficult. When asked what they might want to find out about a simple pendulum, some students may ask, "How high does it swing?" Although this is a starting point from which a teacher may build, students need to be guided toward refining "fuzzy" questions and relating questions to relevant models and theories. As a first step to refining this question, students might first consider in what ways one can measure physical quantities relevant to the pendulum's motion, leading to a discussion of time, angle (amplitude), and mass. Follow–up discussions can lead to how one goes about evaluating questions such as, "Upon what does the period of a simple pendulum depend?" by designing and carrying out experiments, and then evaluating data and findings.

3.1 The student can *pose scientific questions.*

3.2 The student can *refine scientific questions.*

3.3 The student can *evaluate scientific questions.*

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

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

Scientific questions can range in scope from broad to narrow, as well as in specificity, from determining influencing factors and/or causes to determining mechanism. The question posed will determine the type of data to be collected and will influence the plan for collecting data. An example of a broad question is, "What caused the extinction of the dinosaurs?" whereas a narrow one is, "Upon what does the period of a simple pendulum depend?" Both questions ask for influencing factors and/or causes; an answer to the former might be "An asteroid collision with the 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 ten round-trips and divided by ten. Such discussions can reveal issues of measurement uncertainty and assumptions about the motion. Students need to understand that the result of collecting and using data to determine a numerical answer to a question is best thought of as an interval, not a single number. This interval, the experimental uncertainty, is due to a combination of uncertainty in the instruments used and the process of taking the measurement. Although detailed error analysis is not necessary to convey this pivotal idea, it is important that students make some reasoned estimate of the interval within which they know the value of a measured data point and express their results in a way that makes this clear.

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

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

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

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

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

Students often think that to make a graph they need to connect the data points or that the best–fit function is always linear. Thus it is important that they can construct a best–fit curve even for data that do not fit a linear relationship (such as quadratic or exponential functions).

Students should be able to represent data points as intervals whose size depends on the experimental uncertainty. After students find a pattern in the data they need to ask why this pattern is present and try to explain it using the knowledge that they have. When dealing with a new phenomenon, they should be able to devise a testable explanation of the pattern if possible (see Science Practice 6.4). It is important that students understand that instruments do not produce exact measurements and learn what steps they can take to decrease the uncertainty. Students should be able to design a second experiment to determine the same quantity and then check for consistency across the two measurements, comparing two results by writing them both as intervals and not as single, absolute numbers. Finally, students should be able to revise their reasoning based on the new data, data that for some may appear anomalous.

5.1 The student can *analyze data* to identify patterns or relationships.

5.2 The student can *refine observations and measurements* based on data analysis.

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

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

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

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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.

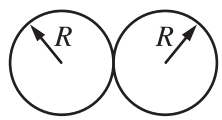
7.2 The student can *connect concepts* in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Sample Questions with Targeted Learning Objectives

The correlation between the curriculum framework and the AP Physics 1: Algebra-based and AP Physics 2: Algebra–based Exams is demonstrated in this section through a selection of multiple–choice and free–response questions. Each question clearly shows the targeted learning objective(s) from the curriculum framework. These sample questions will help illustrate how the learning objectives for both courses will be assessed and are comparable to what students will encounter on the actual exams.

AP Physics 1: Algebra–based Sample Exam Questions

Sample Multiple–Choice Questions



1. Two solid spheres of radius R made of the same type of steel are placed in contact, as shown in the figures above. The magnitude of the gravitational force that they exert on each other is F_1 . When two other solid spheres of radius $3R$ made of this steel are placed in contact, what is the magnitude of the gravitational force that they exert on each other?

   (A) F_1

   (B) $3F_1$

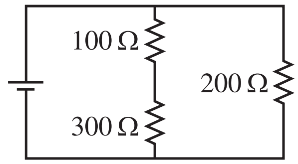
   (C) $9F_1$

   (D) $81F_1$

   Answer: D

Targeted Learning Objective:

Learning Objective (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. [See Science Practice 2.2]



2. The figure above shows three resistors connected in a circuit with a battery. Which of the following correctly ranks the energy E dissipated in the three resistors during a given time interval?

(A) $E_{300\Omega} > E_{200\Omega} > E_{100\Omega}$

(B) $E_{300\Omega} > E_{100\Omega} > E_{200\Omega}$

(C) $E_{200\Omega} > E_{300\Omega} > E_{100\Omega}$

(D) $E_{200\Omega} > E_{100\Omega} > E_{300\Omega}$

Answer: C

Targeted Learning Objectives:

Learning Objective (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. [See Science Practices 2.2, 6.4, and 7.2]

Learning Objective (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. [See Science Practices 6.4 and 7.2]

3. A person driving a car suddenly applies the brakes. The car takes 4 s to come to rest while traveling 20 m at constant acceleration. Can the speed of the car immediately before the brakes were applied be determined without first determining the car's acceleration?

   (A) Yes, by dividing the distance (20 m) by the time (4 s).

   (B) Yes, by determining the average speed while braking and doubling it.

   (C) No, because the acceleration is needed to use standard equations such as $\Delta x = v_o t + \frac{1}{2}at^2$.

   (D) No, because the fundamental relationship that defines velocity contains acceleration.

   Answer: B

Targeted Learning Objectives:

Learning Objective (3.A.1.1): The student is able to express the motion of an object using narrative, mathematical, and graphical representations. [See Science Practices 1.5, 2.1, and 2.2]

Learning Objective (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. [See Science Practice 6.4]

4. While traveling in its elliptical orbit around the Sun, Mars gains speed during the part of the orbit where it is getting closer to the Sun. Which of the following can be used to explain this gain in speed?

   (A) As Mars gets closer to the Sun, the Mars–Sun system loses potential energy and Mars gains kinetic energy.

   (B) A component of the gravitational force exerted on Mars is perpendicular to the direction of motion, causing an acceleration and hence a gain in speed along that direction.

   (C) The torque exerted on Mars by the Sun during this segment of the orbit increases the Mars–Sun system's angular momentum.

   (D) The centripetal force exerted on Mars is greater than the gravitational force during this segment of the orbit, causing Mars to gain speed as it gets closer to the Sun.

   Answer: A

Targeted Learning Objectives:

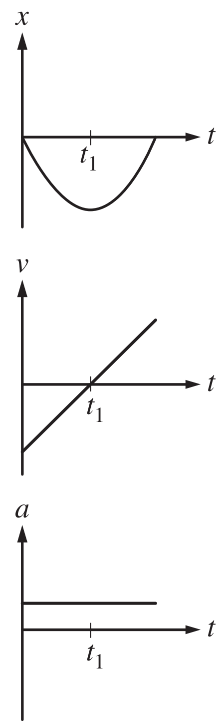
Learning Objective (3.B.1.1): The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's Second Law in a variety of physical situations with acceleration in one dimension. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practice 6.4]

Learning Objective (5.B.4.1): The student is able to describe and make predictions about the internal energy of systems. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practice 2.2]



5. The graphs above represent the position x, velocity v, and acceleration a as a function of time t for a marble moving in one dimension. Which of the following could describe the motion of the marble?

   (A) Rolling along the floor and then bouncing off a wall

   (B) Rolling down one side of a bowl and then rolling up the other side

   (C) Rolling up a ramp and then rolling back down

   (D) Falling and then bouncing elastically off a hard floor

   Answer: C

Targeted Learning Objective:

Learning Objective (3.A.1.1): The student is able to express the motion of an object using narrative, mathematical, and graphical representations. [See Science Practices 1.5, 2.1, and 2.2]

Multi–Correct: Students will need to select all the correct answers to the question below in order to earn credit.

6. A race car going around a flat, unbanked circular track gradually increases speed as it completes one full trip around the track. Which of the following can explain why the car gains speed?

   (A) Energy stored in the fuel is converted to mechanical energy.

   (B) A component of the frictional force exerted by the ground on the tires is directed toward the center of the circle.

   (C) A component of the frictional force exerted by the ground on the tires is in the direction of motion.

   (D) The car's velocity and acceleration are perpendicular.

   Answer: A and C

Targeted Learning Objectives:

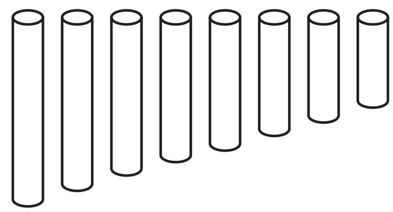
Learning Objective (3.E.1.1): The student is able to make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practice 1.4]

Learning Objective (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. [See Science Practice 6.4]

Sample Free–Response Questions

Experimental Design



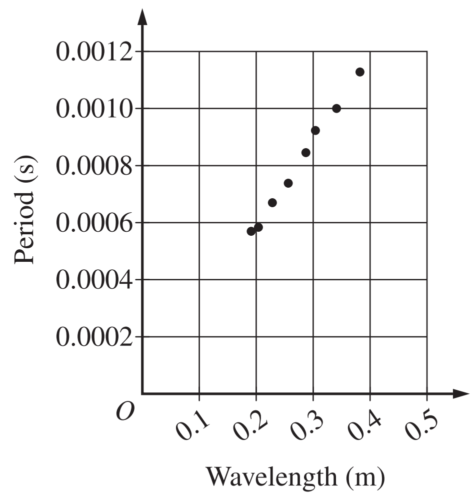
1. You are given a set of chimes that consists of eight hollow metal tubes open at both ends, as shown above. The chimes are played by striking them with a small hammer to produce musical sounds. Your task is to use the chimes to determine the speed of sound in air at room temperature. You have available a set of tuning forks and other common laboratory equipment but are not allowed to use electronic equipment, such as a sound sensor. (A tuning fork vibrates when struck and produces sound at a particular frequency, which is printed on the tuning fork.)

   (a) Describe your experimental procedure in enough detail so that another student could perform your experiment. Include what measurements you will take and how you will take them.

   (b) Describe how you will use your measurements to determine the speed of sound, in enough detail that another student could duplicate your process.

   (c) Describe one assumption you made about the design of your experiment, and explain how it might affect the value obtained for the speed of sound.

(d) A student doing a different experiment to determine the speed of sound in air obtained wavelength and period measurements and created the following plot of the data. Use the graph to calculate the speed of sound and include an explanation of your method.

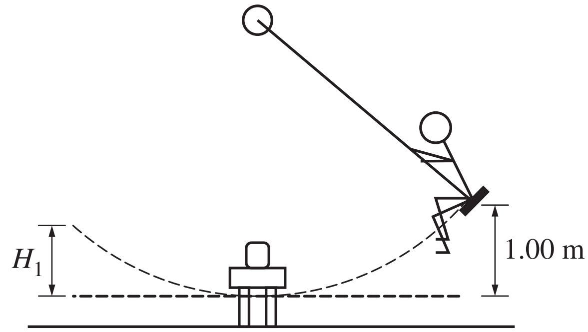


Targeted Learning Objectives:

Learning Objective (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. [See Science Practices 4.2, 5.1, and 7.2]

Learning Objective (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. [See Science Practices 3.2, 4.1, 5.1, 5.2, and 5.3]

Short Answer



Note: Figure not drawn to scale.

2. A student of mass 50.0 kg swings on a playground swing, which is very light compared to the student. A friend releases the seat of the swing from rest at a height of 1.00 m above the lowest point of the motion. The student swings down and, at the lowest point of the motion, grabs a jug of water of mass 4.00 kg. The jug is initially at rest on a small table right next to the swing, so it does not move vertically as the student grabs it. The student keeps swinging forward while holding the jug, and the seat reaches a maximum height H_1 above the lowest point. Air resistance and friction are negligible.

   (a) Indicate whether H_1 is greater than, less than, or equal to 1.00 m.
   ____ Greater than 1.00 m
   ____ Less than 1.00 m
   ____ Equal to 1.00 m

   Justify your answer qualitatively, with no equations or calculations.

   (b) Explain how H_1 can be calculated. You need not actually do the calculations, but provide complete instructions so that another student could use them to calculate H_1.

   (c) The student now swings backward toward the starting point. At the lowest point of the motion, the student drops the water jug. Indicate whether the new maximum height that the seat reaches is greater than, less than, or equal to H_1.
   ____ Greater than H_1
   ____ Less than H_1
   ____ Equal to H_1
   Justify your answer.

Targeted Learning Objectives:

Learning Objective (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. [See Science Practices 1.4, 2.1, and 2.2]

Learning Objective (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. [See Science Practices 2.1 and 2.2]

Learning Objective (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. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practices 6.4 and 7.2]

Learning Objective (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. [See Science Practices 2.1 and 2.2]

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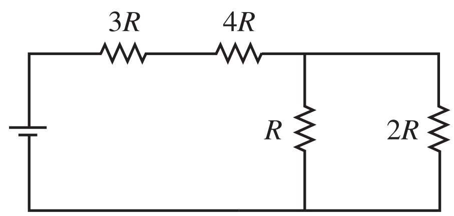
AP Physics 2: Algebra–based Sample Exam Questions

Sample Multiple–Choice Questions



1. The figure above shows four resistors connected in a circuit with a battery. Which of the following correctly ranks the potential difference, ΔV, across the four resistors?

   (A) $\Delta V_{4R} > \Delta V_{3R} > \Delta V_{2R} > \Delta V_{R}$

   (B) $\Delta V_{4R} > \Delta V_{3R} > \Delta V_{2R} = \Delta V_{R}$

   (C) $\Delta V_{4R} = \Delta V_{3R} > \Delta V_{R} > \Delta V_{2R}$

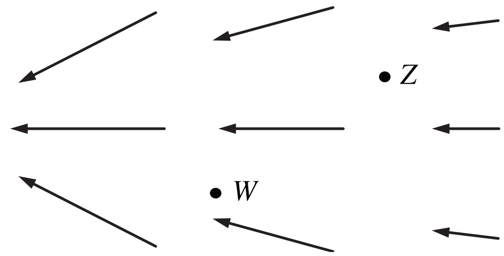
   (D) $\Delta V_{2R} = \Delta V_{R} > \Delta V_{3R} > \Delta V_{4R}$

   Answer: B

Targeted Learning Objective:

Learning Objective (5.B.9.5): The student is able to use conservation of energy principles (Kirchhoff's Loop Rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady–state circuits composed of various combinations of resistors and capacitors. [See Science Practice 6.4]

Refer to the diagram below for questions 2–3



The figure above represents an electric field created by charged objects that are not shown. The field vectors and the locations *W* and *Z* are in the plane of the page.

2. At which location is the electric potential greater?

   (A) *W*

   (B) *Z*

   (C) Neither; the potential is the same at both locations.

   (D) It cannot be determined without knowing the values of the charges on the objects creating the electric field.

   Answer: B

Targeted Learning Objectives:

Learning Objective (1.A.5.2): The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures. [See Science Practices 1.1, 1.4, and 7.1]

Learning Objective (2.E.2.1): The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field. [See Science Practices 6.4 and 7.2]

3. A small charged bead held inside the electric field has an electric force exerted upon it. At which location does the electric force have a greater magnitude?

   (A) W

   (B) Z

   (C) Neither; the magnitude of the force is the same at both locations.

   (D) It cannot be determined without knowing the sign of the charge on the bead.

   Answer: A

Targeted Learning Objective:

Learning Objective (2.C.1.1): The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $\vec{F} = q\vec{E}$; a vector relation. [See Science Practices 6.4 and 7.2]

4. A student writes the following information for a process that involves a fixed quantity of ideal gas.

   $W = -P\Delta V$

   $\Delta U = Q + W$

   $P = 2.0x10^5\ \text{Pa}$

   $\Delta V = -\ 2.0x10^{-3}\ \text{m}^3$

   $\Delta U = -\ 600J$

   Which of the following descriptions best represents the process?

   (A) The gas expands at a constant pressure of 200 kPa.

   (B) The gas is cooled at constant volume until its pressure falls to 200 kPa.

   (C) The gas is compressed at a constant pressure of 200 kPa.

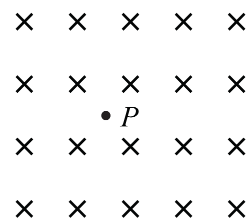
   (D) The gas is heated and its pressure increases at constant volume.

   Answer: C

Targeted Learning Objective:

Learning Objective (5.B.7.1): The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. [See Science Practices 6.4 and 7.2]

Multi–Correct: Students will need to select all the correct answers to the question below in order to earn credit.



5. An electron is at point *P* in a uniform magnetic field directed into the page, as depicted above. For which of the following states of motion of the electron is the magnetic force exerted on the electron equal to zero?

   (A) The electron is not moving.

   (B) The electron is moving perpendicularly into the page.

   (C) The electron is moving perpendicularly out of the page.

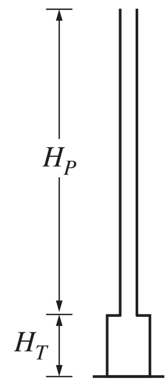
   (D) The electron is moving in a circle in the plane of the page at constant speed.

   Answer: A, B, C

Targeted Learning Objective:

Learning Objective (2.D.1.1): The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. [See Science Practice 2.2]

Multi–Correct: Students will need to select all the correct answers to the question below in order to earn credit.



6. The figure above shows a pipe of height H_P and cross–sectional area A_P attached to the top of a tank of height H_T and cross–sectional area A_T. The pipe and tank are completely filled with water. The force exerted by the water on the bottom of the tank depends on which of the given quantities?

(A) A_P

(B) A_T

(C) H_P

(D) H_T

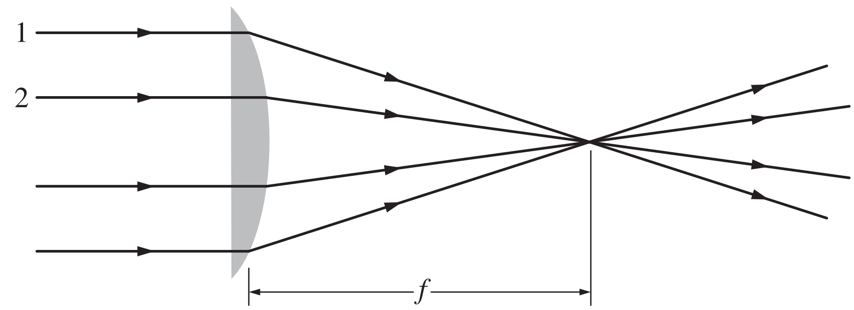
Answer: B, C, D

Targeted Learning Objective:

Learning Objective (5.B.10.2): The student is able to use Bernoulli's equation and the relationship between force and/or pressure to make calculations related to a moving fluid. [See Science Practice 2.2]

Sample Free–Response Questions

Quantitative/Qualitative Translation



1. The figure above represents a glass lens that has one flat surface and one curved surface. After incoming parallel rays pass through the lens, the rays pass through a focal point. The focal length f is the distance from the center of the lens to the focal point.

   (a) The rays undergo refraction and change direction at the right surface of the lens, as shown. Explain why the angle of refraction of ray 1 is greater than that of ray 2.

   (b) The index of refraction of the glass is n_{glass}, and the radius of curvature of the lens's right edge is R. (The radius of curvature is the radius of the sphere of which that edge is a part. A smaller R corresponds to a lens that curves more.) A teacher who wants to test a class's understanding about lenses asks the students if the equation $f = n_{glass} R$ makes sense for the focal length of the lens in air. Is the teacher's equation reasonable for determination of the focal length? Qualitatively explain your reasoning, making sure you address the dependence of the focal length on both R and n_{glass}.

   (c) An object is placed a distance $f / 2$ (half of the focal length) to the left of the lens. On which side of the lens does the image form, and what is its distance from the lens in terms of f? Justify your answer. (Assume this is a thin lens.)

   (d) The lens is now placed in water, which has an index of refraction that is greater than air but less than the glass. Indicate below whether the new focal length is greater than, less than, or equal to the focal length f in air.

   ____ Greater than in air
   ____ Less than in air
   ____ The same as in air

   Justify your answer qualitatively, with no equations or calculations.

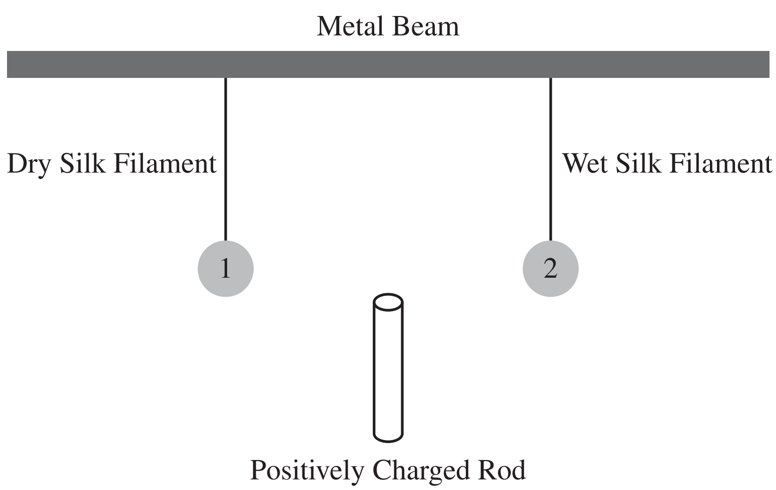
Targeted Learning Objectives:

Learning Objective (6.E.3.1): The student is able to describe models of light traveling across a boundary from one transparent material to another when the speed of propagation changes, causing a change in the path of the light ray at the boundary of the two media. [See Science Practices 1.1 and 1.4]

Learning Objective (6.E.3.3): The student is able to make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non–normal angles resulting from changes in the speed of propagation. [See Science Practices 6.4 and 7.2]

Learning Objective (6.E.5.1): The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses. [See Science Practices 1.4 and 2.2]

Short Answer



2. Two small conducting spheres attached to very thin silk filaments hang from a very large metal beam. The silk attached to sphere 1 is dry and therefore nonconducting, while the silk attached to sphere 2 is wet, making it a conductor. Initially the spheres are uncharged. A student takes a positively charged plastic rod and moves it close to both spheres, holding the rod the same distance from each sphere as shown above. Throughout the experiment, the rod never touches the spheres, and the spheres never touch each other.

(a) Which of the spheres moves toward the rod? If they both do, which one moves closer to the rod? Explain your reasoning, using words and diagrams.

The wet silk filament attached to sphere 2 gradually dries out. After the silk is completely dry, the rod is moved far away from both spheres.

(b) Indicate below how the two spheres are now positioned, relative to their original vertical positions.

____ Closer to each other
____ Farther from each other
____ In their original vertical positions

Explain your reasoning.

(c) Which of the following describes how the forces exerted by the spheres on each other now compare?

____ Sphere 1 exerts a greater force on sphere 2 than sphere 2 exerts on sphere 1.

____ Sphere 2 exerts a greater force on sphere 1 than sphere 1 exerts on sphere 2.

____ Sphere 1 exerts the same force on sphere 2 that sphere 2 exerts on sphere 1.

Briefly explain your reasoning.

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Targeted Learning Objectives:

Learning Objective (3.A.3.4): The student is able to make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge. [See Science Practices 6.1 and 6.4]

Learning Objective (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. [See Science Practices 6.4 and 7.2]

Learning Objective (4.E.3.2): The student is able to make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects. [See Science Practices 6.4 and 7.2]

Learning Objective (4.E.3.4): The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction. [See Science Practices 1.1, 1.4, and 6.4]

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.

Appendix A: AP Physics 1 Concepts at a Glance

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.
	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.
	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.
	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.
	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.
	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.
	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.
	Essential Knowledge 3.A.2: Forces are described by vectors.
	Essential Knowledge 3.A.3: A force exerted on an object is always due to the interaction of that object with another object.
	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 $\vec{a} = \frac{\Sigma\vec{F}}{m}$.	**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.
	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.
	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 should include gravitational force exerted by the Earth on a simple pendulum, 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.
	Essential Knowledge 3.C.2: Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.
	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.
	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 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.
	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.
	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 $\vec{a} = \frac{\Sigma \vec{F}}{m}$.	**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.
	Essential Knowledge 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.
	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.
	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 should include gravitational potential energy, elastic potential energy, and kinetic energy.
	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.
	Essential Knowledge 4.D.2: The angular momentum of a system may change due to interactions with other objects or systems.
	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.
	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.
	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.
	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.
	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.]
	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.
	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.
	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.]

	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 should 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.
	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.
	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.
	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 should 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.

Big Idea 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding 6.A: A wave is a traveling disturbance that transfers energy and momentum.	**Essential Knowledge 6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal.
	Essential Knowledge 6.A.2: For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples should include light traveling through a vacuum and sound not traveling through a vacuum.
	Essential Knowledge 6.A.3: The amplitude is the maximum displacement of a wave from its equilibrium value.
	Essential Knowledge 6.A.4: Classically, the energy carried by a wave depends upon and increases with amplitude. Examples should 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.
	Essential Knowledge 6.B.2: For a periodic wave, the wavelength is the repeat distance of the wave.
	Essential Knowledge 6.B.4: For a periodic wave, wavelength is the ratio of speed over frequency.
	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.
	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.
	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 should include waves on a fixed length of string, and sound waves in both closed and open tubes.
	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.
	Essential Knowledge 6.D.5: Beats arise from the addition of waves of slightly different frequency.

Appendix B: AP Physics 2 Concepts at a Glance

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

Enduring Understanding 1.A: The internal structure of a system determines many properties of the system.	**Essential Knowledge 1.A.2:** Fundamental particles have no internal structure.
	Essential Knowledge 1.A.3: Nuclei have internal structures that determine their properties.
	Essential Knowledge 1.A.4: Atoms have internal structures that determine their properties.
	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.
	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.
	Essential Knowledge 1.B.3: The smallest observed unit of charge that can be isolated is the electron charge, also known as the elementary charge.
Enduring Understanding 1.C: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.	**Essential Knowledge 1.C.4:** In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.
Enduring Understanding 1.D: Classical mechanics cannot describe all properties of objects.	**Essential Knowledge 1.D.1:** Objects classically thought of as particles can exhibit properties of waves.
	Essential Knowledge 1.D.2: Certain phenomena classically thought of as waves can exhibit properties of particles.
	Essential Knowledge 1.D.3: Properties of space and time cannot always be treated as absolute.

Enduring Understanding 1.E: Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.	**Essential Knowledge 1.E.1:** Matter has a property called density.
	Essential Knowledge 1.E.2: Matter has a property called resistivity.
	Essential Knowledge 1.E.3: Matter has a property called thermal conductivity.
	Essential Knowledge 1.E.4: Matter has a property called electric permittivity.
	Essential Knowledge 1.E.5: Matter has a property called magnetic permeability.
	Essential Knowledge 1.E.6: Matter has a property called magnetic dipole moment.

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

Enduring Understanding 2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.	**Essential Knowledge 2.A.1:** A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.
	Essential Knowledge 2.A.2: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential.
Enduring Understanding 2.C: An electric field is caused by an object with electric charge.	**Essential Knowledge 2.C.1:** The magnitude of the electric force F exerted on an object with electric charge q by an electric field $\vec{E}$ is $\vec{F} = q\vec{E}$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distribution, and uniformly charged parallel plates.
	Essential Knowledge 2.C.2: The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.
	Essential Knowledge 2.C.3: The electric field outside a spherically symmetric charged object is radial and its magnitude varies as the inverse square of the radial distance from the center of that object. Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.

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	Essential Knowledge 2.C.4: The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.
	Essential Knowledge 2.C.5: Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.
Enduring Understanding 2.D: A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.	**Essential Knowledge 2.D.1:** The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity and the magnitude of the magnetic field. It also depends on the angle between the velocity, and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles.
	Essential Knowledge 2.D.2: The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.
	Essential Knowledge 2.D.3: A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.
	Essential Knowledge 2.D.4: Ferromagnetic materials contain magnetic domains that are themselves magnets.
Enduring Understanding 2.E: Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.	**Essential Knowledge 2.E.1:** Isolines on a topographic (elevation) map describe lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential). As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational and electrical potential and potential differences.]
	Essential Knowledge 2.E.2: Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as equipotential lines.
	Essential Knowledge 2.E.3: The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

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

Enduring Understanding 3.A: All forces share certain common characteristics when considered by observers in inertial reference frames.	**Essential Knowledge 3.A.2:** Forces are described by vectors.
	Essential Knowledge 3.A.3: A force exerted on an object is always due to the interaction of that object with another object.
	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 $\vec{a} = \frac{\Sigma \vec{F}}{m}$.	**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.
	Essential Knowledge 3.B.2: Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.
Enduring Understanding 3.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.	**Essential Knowledge 3.C.2:** Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.
	Essential Knowledge 3.C.3: A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.
	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.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.
	Essential Knowledge 3.G.2: Electromagnetic forces are exerted at all scales and can dominate at the human scale.
	Essential Knowledge 3.G.3: The strong force is exerted at nuclear scales and dominates the interactions of nucleons.

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

Enduring Understanding 4.C: Interactions with other objects or systems can change the total energy of a system.	**Essential Knowledge 4.C.3:** Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process through which energy is transferred between systems at different temperatures is called heat.
	Essential Knowledge 4.C.4: Mass can be converted into energy and energy can be converted into mass.
Enduring Understanding 4.E: The electric and magnetic properties of a system can change in response to the presence of, or changes in, other objects or systems.	**Essential Knowledge 4.E.1:** The magnetic properties of some materials can be affected by magnetic fields at the system. Students should focus on the underlying concepts and not the use of the vocabulary.
	Essential Knowledge 4.E.2: Changing magnetic flux induces an electric field that can establish an induced emf in a system.
	Essential Knowledge 4.E.3: The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.
	Essential Knowledge 4.E.4: The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.
	Essential Knowledge 4.E.5: The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors.

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

Enduring Understanding 5.B: The energy of a system is conserved.	**Essential Knowledge 5.B.2:** A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. [Physics 1: includes mass-spring oscillators and simple pendulums. Physics 2: includes charged object in electric fields and examining changes in internal energy with changes in configuration.]
	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.
	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.]
	Essential Knowledge 5.B.6: Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.
	Essential Knowledge 5.B.7: The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples should include P-V diagrams — isovolumetric process, isothermal process, isobaric process, adiabatic process. No calculations of heat or internal energy from temperature change; and in this course, examples of these relationships are qualitative and/or semi-quantitative.
	Essential Knowledge 5.B.8: Energy transfer occurs when photons are absorbed or emitted, for example, by atoms or nuclei.
	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.
	Essential Knowledge 5.B.10: Bernoulli's equation describes the conservation of energy in fluid flow.

	Essential Knowledge 5.B.11: Beyond the classical approximation, mass is actually part of the internal energy of an object or system with $E = mc^2$.
Enduring Understanding 5.C: The electric charge of a system is conserved.	**Essential Knowledge 5.C.1:** Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples should include equations representing nuclear decay.
	Essential Knowledge 5.C.2: The exchange of electric charges among a set of objects in a system conserves electric charge.
	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 should 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.
	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.
	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.F: Classically, the mass of a system is conserved.	**Essential Knowledge 5.F.1:** The continuity equation describes conservation of mass flow rate in fluids. Examples should include volume rate of flow, mass flow rate.
Enduring Understanding 5.G: Nucleon number is conserved.	**Essential Knowledge 5.G.1:** The possible nuclear reactions are constrained by the law of conservation of nucleon number.

Big Idea 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding 6.A: A wave is a traveling disturbance that transfers energy and momentum.	**Essential Knowledge 6.A.1:** Waves can propagate via different oscillation modes such as transverse and longitudinal.
	Essential Knowledge 6.A.2: For propagation, mechanical waves require a medium, while electromagnetic waves do not require a physical medium. Examples should include light traveling through a vacuum and sound not traveling through a vacuum.
Enduring Understanding 6.B: A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.	**Essential Knowledge 6.B.3:** A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave.
Enduring Understanding 6.C: Only waves exhibit interference and diffraction.	**Essential Knowledge 6.C.1:** When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called superposition.
	Essential Knowledge 6.C.2: When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.
	Essential Knowledge 6.C.3: When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples should include monochromatic double-slit interference.
	Essential Knowledge 6.C.4: When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples should include hearing around corners, but not seeing around them, and water waves bending around obstacles.
Enduring Understanding 6.E: The direction of propagation of a wave such as light may be changed when the wave encounters an interface between two media.	**Essential Knowledge 6.E.1:** When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed. (Qualitative understanding only.)
	Essential Knowledge 6.E.2: When light hits a smooth reflecting surface at an angle, it reflects at the same angle on the other side of the line perpendicular to the surface (specular reflection); and this law of reflection accounts for the size and location of images seen in plane mirrors.

	Essential Knowledge 6.E.3: When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.
	Essential Knowledge 6.E.4: The reflection of light from surfaces can be used to form images.
	Essential Knowledge 6.E.5: The refraction of light as it travels from one transparent medium to another can be used to form images.
Enduring Understanding 6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.	**Essential Knowledge 6.F.1:** Types of electromagnetic radiation are characterized by their wavelengths, and certain ranges of wavelength have been given specific names. These include (in order of increasing wavelength spanning a range from picometers to kilometers) gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.
	Essential Knowledge 6.F.2: Electromagnetic waves can transmit energy through a medium and through a vacuum.
	Essential Knowledge 6.F.3: Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck's constant and f is the frequency of the associated light wave.
	Essential Knowledge 6.F.4: The nature of light requires that different models of light are most appropriate at different scales.
Enduring Understanding 6.G: All matter can be modeled as waves or as particles.	**Essential Knowledge 6.G.1:** Under certain regimes of energy or distance, matter can be modeled as a classical particle.
	Essential Knowledge 6.G.2: Under certain regimes of energy or distance, matter can be modeled as a wave. The behavior in these regimes is described by quantum mechanics.

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

Enduring Understanding 7.A: The properties of an ideal gas can be explained in terms of a small number of macroscopic variables including temperature and pressure.	**Essential Knowledge 7.A.1:** The pressure of a system determines the force that the system exerts on the walls of its container and is a measure of the average change in the momentum or impulse of the molecules colliding with the walls of the container. The pressure also exists inside the system itself, not just at the walls of the container.
	Essential Knowledge 7.A.2: The temperature of a system characterizes the average kinetic energy of its molecules.
	Essential Knowledge 7.A.3: In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation $PV = nRT$.
Enduring Understanding 7.B: The tendency of isolated systems to move toward states with higher disorder is described by probability.	**Essential Knowledge 7.B.1:** The approach to thermal equilibrium is a probability process.
	Essential Knowledge 7.B.2: The second law of thermodynamics describes the change in entropy for reversible and irreversible processes. Only a qualitative treatment is considered in this course.
Enduring Understanding 7.C: At the quantum scale, matter is described by a wave function, which leads to a probabilistic description of the microscopic world.	**Essential Knowledge 7.C.1:** The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region. (Qualitative treatment only, using graphical analysis.)
	Essential Knowledge 7.C.2: The allowed states for an electron in an atom can be calculated from the wave model of an electron.
	Essential Knowledge 7.C.3: The spontaneous radioactive decay of an individual nucleus is described by probability.
	Essential Knowledge 7.C.4: Photon emission and absorption processes are described by probability.

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