PHYSICS 2

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

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**]

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 amount of energy transferred through work done on or by a system is called work and the amount of energy transferred by heating a system is called heat. Work and heat are not "kinds" of energy (like potential or kinetic), rather they are the specific amount of energy transferred by each process. 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. This process of transferring energy is called heating. The amount of energy transferred 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**]

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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 magnet 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**]

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**]

Learning Objective 4.E.3.5:
The student is able to explain and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure.
[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_0.

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

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

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**]

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 and isolated 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