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**]

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**]

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**]

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 an object. The object's acceleration also depends on its 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 should be the result of an experiment, rather than the solution of the differential equation.

Return to the Table of Contents

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**]

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**]

Return to the Table of Contents

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 and 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, the period increases with the length of the pendulum and decreases with the magnitude of the gravitational field.

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**]

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**]

Return to the Table of Contents

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**]

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.

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 time 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**]

PHYSICS 2

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

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**]