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 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 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, 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.

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/isolated 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**]

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 and 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**]

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 process is called doing work on a system. The amount of energy transferred by this mechanical process 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 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**]

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 processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of internal energy change from temperature change are required; in this course, examples of these relationships are qualitative and/or semiquantitative.

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**]

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.

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 ($\Sigma\Delta V = 0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches.
[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**]

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 ($\Sigma \Delta V = 0$).
[See **Science Practice 5.1**]

PHYSICS 2

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**]

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 nonohmic 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**]

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

PHYSICS 2

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**]

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.

PHYSICS 2

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.

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**]

PHYSICS 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).

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**]

PHYSICS 1

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.]

PHYSICS 2

PHYSICS 1

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**]

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 nonrotating 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

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 an isolated system, the linear momentum is constant throughout the collision.

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

PHYSICS 2

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**]

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**]

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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 an isolated system, the linear momentum is constant throughout the collision.

b. In an isolated 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 1

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**]

Learning Objective 5.D.2.6:
The student is able to apply the conservation of linear momentum to an isolated 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 an isolated 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 and 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**]

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**]

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