AP PHYSICS 1 Content Outline arranged TOPICALLY

with

- o Big Ideas
- o Enduring Understandings
- o Essential Knowledges
- o Learning Objectives
- o Science Practices
- o Correlation to Common Textbook Chapters

Much thanks to the others that have worked on organizing the frameworks topically (especially Dolores Gende)

I took the work she and others did and added the Big Ideas, Enduring Understandings and Essential Knowledges. You will notice that I have repeated the text of the BI's, EU's and EK's in each topical unit because I find referring back to them makes the LO's a bit more understandable. I have also included the text of the SP's in the body of the document.

I find unit planning to be easier if everything I need is right in front of me instead of having to cross reference back and forth. I hope it helps you.

KINEMATICS

- **Reference Frames and Displacement**
- **Average Velocity and Instantaneous Velocity**
- **Motion at Constant Acceleration**
- **Falling Objects**
- **Adding Vectors by Components**
- **Projectile Motion: Projectiles fired horizontally and at an angle**
- **Graphical Analysis of Motion**

GIANCOLI (7e): Chapter 2 (2-1 through 2-8) and Chapter 3 (3-1, 3-4 through 3-6, 3-8)
ETKINA: Chapter 1 (1-1 through 1-9) and Chapter 3 (3-1, 3-4 through 3-6, 3-8)
KNIGHT (3e): Chapter 1 (1-1 through 1-5); Chapter 2 (2-1 through 2-8); Chapter 3 (3-1, 3-5 through 3-7)
CUTNELL (9e): Chapter 2 (2-1 through 2-8) and Chapter 3 (3-1 through 3-5)
SERWAY (10e): Chapter 2 (2-1 through 2-6) and Chapter 3 (3-1 through 3-5)
WALKER (4e): Chapter 2 (2-1 through 2-7); Chapter 3 (3-1 through 3-3, 3-5, 3-6); Chapter 4 (4-1 through 4-5)

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.

AP Physics 1 Topical Outline

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.

3.A.1.1: The student is able to express the motion of an object using narrative, mathematical, and graphical representations.
[SP 1.5, 2.1, 2.2]
1.5 The student can reexpress key elements of natural phenomena across multiple representations in the domain.
2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

3.A.1.2: The student is able to design an experimental investigation of the motion of an object.
[SP 4.2]
4.2 The student can design a plan for collecting data to answer a particular scientific question.

3.A.1.3: The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations.
[SP 5.1]
5.1 The student can analyze data to identify patterns or relationships.

DYNAMICS
- **Forces**
- **Free-Body-Diagrams**
- **Newton's Laws of Motion**
- **Mass and Weight**
- **Applications Involving Friction, Inclines**

GIANCOLI (7e): Chapter 4 (4-1 through 4-8)
ETKINA: Chapter 2 (2-1 through 2-10) and Chapter 3 (3-1through 3-4, 3-6)
KNIGHT (3e): Chapter 4 (4-1 through 4-7); Chapter 5 (5-1 through 5-8)
CUTNELL (9e): Chapter 4 (4-1 through 4-13)
SERWAY (10e): Chapter 4 (4-1 through 4-6)
WALKER (4e): Chapter 5 (5-1 through 5-7) and Chapter 6 (6-1 through 6-5)

BIG IDEA 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.
This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.
A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball   can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.C:
Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.
Inertial mass is the property of an object or a system that determines how its motion changes when it interacts with other objects or systems. Gravitational mass is the property of an object or a system that determines the magnitude   of its gravitational interaction with other objects, systems, or gravitational fields. From these definitions, classically, there is no expectation that these quantities would be identical. Einstein's assumption that these two quantities, experimentally verified to be equivalent, are in fact the same, is fundamental to the general theory of relativity (which is not part of this course).
Mass is conserved in any process, such as change of shape, change of state, or dissolution, when it is not converted to energy or when energy is not converted to mass. Mass is a central concept in this course; further discussions of mass are found throughout.

Essential Knowledge 1.C.1: Inertial mass is the property of an object or a system that determines how its motion changes when it interacts with other objects or systems.

1.C.1.1: The student is able to design an experiment for collecting data to determine the relationship between the net force exerted on an object its inertial mass and its acceleration. **[SP 4.2]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.

AP Physics 1 Topical Outline

Essential Knowledge 1.C.3: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

1.C.3.1: The student is able to design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.

BIG IDEA 2: Fields existing in space can be used to explain interactions.
All of the fundamental forces, including the gravitational force and the electric and magnetic forces, are exerted "at a distance"; the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields, which associate a value of some quantity with every point in space. Forces are vectors and so the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, for instance, temperature and pressure, vary with position. In general, a field created by an array of "sources" can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition. For a gravitational field the source is an object with mass. For an electric field the source is an object with electric charge. For a magnetic field the source is a magnet or a moving object with electric charge. Visual representations are extensively used by physicists in the analysis of many situations. A broadly used example across many applications involving fields is a map of isolines connecting points of equal value for some quantity related to a field, such as topographical maps that display lines of approximately equal gravitational potential.

Enduring Understanding 2.B:
A gravitational field is caused by an object with mass.
The gravitational field is the field most accessible to students. The effect of a gravitational field on an object with mass m positioned in the field is a force of magnitude mg that points in the direction of the field. The gravitational field can be represented mathematically. The gravitational field at a point in space due to a spherical object with mass M is a vector whose magnitude is equal to the gravitational force per unit of mass placed at that point. The direction of the field at the point is toward the center of mass of the source object.

The magnitude of the field outside the object is equal to $g = G\dfrac{M}{r^2}$, where r is the distance between the center of mass of the object and the point of interest and G is a constant. As with any vector field, a gravitational field can be represented by a drawing that shows arrows at points that are uniformly distributed in space.

Essential Knowledge 2.B.1: A gravitational field at the location of an object with mass m causes a gravitational force of magnitude mg to be exerted on the object in the direction of the field.

a. On Earth, this gravitational force is called weight.
b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.
c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in newtons/kilogram) at that location.

2.B.1.1: The student is able to apply $\mathbf{F} = m\vec{\boldsymbol{g}}$ to calculate the gravitational force on an object with mass m in a gravitational field of strength g in the context of the effects of a net force on objects and systems.
[SP 2.2, 7.2]
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.

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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.

3.A.2.1: The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**
  1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

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.

3.A.3.1: The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]**
  6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
  7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself. **[SP 6.1]**
   6.1 The student can justify claims with evidence.

3.A.3.3: The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

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.

3.A.4.1: The student is able to construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
   6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

3.A.4.2: The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.4.3: The student is able to analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Enduring Understanding 3.B:

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$

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 $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$ 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.

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.

3.B.1.1: The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations with acceleration in one dimension. **[SP 6.4, 7.2]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.B.1.2: The student is able to design a plan to collect and analyze data for motion (static, constant, or

accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**

4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

3.B.1.3: The student is able to reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. **[SP 1.5, 2.2]**

1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

3.B.2.1: The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. **[SP 1.1, 1.4, 2.2]**

1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

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).

3.C.4.1: The student is able to make claims about various contact forces between objects based on the microscopic cause of those forces. **[SP 6.1]**

6.1 The student can justify claims with evidence.

3.C.4.2: The student is able to explain contact forces (tension, friction, normal, buoyant, spring) as arising from

interatomic electric forces and that they therefore have certain directions. **[SP 6.2]**
6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

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, 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.

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.

4.A.1.1 The student is able to use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semiquantitatively. **[SP 1.2, 1.4, 2.3, 6.4]**
1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.3 The student can estimate numerically, quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

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.

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

4.A.2.1: The student is able to make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.A.2.2: The student is able to evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]**

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

4.A.2.3: The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

4.A.3.1: The student is able to apply Newton's second law to systems to calculate the change in the center-of-mass velocity when an external force is exerted on the system. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

4.A.3.2: The student is able to use visual or mathematical representations of the forces between objects in a system to predict whether or not there will be a change in the center-of-mass velocity of that system. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

CIRCULAR MOTION AND GRAVITATION

- **Kinematics of Uniform Circular Motion**
- **Dynamics of Uniform Circular Motion**
- **Newton's Law of Universal Gravitation**
- **Gravity Near the Earth's Surface**
- **Satellites and "Weightlessness"**
- **Kepler's Laws**

GIANCOLI (7e): Chapter 5 (5-1, 5-2 and 5-5 through 5-8)
ETKINA: Chapter 4 (4-1 through 4-6)
KNIGHT (3e): Chapter 6 (6-1 through 6-6)
CUTNELL (9e): Chapter 5 (5-1 through 5-3 and 5-6 through 5-8)
SERWAY (10e): Chapter 7 (7-4 through 7-6)
WALKER (4e): Chapter 6 (6-5) and Chapter 12 (12-1 through 12-3)

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

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.C:
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Inertial mass is the property of an object or a system that determines how its motion changes when it interacts with other objects or systems. Gravitational mass is the property of an object or a system that determines the magnitude of its gravitational interaction with other objects, systems, or gravitational fields. From these definitions, classically, there is no expectation that these quantities would be identical. Einstein's assumption that these two quantities, experimentally verified to be equivalent, are in fact the same, is fundamental to the general theory of relativity (which is not part of this course).

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

Essential Knowledge 1.C.3: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

1.C.3.1: The student is able to design a plan for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments. **[SP 4.2]**

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

BIG IDEA 2: Fields existing in space can be used to explain interactions.
All of the fundamental forces, including the gravitational force and the electric and magnetic forces, are exerted "at a distance"; the two objects involved in the interaction do not "physically touch" each other. To understand and calculate such forces, it is often useful to model them in terms of fields, which associate a value of some quantity with every point in space. Forces are vectors and so the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, for instance, temperature and pressure, vary with position. In general, a field created by an array of "sources" can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition. For a gravitational field the source is an object with mass. For an electric field the source is an object with electric charge. For a magnetic field the source is a magnet or a moving object with electric charge. Visual representations are extensively used by physicists in the analysis of many situations. A broadly used example across many applications involving fields is a map of isolines connecting points of equal value for some quantity related to a field, such as topographical maps that display lines of approximately equal gravitational potential.

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The magnitude of the field outside the object is equal to $g = G\dfrac{M}{r^2}$, where r is the distance between the center of mass of the object and the point of interest and G is a constant. As with any vector field, a gravitational field can be represented by a drawing that shows arrows at points that are uniformly distributed in space.

Essential Knowledge 2.B.1: A gravitational field at the location of an object with mass m causes a gravitational force of magnitude mg to be exerted on the object in the direction of the field.

   a.   On Earth, this gravitational force is called weight.
   b.   The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.

   c.   If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in newtons/kilogram) at that location.

2.B.1.1: The student is able to apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass m in a gravitational field of strength g in the context of the effects of a net force on objects and systems. **[SP 2.2, 7.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Essential Knowledge 2.B.2: The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object.

   a. The gravitational field caused by a spherically symmetric object is a vector whose magnitude outside the object is   equal to

$$g = G \frac{M}{r^2}$$

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

2.B.2.1: The student is able to apply $g = G \frac{M}{r^2}$ to calculate the gravitational field due to an object with mass M, where the field is a vector directed toward the center of the object of mass M. **[SP 2.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

2.B.2.2: The student is able to approximate a numerical value of the gravitational field (g) near the surface of an object from its radius and mass relative to those of the Earth or other reference objects. **[SP 2.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

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.

3.A.2.1: The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. **[SP 1.1]**
   1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.

AP Physics 1 Topical Outline

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.

3.A.3.1: The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.3.3: The student is able to describe a force as an interaction between two objects and identify both objects for any force. **[SP 1.4]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

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.

3.A.4.1: The student is able to construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces. **[SP 1.4, 6.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

3.A.4.2: The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.A.4.3: The student is able to analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces. **[SP 1.4]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Enduring Understanding 3.B:

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$

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 $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$ 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.

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.

3.B.1.2: The student is able to design a plan to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces. **[SP 4.2, 5.1]**
> *4.2 The student can design a plan for collecting data to answer a particular scientific question.*
> *5.1 The student can analyze data to identify patterns or relationships.*

3.B.1.3: The student is able to reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. **[SP 1.5, 2.2]**
> *1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.*
> *2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

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

3.B.2.1: The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. **[SP 1.1, 1.4, 2.2]**
> *1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.*
> *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*
> *2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

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.

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 $F = \dfrac{Gm_1m_2}{r^2}$

        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.

3.C.1.1: The student is able to use Newton's law of gravitation to calculate the gravitational force the two objects exert on each other and use that force in contexts other than orbital motion. **[SP 2.2]**
    2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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 **[SP 2.2]**
    2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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 non-fundamental 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.

3.C.2.2: The student is able to connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[SP 7.2]**
    7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.)

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

3.G.1.1: The student is able to articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored. **[SP 7.1]**
> *7.1 The student can connect phenomena and models across spatial and temporal scales.*

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, 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 $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$. 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.

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.

4.A.2.2: The student is able to evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. **[SP 5.3]**
   5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

ENERGY

- **Work**
- **Kinetic Energy and the Work-Energy Theorem**
- **Potential Energy: Gravitational and Elastic**
- **Mechanical Energy and its Conservation**
- **Power**

GIANCOLI (7e): Chapter 6 (6-1, 6-2 through 6-10)
ETKINA: Chapter 6 (6-1 through 6-6 and 6-8 through 6-9)
KNIGHT (3e): Chapter 10 (10-1 through 10-6 and 10-8)
CUTNELL (9e): Chapter 6 (6-1 through 6-5 and 6-7)
SERWAY (10e): Chapter 5 (5-1 through 5-6); Chapter 13 (13-2)
WALKER (4e): Chapter 7 (7-1, 7-2 and 7-4); Chapter 8 (8-1 through 8-4); Chapter 12 (12-4)

BIG IDEA 3: The interactions of an object with other objects can be described by forces.
An object either has no internal structure or can be analyzed without reference to its internal structure. An interaction between two objects causes changes in the translational and/or rotational motion of each object. When more than one interaction is involved, an object's change in motion is determined by the combination of interactions (the net force). We know of three fundamental interactions or forces in nature: the gravitational force, the electroweak force, and the strong force. The electroweak force unifies the electromagnetic force and the weak force. These two aspects of the electroweak force dominate at different scales, so are discussed separately. These fundamental forces are dominant at different length scales, and all other known "forces" are manifestations of one or the other of these fundamental interactions. The fundamental forces determine both the structure of objects and the motion of objects, from the very small molecular scale (micro and molecular machines and chemical reactions), to the motion of everyday objects such as automobiles and wind turbines, to the motion of tectonic plates, to the motion of objects and systems at the cosmological scale.

Enduring Understanding 3.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.

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.

3.E.1.1: The student is able to make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.E.1.2: The student is able to use net force and velocity vectors to determine qualitatively whether kinetic energy of an object would increase, decrease, or remain unchanged. **[SP 1.4]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

3.E.1.3: The student is able to use force and velocity vectors to determine qualitatively or quantitatively the net force exerted on an object and qualitatively whether kinetic energy of that object would increase, decrease, or remain unchanged. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

3.E.1.4: The student is able to apply mathematical routines to determine the change in kinetic energy of an object given the forces on the object and the displacement of the object. **[SP 2.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.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 the system

Essential Knowledge 4.C.1: The energy of a system includes its kinetic energy, potential energy, and microscopic internal energy. Examples should include gravitational potential energy, elastic potential energy, and kinetic energy.

4.C.1.1: The student is able to calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. **[SP 1.4, 2.1, 2.2]**
>   *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*
>   *2.1 The student can justify the selection of a mathematical routine to solve problems.*
>   *2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

4.C.1.2: The student is able to predict changes in the total energy of a system due to changes in position and speed of objects or frictional interactions within the system. **[SP 6.4]**
>   *6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.*

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.

4.C.2.1: The student is able to make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

4.C.2.2: The student is able to apply the concepts of Conservation of Energy and the Work-Energy theorem to determine qualitatively and/or quantitatively that work done on a two-object system in linear motion will change the kinetic energy of the center of mass of the system, the potential energy of the systems, and/or the internal energy of the system. **[SP 1.4, 2.2, 7.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.

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.

5.A.2.1: The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

> *6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.*
> *7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.*

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.

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

5.B.1.1: The student is able to set up a representation or model showing that a single object can only have kinetic energy and use information about that object to calculate its kinetic energy. **[SP 1.4, 2.2]**

> *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*
> *2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

5.B.1.2: The student is able to translate between a representation of a single object, which can only have kinetic energy, and a system that includes the object, which may have both kinetic and potential energies**. [SP 1.5]**

> *1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.*

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.**]
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5.B.2.1: The student is able to calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. **[SP 1.4, 2.1]**

> *1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*
> *2.1 The student can justify the selection of a mathematical routine to solve problems.*

AP Physics 1 Topical Outline

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.]

5.B.3.1: The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]**
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.3.2: The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.3.3: The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.4.2: The student is able to calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. **[SP 1.4, 2.1, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

AP Physics 1 Topical Outline

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.]

5.B.5.1: The student is able to design an experiment and analyze data to examine how a force exerted on an object or system does work on the object or system as it moves through a distance. **[SP 4.2, 5.1]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

5.B.5.2: The student is able to design an experiment and analyze graphical data in which interpretations of the area under a force-distance curve are needed to determine the work done on or by the object or system. **[SP 4.2, 5.1]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

5.B.5.3: The student is able to predict and calculate from graphical data the energy transfer to or work done on an object or system from information about a force exerted on the object or system through a distance. **[SP 1.4, 2.2, 6.4]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.B.5.4: The student is able to make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.5.5: The student is able to predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. **[SP 2.2, 6.4]**
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

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.

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.

5.D.1.1: The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.D.1.2: The student is able to apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and only qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]**
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
3.2 The student can refine scientific questions.
5.1 The student can analyze data to identify patterns or relationships.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

5.D.1.3: The student is able to apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]**
2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.D.1.4: The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.D.1.5: The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**
2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

5.D.2.1: The student is able to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.D.2.3: The student is able to apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

MOMENTUM

- **Impulse and Change in Momentum**
- **Conservation of Momentum**
- **Conservation of Energy and Momentum in Collisions (1 dimension)**
- **Conservation of Momentum in Collisions (2 dimensions: qualitative and semi-quantitative only)**

GIANCOLI (7e): Chapter 7 (7-1through 7-6)
ETKINA: Chapter 5 (5-1 through 5-5)
KNIGHT (3e): Chapter 9 (10-1 through 10-6 and 10-8)
CUTNELL (9e): Chapter 7 (7-1 through 7-3)
SERWAY (10e): Chapter 6 (6-1 through 6-3)
WALKER (4e): Chapter 9 (9-1 through 9-6)

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.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.

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.

3.D.1.1: The student is able to justify the selection of data needed to determine the relationship between the direction of the force acting on an object and the change in momentum caused by that force. **[SP 4.1]**
   4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.

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.

3.D.2.1: The student is able to justify the selection of routines for the calculation of the relationships between changes in momentum of an object, average force, impulse, and time of interaction. **[SP 2.1]**
   2.1 The student can justify the selection of a mathematical routine to solve problems.

3.D.2.2: The student is able to predict the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 6.4]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

3.D.2.3: The student is able to analyze data to characterize the change in momentum of an object from the average force exerted on the object and the interval of time during which the force is exerted. **[SP 5.1]**
5.1 The student can analyze data to identify patterns or relationships.

3.D.2.4: The student is able to design a plan for collecting data to investigate the relationship between changes in momentum and the average force exerted on an object over time. **[SP 4.2]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.

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.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.

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.

4.B.1.1: The student is able to calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). **[SP 1.4, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

4.B.1.2: The student is able to analyze data to find the change in linear momentum for a constant-mass system using the product of the mass and the change in velocity of the center of mass. **[SP 5.1]**
5.1 The student can analyze data to identify patterns or relationships.

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.

4.B.2.1: The student is able to apply mathematical routines to calculate the change in momentum of a system by analyzing the average force exerted over a certain time on the system. **[SP 2.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

4.B.2.2: The student is able to perform analysis on data presented as a force-time graph and predict the change in momentum of a system. **[SP 5.1]**
   5.1 The student can analyze data to identify patterns or relationships.

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.

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.

5.A.2.1: The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge, and linear momentum to those situations. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.

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.

5.D.1.1: The student is able to make qualitative predictions about natural phenomena based on conservation of linear momentum and restoration of kinetic energy in elastic collisions. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.D.1.2: The student is able to apply the principles of conservation of momentum and restoration of kinetic energy to reconcile a situation that appears to be isolated and elastic, but in which data indicate that linear momentum and kinetic energy are not the same after the interaction, by refining a scientific question to identify interactions that have not been considered. Students will be expected to solve qualitatively and/or quantitatively for one-dimensional situations and only qualitatively in two-dimensional situations. **[SP 2.2, 3.2, 5.1, 5.3]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
3.2 The student can refine scientific questions.
5.1 The student can analyze data to identify patterns or relationships.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

5.D.1.3: The student is able to apply mathematical routines appropriately to problems involving elastic collisions in one dimension and justify the selection of those mathematical routines based on conservation of momentum and restoration of kinetic energy. **[SP 2.1, 2.2]**

2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

AP Physics 1 Topical Outline

5.D.1.4: The student is able to design an experimental test of an application of the principle of the conservation of linear momentum, predict an outcome of the experiment using the principle, analyze data generated by that experiment whose uncertainties are expressed numerically, and evaluate the match between the prediction and the outcome. **[SP 4.2, 5.1, 5.3, 6.4]**
 4.2 The student can design a plan for collecting data to answer a particular scientific question.
 5.1 The student can analyze data to identify patterns or relationships.
 5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.
 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

5.D.1.5: The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. **[SP 2.1, 2.2]**
 2.1 The student can justify the selection of a mathematical routine to solve problems.
 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

5.D.2.1: The student is able to qualitatively predict, in terms of linear momentum and kinetic energy, how the outcome of a collision between two objects changes depending on whether the collision is elastic or inelastic. **[SP 6.4, 7.2]**
 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.D.2.2: The student is able to plan data collection strategies to test the law of conservation of momentum in a two-object collision that is elastic or inelastic and analyze the resulting data graphically. **[SP 4.1, 4.2, 5.1]**
 4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
 4.2 The student can design a plan for collecting data to answer a particular scientific question.
 5.1 The student can analyze data to identify patterns or relationships.

5.D.2.3: The student is able to apply the conservation of linear momentum to a closed system of objects involved in an inelastic collision to predict the change in kinetic energy. **[SP 6.4, 7.2]**
 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.D.2.4: The student is able to analyze data that verify conservation of momentum in collisions with and without an external friction force. **[SP 4.1, 4.2, 4.4, 5.1, 5.3]**
 4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
 4.2 The student can design a plan for collecting data to answer a particular scientific question.
 4.4 The student can evaluate sources of data to answer a particular scientific question.
 5.1 The student can analyze data to identify patterns or relationships.
 5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

5.D.2.5: The student is able to classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum as the appropriate solution method for an inelastic collision, recognize that there is a common final velocity for the colliding objects in the totally inelastic case, solve for missing variables, and calculate their values**. [SP 2.1, 2.2]**

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.

5.D.3.1: The student is able to predict the velocity of the center of mass of a system when there is no interaction outside of the system but there is an interaction within the system (i.e., the student simply recognizes that interactions within a system do not affect the center of mass motion of the system and is able to determine that there is no external force). **[SP 6.4]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

SIMPLE HARMONIC MOTION

- **Simple Harmonic Motion**
- **SHM Graphs: position, velocity, acceleration, energy**
- **Energy in SHM**
- **Mass-Spring Systems**
- **Simple Pendulum**

GIANCOLI (7e): Chapter 11 (11-1through 11-4)
ETKINA: Chapter 19 (19-1 through 19-7)
KNIGHT (3e): Chapter 14 (14-1 through 14-5)
CUTNELL (9e): Chapter 10 (10-1 through 10-4)
SERWAY (10e): Chapter 13 (13-1 through 13-5)
WALKER (4e): Chapter 13 (13-1 through 13-6)

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.B:

Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$

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 $\vec{a} = \dfrac{\Sigma \vec{F}}{m}$ 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.

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.

3.B.3.1: The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. **[SP 6.4, 7.2]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.B.3.2: The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. **[SP 4.2]**
   4.2 The student can design a plan for collecting data to answer a particular scientific question.

3.B.3.3: The student can analyze data to identify qualitative or quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion to use that data to determine the value of an unknown. **[SP 2.2, 5.1]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
   5.1 The student can analyze data to identify patterns or relationships.

3.B.3.4: The student is able to construct a qualitative and/or a quantitative explanation of oscillatory behavior given evidence of a restoring force. **[SP 2.2, 6.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
   6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

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.

AP Physics 1 Topical Outline

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.

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.]

5.B.2.1: The student is able to calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. **[SP 1.4, 2.1]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
   2.1 The student can justify the selection of a mathematical routine to solve problems.

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.]

5.B.3.1: The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. **[SP 2.2, 6.4, 7.2]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.3.2: The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. **[SP 1.4, 2.2]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

5.B.3.3: The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. **[SP 1.4, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.4.2: The student is able to calculate changes in kinetic energy and potential energy of a system, using information from representations of that system. **[SP 1.4, 2.1, 2.2]**
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.1 The student can justify the selection of a mathematical routine to solve problems.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

TORQUE AND ROTATIONAL MOTION

- **Torque**
- **Center of Mass (qualitative)**
- **Rotational Kinematics**
- **Rotational Dynamics and Rotational Inertia**
- **Rolling Motion (without slipping)**
- **Rotational Kinetic Energy**
- **Angular Momentum and its Conservation**

GIANCOLI (7e): Chapter 7 (7-8); Chapter 8 (8-1 through 8-8)
ETKINA: Chapter 7 (7-1 through 7-7); Chapter 8 (8-1 through 8-7)
KNIGHT (3e): Chapter 7 (7-1 through 7-7)
CUTNELL (9e): Chapter 7 (7-5); Chapter 8 (8-1 through 8-6); Chapter 9 (9-1 through 9-7)
SERWAY (10e): Chapter 7 (7-1 through 7-3); Chapter 8 (8-1 through 8-7)
WALKER (4e): Chapter 9 (9-7); Chapter 10 (10-1 through 10-7); Chapter 11 (11-1 through 11-7)

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.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.

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.

3.F.1.1: The student is able to use representations of the relationship between force and torque. **[SP 1.4]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and

quantitatively.

3.F.1.2: The student is able to compare the torques on an object caused by various forces. **[SP 1.4]**
  1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

3.F.1.3: The student is able to estimate the torque on an object caused by various forces in comparison to other situations. **[SP 2.3]**
  2.3 The student can estimate numerically, quantities that describe natural phenomena.

3.F.1.4: The student is able to design an experiment and analyze data testing a question about torques in a balanced rigid system. **[SP 4.1, 4.2, 5.1]**
  4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
  4.2 The student can design a plan for collecting data to answer a particular scientific question.
  5.1 The student can analyze data to identify patterns or relationships.

3.F.1.5: The student is able to calculate torques on a two-dimensional system in static equilibrium, by examining a representation or model (such as a diagram or physical construction). **[SP 1.4, 2.2]**
  1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
  2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

3.F.2.1: The student is able to make predictions about the change in the angular velocity about an axis for an object when forces exerted on the object cause a torque about that axis. **[SP 6.4]**:
  6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

3.F.2.2: The student is able to plan data collection and analysis strategies designed to test the relationship between a torque exerted on an object and the change in angular velocity of that object about an axis. **[SP 4.1, 4.2, 5.1]**
  4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
  4.2 The student can design a plan for collecting data to answer a particular scientific question.
  5.1 The student can analyze data to identify patterns or relationships.

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.

3.F.3.1: The student is able to predict the behavior of rotational collision situations by the same processes that are used to analyze linear collision situations using an analogy between impulse and change of linear momentum and angular impulse and change of angular momentum. **[SP 6.4, 7.2]**
    6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
    7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

3.F.3.2: In an unfamiliar context or using representations beyond equations, the student is able to justify the selection of a mathematical routine to solve for the change in angular momentum of an object caused by torques exerted on the object. **[SP 2.1]**
    2.1 The student can justify the selection of a mathematical routine to solve problems.

3.F.3.3: The student is able to plan data collection and analysis strategies designed to test the relationship between torques exerted on an object and the change in angular momentum of that object. **[SP 4.1, 4.2, 5.1, 5.3]**
    4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
    4.2 The student can design a plan for collecting data to answer a particular scientific question.
    5.1 The student can analyze data to identify patterns or relationships.
    5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

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, 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.

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.

4.A.1.1 The student is able to use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semiquantitatively. **[SP 1.2, 1.4, 2.3, 6.4]**
  1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.
  1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
  2.3 The student can estimate numerically, quantities that describe natural phenomena.
  6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

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.

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.

4.D.1.1: The student is able to describe a representation and use it to analyze a situation in which several forces exerted on a rotating system of rigidly connected objects change the angular velocity and angular momentum of the system. **[SP 1.2, 1.4]**
  1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.
  1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

AP Physics 1 Topical Outline

4.D.1.2: The student is able to plan data collection strategies designed to establish that torque, angular velocity, angular acceleration, and angular momentum can be predicted accurately when the variables are treated as being clockwise or counterclockwise with respect to a well-defined axis of rotation, and refine the research question based on the examination of data. [**SP 3.2, 4.1, 4.2, 5.1, 5.3**]
>*3.2 The student can refine scientific questions.*
>*4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.*
>*4.2 The student can design a plan for collecting data to answer a particular scientific question.*
>*5.1 The student can analyze data to identify patterns or relationships.*
>*5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.*

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.

4.D.2.1: The student is able to describe a model of a rotational system and use that model to analyze a situation in which angular momentum changes due to interaction with other objects or systems. [**SP 1.2, 1.4**]
>*1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.*
>*1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.*

4.D.2.2: The student is able to plan a data collection and analysis strategy to determine the change in angular momentum of a system and relate it to interactions with other objects and systems. [**SP 4.2**]
>*4.2 The student can design a plan for collecting data to answer a particular scientific question.*

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.

4.D.3.1: The student is able to use appropriate mathematical routines to calculate values for initial or final angular momentum, or change in angular momentum of a system, or average torque or time during which the torque is exerted in analyzing a situation involving torque and angular momentum. [**SP 2.2**]
>*2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

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. [**SP 4.1, 4.2**]
>*4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.*
>*4.2 The student can design a plan for collecting data to answer a particular scientific question.*

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.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.

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.

5.E.1.1: The student is able to make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. **[SP 6.4, 7.2]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.E.1.2: The student is able to make calculations of quantities related to the angular momentum of a system when the net external torque on the system is zero. **[SP 2.1, 2.2]**
   2.1 The student can justify the selection of a mathematical routine to solve problems.
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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.

5.E.2.1: The student is able to describe or calculate the angular momentum and rotational inertia of a system in terms of the locations and velocities of objects that make up the system. Students are expected to do qualitative reasoning with compound objects. Students are expected to do calculations with a fixed set of extended objects

and point masses. **[SP 2.2]**
> *2.2 The student can apply mathematical routines to quantities that describe natural phenomena.*

ELECTRIC CHARGE AND ELECTRIC FORCE

- **Static Electricity; Electric Charge and its Conservation**
- **Electric Charge in the Atom**
- **Charging Processes**
- **Coulomb's Law**

GIANCOLI (7e): Chapter 16 (16-1 through 16-5)
ETKINA: Chapter 14 (14-1 through 14-4)
KNIGHT (3e): Chapter 20 (20-1 through 20-3)
CUTNELL (9e): Chapter 18 (18-1 through 18-5)
SERWAY (10e): Chapter 15 (15-1 through 15-3)
WALKER (4e): Chapter 19 (19-1 through 19-3)

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

This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.

A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in

AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.B:
Electric charge is a property of an object or system that affects its interactions with other objects or systems containing charge.

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

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

a. An electrical current is a movement of charge through a conductor.
b. A circuit is a closed loop of electrical current.

1.B.1.1: The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**
> *6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.*

1.B.1.2: The student is able to make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. **[SP 6.4, 7.2]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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

   a. Like-charged objects and systems repel, and unlike- charged objects and systems attract.
   b. Charged objects or systems may attract neutral systems by changing the distribution of charge in the neutral system.

1.B.2.1 The student is able to construct an explanation of the two-charge model of electric charge based on evidence produced through scientific practices. **[SP 6.2]**:
6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

Essential Knowledge 1.B.3: The smallest observed unit of charge that can be isolated is the electron charge, also known as the elementary charge.

   a. The magnitude of the elementary charge is equal to 1.6×10^{-19} coulombs.
   b. Electrons have a negative elementary charge; protons have a positive elementary charge of equal magnitude, although the mass of a proton is much larger than the mass of an electron.

1.B.3.1: The student is able to challenge the claim that an electric charge smaller than the elementary charge has been isolated. **[SP 1.5, 6.1, 7.2]**
1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
6.1 The student can justify claims with evidence.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.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.

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.

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. **[SP 2.2, 6.4]**
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

3.C.2.2: The student is able to connect the concepts of gravitational force and electric force to compare similarities and differences between the forces. **[See SP 7.2]**
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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.

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.

5.A.2.1: The student is able to define open and closed systems for everyday situations and apply conservation concepts for energy, charge and linear momentum to those situations. **[SP 6.4, 7.2]**
   6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
   7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

DC CIRCUITS

- **Electric Current**
- **Ohm's Law: Resistance and Resistors**
- **Resistivity**
- **Electric Power**
- **DC Circuits**
- **Resistors in Series and Parallel**
- **Kirchhoff's Rules (circuits with one battery only)**
- **Internal Resistance is NOT covered in AP Physics 1**

GIANCOLI (7e): Chapter 18 (18-1 through 18-5); Chapter 19 (19-1 through 19-4)
ETKINA: Chapter 16 (16-1 through 16-5 and 16-7 through 16-10)
KNIGHT (3e): Chapter 22 (22-1 through 22-6); Chapter 23 (23-1 through 23-5)
CUTNELL (9e): Chapter 20 (20-1 through 20-4; 20-6 through 20-8; 20-10 and 20-11)
SERWAY (10e): Chapter 17 (17-1 through 17-4 and 17-6); Chapter 18 (18-1 through 18-4)
WALKER (4e): Chapter 21 (21-1 through 21-5)

BIG IDEA 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.
This big idea collects the properties of matter into one area so that they can be employed in other big ideas. The universe contains fundamental particles with no internal structure such as electrons, and systems built from fundamental particles, such as protons and neutrons. These further combine to form atoms, molecules, and macroscopic systems, all of which have internal structures.
A system has various attributes or "properties" that determine how it behaves in different situations. When the properties of the system depend on the internal structure of the system, we must treat it as a system. In other cases, the properties of interest may not depend on the internal structure — in
AP Physics we call these *objects*. For example, the free-fall motion of a ball can be understood without consideration of the internal structure of the ball, so in this case the ball can be treated as an object. Objects and systems have properties that determine their interactions with other objects and systems. The choice of modeling something as an object or a system is a fundamental step in determining how to describe and analyze a physical situation.

Enduring Understanding 1.B:
Electric charge is   a property of an object or system that affects its interactions with other objects or systems containing charge.
Electric charge is the fundamental property of an object that determines how the object interacts with other electrically charged objects. The interaction of a charged object with a distribution of other charged objects is simplified by the field model, where a distribution of charged objects creates a field at every point and the charged object interacts with the field. There are two types of electric charge, positive and negative. Protons are examples of positively charged objects, and electrons are examples of negatively charged objects. Neutral objects and systems are ones whose net charge is zero. The magnitudes of the charge of a proton and of an electron are equal, and this is the smallest unit of charge that is found in an isolated object. Electric charge is conserved in all known processes and interactions.

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

   a. An electrical current is a movement of charge through a conductor.
   b. A circuit is a closed loop of electrical current.

1.B.1.1: The student is able to make claims about natural phenomena based on conservation of electric charge. **[SP 6.4]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

1.B.1.2: The student is able to make predictions, using the conservation of electric charge, about the sign and relative quantity of net charge of objects or systems after various charging processes, including conservation of charge in simple circuits. **[SP 6.4, 7.2]**

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

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

Enduring Understanding 1.E:

Materials have many macroscopic properties that result from the arrangement and interactions of the atoms and molecules that make up the material.

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

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

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

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

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

1.E.2.1 The student is able to choose and justify the selection of data needed to determine resistivity for a given material. **[SP 4.1]**

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

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.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.

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.

5.B.9.1: The student is able to construct or interpret a graph of the energy changes within an electrical circuit with only a single battery and resistors in series and/or in, at most, one parallel branch as an application of the conservation of energy (Kirchhoff's loop rule). **[SP 1.1, 1.4]**
 1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

5.B.9.2: The student is able to apply conservation of energy concepts to the design of an experiment that will demonstrate the validity of Kirchhoff's loop rule ($\sum \Delta V = 0$) in a circuit with only a battery and resistors either in series or in, at most, one pair of parallel branches. **[SP 4.2, 6.4, 7.2]**
 4.2 The student can design a plan for collecting data to answer a particular scientific question.
 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.B.9.3: The student is able to apply conservation of energy (Kirchhoff's loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. **[SP 2.2, 6.4, 7.2]**

2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

Enduring Understanding 5.C:
The electric charge of a system is conserved.
Conservation of electric charge is a fundamental conservation principle in physics. All processes in nature conserve the net electric charge. The total electric charge after an interaction or any other type of process always equals the total charge before the interaction or process. A common example is found in electric circuits, in which charge (typically electrons) moves around a circuit or from place to place within a circuit. Any increase or decrease in the net charge in one region is compensated for by a corresponding decrease or increase in
the net charge in other regions. In electrostatics, it is common for electrons to move from one object to another, and the number of electrons that leave one object is always equal to the number of electrons that move onto other objects. In some reactions such as radioactive decay or interactions involving elementary particles, it is possible for the number of electrically charged particles after a reaction or decay to be different from the number before. However, the net charge before and after is always equal. So, if a process produces a "new" electron that was not present before the reaction, then a "new" positive charge must also be created so that the net charge is the same before and after the process.

Essential Knowledge 5.C.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.]

5.C.3.1: The student is able to apply conservation of electric charge (Kirchhoff's junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if configurations of the circuit are changed. **[SP 6.4, 7.2]**:

6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

5.C.3.2: The student is able to design an investigation of an electrical circuit with one or more resistors in which evidence of conservation of electric charge can be collected and analyzed. **[SP 4.1, 4.2, 5.1]**

4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

5.C.3.3: The student is able to use a description or schematic diagram of an electrical circuit to calculate unknown values of current in various segments or branches of the circuit. **[SP 1.4, 2.2]**

1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

MECHANICAL WAVES AND SOUND

- **Wave Motion**
- **Types of Waves: Transverse and Longitudinal**
- **Energy Transmitted by Waves: relationship of energy and wave amplitude**
- **Reflection and Interference of Waves**
- **Standing Waves**
- **Sources of Sound:**
  - **Standing waves for stringed instruments**
  - **Standing waves for a tube open at both ends and for a tube closed at one end**
- **Beats**
- **Doppler Effect (qualitative)**

GIANCOLI (7e): Chapter 11 (11-7 through 11-12); Chapter 12 (12-4, 12-6, 12-7)
ETKINA: Chapter 20 (20-1 through 20-3 and 20-5 (only reflection) through 20-11)
KNIGHT (3e): Chapter 15 (15-1, 15-2, 15-7); Chapter 16 (16-1 through 16-4 and 16-7)
CUTNELL (9e): Chapter 16 (16-1 through 16-3 and 16-9); Chapter 17 (17-1, 17-4 through 17-6)
SERWAY (10e): Chapter 13 (13-7 through 13-11); Chapter 14 (14-6 through 14-8; 14-10 and 14-11)
WALKER (4e): Chapter 14 (14-1 through 14-9)

BIG IDEA 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.
Classically, waves are a "disturbance" that propagates through space. Mechanical waves are a disturbance of a mechanical medium such as a string, a solid, or a gas, and they carry energy and momentum from one place to another without any net motion of the medium. Electromagnetic waves are a different type of wave; in this case, the disturbance is in the electromagnetic field itself, and therefore requires no medium. Electromagnetic waves also carry energy and momentum. In most cases, multiple waves can propagate through a medium independently of each other. Two waves do not "collide" as would objects traveling through the same region of space. Waves "pass through" each other, according to the principle of superposition and a phenomenon called interference. Important examples of wave motion are sound (a mechanical wave that can propagate in gases, liquids, and solids), and light (which can be modeled as electromagnetic waves to which our eyes are sensitive). In the quantum regime, all particles can be modeled as waves, although the wavelike behavior is only observable under certain conditions — for example, an electron in an atom behaves in some ways like a classical particle and in other ways like a classical wave.

Enduring Understanding 6.A:
A wave is a traveling disturbance that transfers energy and momentum.
When an object moves as a projectile from one place to another, it possesses kinetic energy and momentum. Such a process thus transfers energy and momentum, and also mass, from place to place. A wave is a disturbance that carries energy and momentum from one place to another without the transfer of mass. Some waves are mechanical in nature — this means that they are a disturbance of a mechanical system such as a solid, a liquid, or a gas; this system is called the medium through which the wave travels. Mechanical waves are then described in terms of the way they disturb or displace their medium. The propagation properties of the mechanical wave, such as the wave speed, also depend on the properties of the medium. Electromagnetic waves do not require a mechanical medium. They are instead associated with oscillating electric and magnetic fields. Electromagnetic waves can travel through a mechanical medium, such as a solid, but they can also travel through a vacuum.

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

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

    b. Electromagnetic waves are transverse waves.   (AP 2)
    c. Transverse waves may be polarized.   (AP 2)

6.A.1.1: The student is able to use a visual representation to construct an explanation of the distinction between transverse and longitudinal waves by focusing on the vibration that generates the wave. **[SP 6.2]**
    6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.

6.A.1.2: The student is able to describe representations of transverse and longitudinal waves. **[SP 1.2]**
    1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

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

6.A.2.1: The student is able to describe sound in terms of transfer of energy and momentum in a medium and relate the concepts to everyday examples. **[SP 6.4, 7.2]**:
    6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
    7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

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

6.A.3.1: The student is able to use graphical representation of a periodic mechanical wave to determine the amplitude of the wave. **[SP 1.4]**
    1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

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

6.A.4.1: The student is able to explain and/or predict qualitatively how the energy carried by a sound wave relates to the amplitude of the wave, and/or apply this concept to a real-world example. **[SP 6.4]**
    6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

Enduring Understanding 6.B:
A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.
The properties of periodic waves are important to understanding wave phenomena in the world around us. These properties are amplitude, frequency, period, speed of the wave in a particular medium, wavelength, and energy.   A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave. Wave speeds depend upon the properties of the medium, but the speed of a wave is generally independent of the frequency and wavelength of the wave. The speed of an electromagnetic wave in a vacuum is a constant, usually referred to as c. In other materials, the apparent speed of an electromagnetic wave depends on properties of the material.
The frequency of a wave, as perceived by observers, depends upon the relative motion of the source and the observer. If the relative motions of the source and observer are away from each other, the perceived frequency decreases.   If the relative motions of the source and observer are toward each other,
the perceived frequency increases. This change in observed frequency or wavelength is known as the Doppler effect and finds uses from astronomy to medicine to radar speed traps.

Essential Knowledge 6.B.1: For a periodic wave, the period is the repeat time of the wave. The frequency is the number of repetitions of the wave per unit time.

6.B.1.1: The student is able to use a graphical representation of a periodic mechanical wave (position versus time) to determine the period and frequency of the wave and describe how a change in the frequency would modify features of the representation. **[SP 1.4, 2.2]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
   2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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

6.B.2.1: The student is able to use a visual representation of a periodic mechanical wave to determine wavelength of the wave. **[SP 1.4]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

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

6.B.4.1: The student is able to design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. **[SP 4.2, 5.1, 7.2]**

Essential Knowledge 6.B.5: The observed frequency of a wave depends on the relative motion of source and observer. This is a qualitative treatment only.

6.B.5.1: The student is able to create or use a wave front diagram to demonstrate or interpret qualitatively the observed frequency of a wave, dependent upon relative motions of source and observer. **[SP 1.4]**
   1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

Enduring Understanding 6.D:
Interference and superposition lead to standing waves and beats.
Interference and superposition of waves find application in many areas.   These include musical instruments, lasers, medical imaging, and the search   for gravitational waves. Two wave pulses can overlap to produce amplitude variations in the resultant wave. At the moment of overlap, the displacement   at each point can be determined by superposition, adding the displacements at each point due to the individual pulses. This principle applies to all waves from pulses to traveling periodic waves.
When incident and reflected traveling waves are confined to a region, their superposition or addition can result in standing waves with constructive and destructive interference at different points in space. Examples include waves on a fixed length of string and sound waves in a tube. When two waves of slightly different frequency superimpose, their superposition or addition can result in beats with constructive and destructive interference at different points in time. Standing waves and beats are important phenomena in music.

Essential Knowledge 6.D.1: Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition.

6.D.1.1: The student is able to use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. **[SP 1.1, 1.4]**
1.1 The student can create representations and models of natural or man–made phenomena and systems in the domain.
1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

6.D.1.2: The student is able to design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for wave pulses or standing waves). **[SP 4.2, 5.1]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.

6.D.1.3: The student is able to design a plan for collecting data to quantify the amplitude variations when two or more traveling waves or wave pulses interact in a given medium. **[SP 4.2]**
4.2 The student can design a plan for collecting data to answer a particular scientific question.

Essential Knowledge 6.D.2: Two or more traveling waves can interact in such a way as to produce amplitude variations in the resultant wave.

6.D.2.1: The student is able to analyze data or observations or evaluate evidence of the interaction of two or more traveling waves in one or two dimensions (i.e., circular wave fronts) to evaluate the variations in resultant amplitudes. **[SP 5.1]**
5.1 The student can analyze data to identify patterns or relationships.

Essential Knowledge 6.D.3: Standing waves are the result of the addition of incident and reflected waves that are confined   to a region and have nodes and antinodes. Examples should include waves on a fixed length of string and sound waves in both closed and open tubes.

6.D.3.1: The student is able to refine a scientific question related to standing waves and design a detailed plan for the experiment that can be conducted to examine the phenomenon qualitatively or quantitatively. **[SP 2.1, 3.2, 4.2]**
2.1 The student can justify the selection of a mathematical routine to solve problems.
3.2 The student can refine scientific questions.
4.2 The student can design a plan for collecting data to answer a particular scientific question.

AP Physics 1 Topical Outline

6.D.3.2: The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. **[SP 6.4]**
6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

6.D.3.3: The student is able to plan data collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared to the prediction, explain any discrepancy and, if necessary, revise the relationship among variables responsible for establishing standing waves on a string or in a column of air. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**
3.2 The student can refine scientific questions.
4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
5.1 The student can analyze data to identify patterns or relationships.
5.2 The student can refine observations and measurements based on data analysis.
5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.

6.D.3.4: The student is able to describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. **[SP 1.2]**
1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.

Essential Knowledge 6.D.4: The possible wavelengths of a standing wave are determined by the size of the region to which it is confined.

a. A standing wave with zero amplitude at both ends can only have certain wavelengths. Examples should include fundamental frequencies and harmonics.
b. Other boundary conditions or other region sizes will result in different sets of possible wavelengths.

6.D.4.1: The student is able to challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source regardless of the size of the region. **[SP 1.5, 6.1]**
1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
6.1 The student can justify claims with evidence.

6.D.4.2: The student is able to calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined, and calculate numerical values of wavelengths and frequencies. Examples should include musical instruments. **[SP 2.2]**
2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

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

a. Because of the different frequencies, the two waves are sometimes in phase and sometimes out of phase. The resulting regularly spaced amplitude changes are called beats. Examples should include the tuning of an instrument.
b. The beat frequency is the difference in frequency between the two waves.

6.D.5.1: The student is able to use a visual representation to explain how waves of slightly different frequency give rise to the phenomenon of beats. **[SP 1.2]**
1.2 The student can describe representations and models of natural or man–made phenomena and systems in the domain.