College Ready
Physics Standards:
A Look to the Future

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Objective 3.1: Constant and Changing Linear Motion (Grades 5-8 and 9-12)
Students understand that linear motion is characterized by speed, velocity, and acceleration, and that velocity and acceleration are vectors.

Objective 3.2: Forces and Changes in Motion (Grades 5-8 and 9-12)
Students understand that interactions can be described in terms of forces. The acceleration of an object is proportional to the vector sum of all the forces (net force) on the object and inversely proportional to the object’s mass \( a = \Sigma F/m \). When two interacting objects push or pull on each other, the force on one object is equal in magnitude but opposite in direction to the force on the other object.

Objective 3.3: Contact Interactions and Forces (Grades 5-8 and 9-12)
Students understand that contact interactions occur when two objects in contact push or pull on each other, which can cause a change in the motion of the objects. Some types of contact interactions have force laws that are empirical approximations; some have no force laws.

Objective 3.4: Gravitational Interactions and Forces (Grades 5-8 and 9-12)
Students understand that gravity is an attractive interaction between any two objects with mass, which can cause a change in the motion of the objects. Gravitational interactions are governed by a force law.

Objective 3.5: Magnetic and Electrical Interactions and Forces (Grades 5-8 and 9-12)
Students understand that both magnetic interactions and electrical interactions occur between mutually attracting or repelling objects, which can cause a change in the motion of the objects. Electrical interactions apply to point charges, and are governed by a force law.

Standard 3
Newton’s Laws of Motion

Interactions of an object with other objects can be described, explained, and predicted using the concept of forces, which can cause a change in motion of one or both interacting objects. Different types of interactions are identified by their defining characteristics. At the macro (human) scale, interactions are governed by Newton’s second and third laws of motion.

Students understand that scientists believe that the things and events we observe occur in consistent patterns that are comprehensible through careful, systematic investigations. To search for consistent patterns in the multitude of interactions and changes we observe, scientists classified different types of interactions, for example contact interactions, gravitational interactions, magnetic interactions, and electrical (electrostatic) interactions. The defining characteristics of an interaction are: (1) the conditions necessary for the interaction to occur (e.g., two objects must be touching, one object must be charged, one object must be a solid and the other a fluid, and so on); (2) the evidence of the interaction – the observed changes; and (3) the variables that influence the strength of the interaction.

One way scientists describe different types of interactions is with the idea that during some interactions, objects exert forces on each other which can cause a change in motion of one or both objects (the evidence of an interaction). Changes in the linear motion of an object are characterized by speed, velocity, and acceleration, and velocity and acceleration are vectors. Many of the “formulas” in physics are the third defining characteristic of different types of interactions – empirical approximations (e.g., \( f_k = \mu N \) for friction) or force laws (e.g., Newton’s Universal Law of Gravitation, Coulomb’s Law) of the variables that determine the strength of the forces between two interacting objects. When an object is simultaneously interacting with more than one other object, then the acceleration of the object is proportional to the vector sum of the forces acting on the object \( \sum \vec{F} = m \vec{a} \), Newton’s second law of motion). When interacting objects push or pull on each other, the force on one object is equal in magnitude but opposite in direction to the force on the other object (Newton’s third law of motion).

Clarification. The objectives for this standard are limited to linear or uniform circular motion and forces in order to meet the college-ready goal of depth of understanding, yet leave no important content gaps. The objectives in this standard provide a strong foundation to extend the content and skills to two- and three dimensional motion and forces in college introductory physics courses.
**Objective 3.1**

**Constant and Changing Linear Motion (Grades 5-8 and Grades 9-12)**

Students understand that linear motion is characterized by speed, velocity, and acceleration, and that velocity and acceleration are vectors.

**Elementary Foundations**

By the end of grade 4, students know that:

1. An object’s position can be described by locating the object relative to other objects or a background. The position of an object from one observer’s view may be different from that reported from a different observer’s view.

2. Two clock readings, a start clock reading and an end clock reading, are required to determine an amount of time or time interval. Common units of time intervals are seconds, minutes, hours, days, and years. A time interval does not depend on the choice of the start clock reading.

3. Often the best way to tell which kinds of change are happening is to make a table or graph of measurements. [BSL 1IC/E2b]

4. An object is in motion when its position changes over time. Tracing and measuring its position over time can describe an object’s motion. [NSES K-4B2.1]

5. The (constant) speed of an object tells us the distance the object moves in each unit time interval. The speed of things differs greatly. Some things are so slow that their journey takes a long time; others move too fast for people to even see them. [BSL 4F/E2]

**Grades 5 - 8**

*Clarification.* Students in grades 5-8 begin to develop fluency with different representations for describing, explaining and predicting patterns of straight-line motion of objects: verbal and/or written descriptions, graphs of distance versus time, motion diagrams, and mathematical representations of constant and average speed.

**Boundary.** Motion is limited to objects moving in straight lines horizontally, up an incline, or down an incline. Excluded are the terms “velocity” and “acceleration,” which are introduced at the Grades 9-12 level.

**Essential Knowledge**

Students reason with and apply the following concepts in the learning outcomes:

**M.3.1.1** The basic patterns of the straight-line motion of objects are: no motion, moving with a constant speed, speeding up, slowing down and changing (reversing) direction of motion. Sometimes an object’s motion can be described as a repetition and/or combination of the basic patterns of motion. [SSCS, page 90]

**M.3.1.2** An object that travels the same distance in each successive unit of time has a constant speed. The constant speed of an object can be represented by and calculated from the mathematical representation (speed = distance traveled/time interval), data tables, a motion diagram and the slope of the linear distance versus time graph. [SSCS, page 90]

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* Underlined words and phrases are defined in the glossary.

† For further background and instructional guidance, including restrictions in the scope of the content for the learning outcomes in each objective, see Instructional Guidance for Standard 3, page 99.

‡ For further clarification of the learning outcomes and essential knowledge statements for each objective, see the objective Table of Common Student Conceptual Difficulties in Instructional Guidance for Standard 3.
M.3.1.3 When the distance an object travels increases with each successive unit of time, it is speeding up; when the distance an object travels decreases with each successive unit of time, it is slowing down. [SSCS, page 90]

M.3.1.4 The relationship between distance and time is nonlinear when an object’s speed is changing and when it is moving in a series with different constant speeds. [SSCS, page 90]

a. The constant speed an object would travel to move the same total distance in the same total time interval is the **average speed**.

b. Average speed can be represented and calculated from the mathematical representation (average speed = total distance traveled/total time interval), data tables, and the nonlinear distance versus time graph. [SSCS, page 90]

c. For objects traveling to a final destination in a series of different constant speeds, the average speed is not the same as the average of the constant speeds. [SSCS, page 90]

### LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- **Investigate** the patterns of motion of objects in different experimental situations: [SSCS, page 89]
  - Ask and refine a **scientific question** about the basic pattern of motion of the object.
  - Determine and justify the data needed to answer the scientific question about the pattern of motion of the object.
  - Follow a protocol to collect, record and organize data about the position of the moving object at different times (clock readings). Data include estimates of measurement errors.
  - Analyze the data for outliers, and represent the motion of the object on a graph showing distance versus time, and with a motion diagram.
  - Determine whether the data can be used as evidence to support a **claim** about the pattern of motion.
  - Make a claim about the pattern of motion of the object. Justification should include the evidence and knowledge of the different patterns of motion of objects.

- Translate among different representations (e.g., verbal descriptions, motion diagrams, data tables, distance versus time graphs) of the patterns of motion of objects. [SSCS, page 89]

- Explain what is changing and what is not changing for an object moving at a constant speed. Justify the explanation by constructing sketches of distance versus time graphs. [SSCS, page 89]

- Predict numerically the distance traveled, or the time interval for different situations involving motion with constant speed. Justify the prediction by using the mathematical representation for constant speed. [SSCS, page 89]

- Analyze different problems to determine whether the average speed of an object has been calculated correctly or incorrectly. If correct, interpret the meaning of the average speed. If incorrect, describe how to calculate the average speed correctly.

- Calculate, using the mathematical representation, the average speed of an object for problems in which an object is speeding up, slowing down or traveling in a series of constant speeds. Interpret the meaning of the average speed.

- Explain the differences between the average speed and constant speed for objects undergoing a change in motion. Justification is based on observations, sketches of motion diagrams and of distance versus time graphs, and knowledge of rates of change and changes in motion. [SSCS, page 89]

- Recognize when the evidence is convincing or not convincing to support claims about the pattern of motion of an object, using the criteria: (a) appropriate match of the evidence to the question; (b) adequate precision and **accuracy** (i.e., adequate precision of measuring instruments, adequate care taken in measurement procedures, and sufficient data was collected – sample size was large); (c) adequate data analysis and representation procedures were used; and (d) the investigation was replicated (by other groups or classes).
LEARNING OUTCOMES (5–8), continued

- Recognize when the quality of claims about the pattern of motion of an object are adequate or inadequate (poor) for situations in which the evidence is convincing, using the criteria: (a) the claim is based on the evidence, not opinion; (b) all the evidence is used, not just selected portions of the evidence; (c) the claim is based on correct scientific ideas of the different patterns of motion of objects; and (d) the justification links the evidence and scientific ideas about patterns of motion to the claim in a logical manner.

Grades 9 - 12

Clarification. In grades 9-12, students continue to develop fluency with different representations used to solve problems involving the straight-line motion of objects, including an introduction to simple, one-dimensional vector representations of displacement, velocity, instantaneous velocity and constant acceleration. The change in these quantities is determined by \textit{vector subtraction}.

**BOUNDARY**: Motion is limited to objects moving in straight lines horizontally, up an incline, and/or down an incline. Since motion is linear, the sign determines the direction for all vector quantities.

**ESSENTIAL KNOWLEDGE**

Students reason with and apply the following concepts in the learning outcomes:

- **H.3.1.1** The displacement, or change in position, of an object is a vector quantity that can be calculated by subtracting the initial position from the final position, where initial and final positions can have positive and negative values ($\Delta x = x_f - x_i$). Displacement is not always equal to the distance traveled. [SSCS, page 143]

- **H.3.1.2** An object that travels the same displacement in each successive unit time interval has constant velocity. Constant velocity is a vector quantity and can be represented by and calculated from a position versus time graph, a \textit{motion diagram} or the mathematical representation for average velocity. The sign (+ or -) of the constant velocity indicates the direction of the velocity vector, which is the direction of motion. [SSCS, page 143]

- **H.3.1.3** The constant velocity an object would travel to achieve the same change in position in the same time interval, even when the object’s velocity is changing, is the average velocity for the time interval. Average velocity can be mathematically represented by $v_{\text{ave}} = (x_f - x_i)/(t_f - t_i)$. For straight-line motion, average velocity can be represented by and calculated from the mathematical representation, a curved position versus time graph and a motion diagram. [SSCS, page 143]

- **H.3.1.4** The velocity of an object in straight-line motion changes continuously, from instant to instant while it is speeding up or slowing down and/or changing direction. The velocity of an object at any instant (clock reading) is called its \textit{instantaneous velocity}. The object does not have this velocity over any time interval or travel any distance with this velocity. Instead, the instantaneous velocity is the constant velocity at which an object would continue to move if its motion stopped changing at that instant. An object with zero instantaneous velocity can be accelerating (e.g., motion up a ramp then back down the ramp). [SSCS, page 143]

- **H.3.1.5** When the \textit{change} in an object’s instantaneous velocity is the same in each successive unit time interval, the object has constant acceleration. For straight-line motion, constant acceleration can be represented by and calculated from a linear instantaneous velocity versus time graph, a \textit{motion diagram} and the mathematical representation $[a = (v_f - v_i)/(t_f - t_i)]$. The sign (+ or -) of the constant acceleration indicates the direction of the change-of-velocity vector. A negative sign does not necessarily mean that the object is traveling in the negative direction or that it is slowing down. [SSCS, page 144]

[**BOUNDARY**: The term “deceleration” should be avoided because students tend to associate a negative sign of acceleration only with slowing down.]

- **H.3.1.6** When the acceleration is not constant, the graph of instantaneous velocity versus time is curved. Average acceleration over any interval is the constant acceleration an object would have for the same total change in
velocity in the same time interval. Average acceleration can be calculated from the non-linear instantaneous velocity versus time graph.

**H.3.1.7** When the acceleration is constant, the magnitude of the average velocity during a time interval is one-half of the sum of the initial and final instantaneous velocities \(v = (v_i + v_f)/2\). [SSCS, page 144]

**LEARNING OUTCOMES**

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Represent and calculate the distance traveled by an object, as well as the displacement, the speed and the velocity of an object for different problems. Representations include data tables, distance versus time graphs, position versus time graphs, motion diagrams and their mathematical representations. Interpret the meaning of the sign (+ or -) of the displacement and velocity. [SSCS, page 142]

  *[BOUNDARY: Problems should include situations in which the distance traveled is not the same as the displacement, and objects move from higher to lower positions.]*

- Investigate, and make a claim about the straight-line motion of an object in different laboratory situations. Representations include data tables, position versus time graphs, instantaneous velocity versus time graphs, motion diagrams, and their mathematical representations. When appropriate, calculate the constant velocity, average velocity or constant acceleration of the object. Interpret the meaning of the sign of the constant velocity, average velocity or constant acceleration. Interpret the meaning of the average velocity. [SSCS, page 143]

- **Explain** what is “constant” when an object is moving with a constant velocity and how an object with a negative constant velocity is moving. Justify the explanation by constructing sketches of motion diagrams and using the shape of position and instantaneous velocity versus time graphs. [SSCS, page 143]

- **Explain** what is “constant” when an object is moving with a constant acceleration, the two ways in which an object that has a positive constant acceleration can be moving\(^1\), and the two ways in which an object that has a negative constant acceleration can be moving\(^2\). Justify the explanations by constructing sketches of motion diagrams and using the shape of instantaneous velocity versus time graphs. [SSCS, page 143]

- Compare and contrast the following: distance traveled and displacement; speed and velocity; constant velocity and instantaneous velocity; constant velocity and average velocity; and velocity and acceleration. [SSCS, page 143]

- Translate between different representations of the motion of objects: verbal and/or written descriptions, motion diagrams, data tables, graphical representations (position versus time graphs and instantaneous velocity versus time graphs) and mathematical representations. [SSCS, page 143]

- Predict algebraically a displacement, an initial or final time (clock reading), or a time interval for different problems involving objects that are moving with either a constant velocity or a constant acceleration. Justify the prediction by constructing a motion diagram and using mathematical representations. [SSCS, page 143]

- Predict algebraically a displacement, an initial or final time (clock reading), or an initial or final instantaneous velocity in different problems. Justify the prediction by constructing motion diagrams and using the mathematical representations for constant velocity, constant acceleration, and/or the relationship between average velocity and initial and final instantaneous velocities for constant acceleration. [SSCS, page 143]

  *[BOUNDARY: Students should not be given problems that require them to solve a quadratic equation.]*

- **Evaluate** the evidence for claims about the velocity or acceleration of objects in different experimental problems, using the criteria: (a) appropriate match of the evidence to the question or prediction; (b) adequate precision and accuracy (adequate precision of measuring instruments, careful measurement procedures were followed, enough data collected (sample size is large), a control sample of data is included when appropriate other

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\(^1\) Positive acceleration can be speeding up in the positive direction or slowing down in the negative direction.

\(^2\) Negative acceleration can be slowing down in the positive direction or speeding up in the negative direction.
LEARNING OUTCOMES (9-12), continued

conditions or variables were the same when the measurements were made, and no sampling bias); (c)
correctness of data analysis and representation procedures (e.g., error bars on graphs for best estimate of
slopes); and (d) the investigation was replicated (by other groups or classes).

OBJECTIVE 3.2
FORCES AND CHANGES IN MOTION (Grades 5-8 and Grades 9-12)

Students understand that interactions can be described in terms of forces. The acceleration of an object is
proportional to the vector sum of all the forces (net force) on the object and inversely proportional to the object’s
mass (\(a = \Sigma F/m\)). When two interacting objects push or pull on each other, the force on one object is equal in
magnitude but opposite in direction to the force on the other object.

Clarification. This objective is not a stand-alone objective — it is linked to Objectives 1.3 (Contact Interactions and
Forces), 1.4 (Gravitational Interactions and Forces) and 1.5 (Electrical Interactions and Forces), which provide the specific
types of interaction forces needed to apply Newton’s laws.

BOUNDARY. Two-dimensional forces and motion are excluded. Motion is limited to inertial frames of reference, so Newton’s first
law is a special case of Newton’s second law. Excluded is the distinction between gravitational and inertial mass.

Elementary Foundations

By the end of grade 4, students know that:

1. The speed and direction of motion of objects can be changed by pushing or pulling. [BSL 4F/E1a]

2. The greater the force (push or pull) is, the greater the change in motion will be. The more massive an object is, the
   less effect a given force will have. [BSL 4F/E1bc]

Grades 5 – 8

Clarification. In grades 5–8, students begin to develop fluency with one-dimensional force diagrams and relate the vector sum of all the forces (net force)
acting on an object to changes in the straight-line motion (speeding up, slowing
down and/or changing direction) of the object.

BOUNDARY. Forces and motion are limited to horizontal, one dimension or uniform circular. The terms “net force” and
“acceleration” are not introduced until grades 9-12 because of the conceptual difficulty middle-school students have
understanding and using these terms. In addition, Newton’s third law is not introduced until grades 9-12. This eliminates
problems requiring the third law (e.g., objects at rest, a person who is walking or a moving car).

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

M.3.2.1 One way that scientists describe, explain, and predict interactions is with the idea of forces. A force can be
modeled as a push or pull applied on an object by the interacting object. Forces have both strength
(magnitude) and a direction, and can be measured with calibrated spring scales. The common unit of force is
the Newton (N).
M.3.2.2 Newton’s second law of motion includes the following ideas:

a. A force applied on an object in the direction of its motion causes the object’s speed to increase (the object speeds up).

b. A force applied on an object in a direction opposite its motion causes the object’s speed to decrease (the object to slows down).

c. A force can also change the direction of motion of an object.

d. A force of constant magnitude acting at right angles to the direction of the object’s motion causes the object to move in a circle at a constant speed. [See Objective 3.4]

e. When multiple forces are acting on an object, the change in motion of the object is determined by the sum of the forces (Newton’s second law), which can be found using vector addition. The sum of the forces is not a real force caused by an interacting object; it is the single force that could replace the original multiple forces and cause the same change in motion.

f. When the sum of forces is zero (e.g., two forces on object have same magnitude but act in opposite directions), then there is no change of motion – the object stays still or continues to move with constant speed in the same direction.

M.3.2.3 The forces acting on an object can be represented by arrows (vectors) drawn on an isolated picture of the object, called a force diagram. The direction of each arrow shows the direction of the push or pull. Forces are labeled: “type of interaction) push or pull of (interacting object) on the (object of interest). For example: “drag push of the wind on the sails of the boat.”

**Learning Outcomes**

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- **Investigate** and make a **claim** about the relationship between a constant force on an object and the pattern of motion of the object. Justification is based on data that is **evidence** for the relationship.

- Give examples of how to change the motion of an object (i.e., change speed, change direction or move in a circle) in different situations, and **explain** each example. Justification is based on knowledge of interactions and forces.

- Analyze force diagrams to determine if they accurately represent different problem situations involving contact, magnetic, and/or electrical interactions. [SSCS, page 90]

- Analyze force diagrams of different real-world situations involving magnetic, electrical and/or contact interactions. Predict the object’s motion (object speeds up, slows down, changes direction, moves in a circle, doesn’t move, or continues to move at a constant speed in the same direction). Justify using Newton’s second law. When appropriate, use vector addition to determine the size and direction of the sum of the forces, and interpret the meaning of the sum of the forces.

  **[BOUNDARY: No more than three forces.]**

- Determine, given a force diagram and the initial motion of an object, the change in motion of the object, and explain why the change occurs. Justification is based on Newton’s second law.

- Given real-world situations involving magnetic, electrical and/or contact forces and an identified object of interest. [SSCS, page 90]
  - Identify the objects involved in the interaction, and identify the pattern of motion for each object (i.e., no motion, moving with a constant speed, speeding up, slowing down or changing [reversing] direction of motion).
  - Make a claim about the types of interactions involved in the various situations. Justification is based on the defining characteristics of each type of interaction.
  - Represent the forces acting on the object of interest by drawing a force diagram.
  - Explain the observed motion of the object. Justification is based on Newton’s second law.
Grades 9 - 12

Clarification. In grades 9–12, students continue to develop fluency with force diagrams in more complex situations, relate the linear acceleration of an object with the vector sum of all the forces (net force) on the object and with the mass of the object, and apply Newton’s third law.

BOUNDARY.† Problem types are the same as for grades 5–8, but involve more complex situations, including situations involving linear motion in two parts (e.g., object accelerates and then moves with a constant velocity), situations involving the linear motion of two objects, and situations involving Newton’s third law (e.g., objects at rest, a person who is walking or a moving car).

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes: [SSCS, page 145]

H.3.2.1 The force on a 1 kg mass that causes an acceleration of 1 m/s² is one Newton (N), where a Newton is defined as kg m/s². Since many events consist of a sequence of interactions, the force diagram for an object/system of interest can be different for different time intervals.

H.3.2.2 Newton’s second law of motion includes the following ideas:
  a. The linear acceleration of an object is directly proportional to the vector sum of all the forces acting on the object and inversely proportional to the object’s mass (\(a = \Sigma F/m\)). The vector sum of all the forces (net force) is not a real force caused by an interaction with another object. The single force that could replace the original multiple forces and cause the same acceleration of the object is the vector sum of forces.
  b. A special case of Newton’s second law occurs when the vector sum of all the forces (net force) on an object is zero. In this case, there is no acceleration and the object remains at rest or maintains a constant speed and a constant direction of motion.
  c. An object moves in a circle when the vector sum of all the forces (net force) is constant in magnitude, always directed at right angles to the direction of motion and always directed toward the same point in space, the center of the circle. The speed of the object does not change: the acceleration causes the continual change in the direction of the change-in-velocity vector.

H.3.2.3 When two interacting objects push or pull on each other, the force on one object is equal in magnitude but opposite in direction to the force on the other object (Newton’s third law of motion for an interaction pair).

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective: [SSCS, pages 144-145]

- Analyze force diagrams to determine if they accurately represent different situations involving multiple contact, gravitational and/or electrical interactions. When appropriate, determine the one-dimensional vector sum of all the forces (net force), and interpret the meaning of the vector sum of all the forces (net force).
- Analyze different problems involving at least two different types of interactions (contact, gravitational, magnetic and/or electrical) and an identified object of interest.
- Identify the types of objects interacting with the object of interest, and observe the motion of each object.
LEARNING OUTCOMES (9-12), continued

- Make a claim about the types of interactions. Justification is based on the evidence and the defining characteristics of the different types of interactions.
- Represent the forces acting on the object of interest by drawing a force diagram showing both the vertical and horizontal forces. When appropriate, use vector addition to determine the relative size and direction of the sum of all the forces (net force), and interpret the meaning of the net force.
- Explain the observed motion of the object of interest. Justification is based on Newton’s second law.

- Evaluate explanations and predictions using the following criteria: (a) the explanation or prediction is complete (all relevant evidence and/or scientific ideas are included); (b) the explanation or prediction is based on evidence and correct physics ideas (not opinions); (c) the explanation or prediction is clear and concisely written; and (d) the justification links the evidence and scientific ideas to the claim in a logical manner.
- Identify the interaction (third-law) pair of any force in different problems. Compare the size and direction of the interaction pair of forces. Construct force diagrams that show all interaction (third-law) pairs.
- Predict algebraically a force, the linear acceleration, the initial or final velocity, or the initial or final time (clock readings) in different problems. Justify the prediction by constructing one-dimensional motion and force diagrams and by using the mathematical representations of average velocity and constant acceleration, the defining characteristics of different types of interaction forces, and Newton’s second and third laws of motion.
- Investigate and explain why an object moving at a constant speed in a circle is accelerating. Justify the explanation by constructing a motion diagram and by using knowledge of acceleration and Newton’s second law.

[BOUNDARY: Students are only required to explore two-dimensional vector subtraction in this one case; they are not required to become proficient.]

See Objectives 3.3, 3.4, and 3.5 for additional learning outcomes.

OBJECTIVE 3.3

CONTACT INTERACTION AND FORCES (Grades 5-8 and Grades 9-12)

*Students understand that contact interactions occur when two objects in contact push or pull on each other, which can cause a change in the motion of the objects. Some types of contact interactions have force laws that are empirical approximations; some have no force laws.*

**BOUNDARY. This objective is not a stand-alone objective** – it is related to Objectives 4.2 (Constant and Changing Linear Motion) and Objective 4.3 (Interactions, Forces, and Changing Motion). The situations are limited to one dimension and to horizontal motion and forces.

Elementary Foundations

Same as in Objective 3.2 (Interactions, Forces, and Changes in Motion)

Grades 5 - 8

*Clarification. In grades 5–8, students are introduced to the qualitative defining characteristics of applied, elastic (e.g., spring), sliding (kinetic) friction, and drag interactions.*

**BOUNDARY.** Interactions are limited to horizontal, one-dimension or circular motion, and those in which contact interactions predominate (i.e., other types of simultaneous interactions are negligible). Excluded are problem situations involving gravitational and static friction interactions, and situations requiring the application of Newton’s third law (e.g., an object resting on a table or ground, person walking, an accelerating car).
ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

M.3.3.1 Interactions can be classified by the following defining characteristics: (1) the conditions necessary for the interaction to occur (e.g., two objects must be touching, one object must be charged, one object must be moving, one object must be a solid and the other a fluid, etc.); the evidence of the interaction – the observed changes; and (3) the variables that influence the strength of the interaction (forces, energies, and/or fields).

M.3.3.2 Contact interactions occur when a macro (human) scale object (e.g., rope, baseball, skateboard) pushes or pulls on another object during the time interval while they are touching. The evidence of the interaction is a change in motion of one or both of the interacting objects.

M.3.3.3 During contact interactions, forces are not transferred to objects (unlike energy) — the interaction stops as soon as the objects stop touching. [SSCS, page 92]

M.3.3.4 There are different types of contact interactions based on different defining characteristics.

a. An applied interaction occurs between two objects that do not stretch, change shape, or break during the interaction. An applied force can be either a push or pull. [SSCS, page 92]

b. An elastic interaction occurs when two objects push or pull on each other and at least one solid object is stretched or compressed. A stretched spring or a rubber band pulls on an object attached to its end, and a compressed spring pushes. The magnitude of the force that an elastic object exerts on another object depends on the “stiffness” of the elastic object and on the distance that the elastic object is stretched or compressed.

c. A drag interaction occurs when a solid object is moving through a fluid (gas or liquid) and when a fluid is moving around an object (e.g., wind, a river flowing around a boulder). The drag force on an object is applied to the surface area facing the direction of motion of the object or fluid. The magnitude of the drag force on a solid object increases with the speed of the object or fluid and with the surface area of the object facing the direction of motion of the object or fluid.

d. A sliding (kinetic) friction interaction occurs when the surfaces of two solid objects slide past each other. The kinetic friction force on an object is applied to the sliding surface, and the direction of the force is opposite to the direction of the sliding.

e. For an object with wheels, a rolling friction interaction occurs between the parts of the wheel that rub together and the rest of the object. The rolling friction force is applied by the wheels on the axle-object part of the object, and the direction of the force is opposite to the direction of the rolling.

LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Given real-world situations involving a simple contact interaction between two objects: (a) Identify the objects involved in the contact interaction, and observe the changes in motion of each object. (b) Make a claim about the defining characteristics of each type of contact interaction. Represent the force on the object of interest by drawing a force diagram. [SSCS, pages 91-92]

- Compare and contrast applied, elastic, sliding (kinetic) friction, and drag interactions based on the defining characteristics of the interactions.

- Investigate the variables that could affect the magnitude of the elastic force and drag force on an object. (a) Ask and refine a scientific question about a variable that could affect the magnitude of the elastic or drag force. (b) Follow a structured protocol for observing the motion of the object for different values of the variable and for recording the observations on data tables. (c) Analyze and represent the data on graphs. (d) Make a claim, based on the evidence and Newton’s second law, about the relationship between the variable and the magnitude of the elastic force or drag force.³

³ The variables that affect the magnitude of the kinetic friction force are investigated in grades 9-12.
LEARNING OUTCOMES (5–8), continued

- Analyze real world situations involving contact interactions.
  - Identify the objects involved in the interaction, and identify the pattern of motion for each object (i.e., no motion, moving with a constant speed, speeding up, slowing down or changing [reversing] direction of motion, moving in a circle).
  - Make a claim about the types of contact interactions involved in the various situations. Justification is based on the defining characteristics of each type of interaction.
  - Represent the forces acting on the object of interest by drawing a force diagram.
  - Explain the observed motion of the object. Justification is based on Newton’s second law.
  - When appropriate, use **vector addition** to find the sum of the forces. Interpret the meaning of the sum of the forces.

- Predict what happens to the elastic force on an object (decreases, stays the same, increases) when the “stiffness” of the interacting elastic object changes or when the distance the elastic object is stretched or compressed changes. Justification is based on knowledge of the variables that affect the magnitude of elastic forces. [SSCS, page 92]

- Predict what happens to the drag force on an object (decreases, stays the same, increases) for different problems in which the speed of the object changes, or the surface area facing the direction of motion changes. Justification is based on knowledge of the variables that affect the magnitude of drag forces.

- Make a claim about whether a prediction is good or poor based on the criteria: (a) the prediction uses evidence and/or the correct science ideas; the prediction is complete (all important evidence and/or scientific ideas are used); and (c) it is not based on opinions.

- Identify all of the forces on an object in different real-world situations. Make a claim as to why, in some situations, the drag force of the air on a solid object can be ignored. Justification is based on the size and/or relative speed of the object as it moves through the air. [SSCS, page 92]

**Grades 9 - 12**

*Clarification.* In grades 9–12, contact interactions are expanded to include the defining characteristics of additional types of interactions and the empirical force laws for the elastic, kinetic friction and static friction interactions. Students also explore simplifying assumptions for solving problems involving contact interactions.

**Boundary.** The situations are limited to horizontal or vertical motion and forces in more complex problems than those that are covered in grades 5–8. Such complications as dimpled surfaces (e.g., golf balls, baseballs) are not considered.

**Essential Knowledge**

Students reason with and apply the following concepts in the learning outcomes:

**H.3.3.1** The types of interactions of the object/system of interest with its surroundings and the force laws for each type of interaction must be identified in order to use Newton's laws to quantitatively explain and predict the motion of an object or system. [SSCS, page 147]

**H.3.3.2** There are empirical **force laws** for some types of contact interactions. [SSCS, page 147]

- Elastic materials stretch or compress in proportion to the applied force. The mathematical model (Hooke's Law) for the force that a linearly elastic object exerts on another object is \( F_{\text{elastic}} = k\Delta x \), where \( \Delta x \) is the displacement of the object from its relaxed position. The direction of the elastic force is always toward the relaxed position of the elastic object. The constant of proportionality is the same for compression and extension, and depends on the “stiffness” of the elastic object.
b. The force of kinetic friction always acts in the opposite direction of the relative velocity of the object with respect to the surface it is sliding over. The magnitude of the kinetic friction depends on the types of materials that make up the two surfaces sliding past each other and the magnitude of the compression (normal) force acting on the object. This can be mathematically represented by \( F_k = \mu_k N \).

c. When an external force is applied parallel to two surfaces that are in contact, a force opposes the external force and keeps the objects from moving relative to each other. This interaction is called static friction, which is mathematically represented by an inequality: \( F_S \leq \mu_s N \). The magnitude of the static friction depends on the types of materials that make up the two surfaces and the magnitude of the compression (normal) force acting on the object.

**H.3.3.3** There are no force laws for some types of contact interactions because the complexity of the interactions does not allow the magnitude of the forces to be easily represented. [SSCS, page 147]

a. A contact interaction occurs when the surfaces of two solid objects are pressed together because of other interactions on one or both objects (e.g., a solid sitting on or sliding along a table; a magnet attached to a refrigerator). This is called a compression interaction. A compression (normal) force applied to an object is always a push directed at right angles from the surface of the other interacting object.

b. A contact interaction occurs when a cord (e.g., rope, wire, rod) pulls on another object or system and the cord is not slack. A tension force on an object always points in the direction the cord is pulling.

**H.3.3.4** In static friction and drag interactions, one of the interacting systems can be an energy source with a moving part (e.g., motor moving blades of a helicopter; a person’s moving foot). When the system with an energy source pushes on another object or system (e.g., the air or the ground), the other object pushes back on the system with equal and opposite force (Newton’s third law), which can cause a change in motion of the system with the energy source. [SSCS, page 147]

**H.3.3.5** During contact interactions, forces are not transferred to objects (unlike energy) – the interaction stops as soon as the objects stop touching. Simplifying assumptions are often needed to gain a basic understanding of a real-world situation or to solve a problem (e.g., for contact interactions, “massless” ropes, “frictionless” sliding surfaces, maximum static friction and negligible air resistance).

**H.3.3.6** At the atomic scale, the interaction between the particles (atoms or molecules) of different substances is an electric charge interaction. At this scale, there are no “contact” forces. The strength of the attractive forces between the particles of different substances is different for different pairs of substances, depending on the electron configurations of the atoms or molecules of the two substances. (See Objective 1.3) [SSCS, page 147]

**Learning Outcomes**

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- **Investigate**, and make a claim about, the variables (e.g., materials of the surfaces; an object’s surface area; velocity of an object; mass or weight of an object) that could affect the kinetic frictional force on an object. Justification is based on the evidence and Newton’s second law. [SSCS, page 146]

- Measure and mathematically represent the elastic constant of a linearly elastic object (e.g., a spring, a steel wire, a bungee cord). Measurements and representations are based on data tables, graphs, and the empirical force law for elastic materials. [SSCS, page 146]

- Identify a pair of surfaces and explain why it is best in different situations (e.g., different soled shoes for various surfaces). Justify by using a table of kinetic and static friction coefficients. [SSCS, page 146]

- Predict what happens to the magnitude of the kinetic-friction force in different situations involving a change in the pair of sliding surfaces. Justify the prediction by using a table of kinetic friction coefficients. [SSCS, page 146]

- Analyze problems involving the different types of contact interactions and an identified object of interest.
  - Identify the types of objects interacting with the object of interest, and observe the changes in motion of each object.
LEARNING OUTCOMES (9-12), continued

- Make a claim about the types of contact interactions. Justification is based on the evidence and the defining characteristics of each type of interaction.
- Represent the forces on the object of interest by drawing a force diagram showing both the vertical and horizontal forces (when appropriate).
- Explain the observed motion of the object of interest. Justification is based on Newton’s second law.

- Give examples of everyday phenomena and/or technological devices in which one of the interacting objects is an energy source. Identify interacting objects (such as an energy source [motor]–moving blades of a helicopter interacting with the surrounding air), and draw a force diagram of the energy-source system. Explain the motion of the energy-source system based on Newton’s laws of motion.
- Analyze different problems involving contact interactions to determine whether any simplifying assumptions are needed to solve each problem. Justification is based on the defining characteristics of different types of contact interactions and on knowledge of simplifying assumptions. Solve the problems.
- Explain why the kinetic-friction force and the static-friction force are different for a given pair of surfaces. Justify the explanation by using knowledge of friction interactions and the small-particle model of the forces between the particles of different substances. [SSCS, page 146]
- Explain why the drag force is larger in liquids than in the air. Justify the explanation by using the small-particle model (see Objective 1.3). [SSCS, page 146]
- Evaluate explanations and predictions using the following criteria: (a) the explanation or prediction is complete (all relevant evidence and/or scientific ideas are included); (b) the explanation or prediction is based on evidence and/or correct physics ideas (not opinions); (c) the explanation or prediction is clear and concisely written; and (d) the justification links the evidence and scientific ideas to the claim in a logical manner.

OBJECTIVE 3.4

GRAVITATIONAL INTERACTION AND FORCES (Grades 5-8 and Grades 9-12)

Students understand that gravity is an attractive interaction between any two objects with mass, which can cause a change in the motion of the objects. Gravitational interactions are governed by a force law.

BOUNDARY. Motions are limited to one dimension and to vertical motions of ordinary objects on Earth, and circular motions of moons and planets. Projectile motion can be done as an extension activity in grades 9-12.

Elementary Foundations

By the end of grade 4, students know that:

Same as Objective 3.2, and in addition:

1. With a few exceptions (e.g., helium-filled balloons), objects fall to the ground no matter where the object is located on Earth.

2. Without touching, the Earth pulls down on all objects with a force called gravity or the gravitational force.

Grades 5 - 8

Clarification. Students are introduced to the qualitative defining characteristics of the gravitational interaction. Students in this grade band also distinguish between weight and mass. The field model of the gravitational interaction is developed in Objective 5.1.

RELATED OBJECTIVES:
Forces and Fields (P.4.1)
BOUNDARY: Excluded are situations of objects on Earth at rest. Comparison of the weight of objects on Earth and other planets and moons is in Objective 5.1 (Forces and Fields).

**Essential Knowledge**

Students reason with and apply the following concepts in the learning outcomes:

**M.3.4.1** The Earth is approximately spherical in shape. Like the earth, the sun and planets are approximately spheres. On the surface of the Earth, up and down is the direction of a plumb line – towards the center of the Earth.

**M.3.4.2** The continual attraction that occurs between any two objects with mass is called the gravitational interaction. The evidence of the interaction is a change in motion of one or both objects.

a. Each atom of an object is gravitationally attracted to each atom of the interacting object. Thus, the gravitational force on an object is the sum of the forces on each atom of the object. On a force diagram this is represented by drawing the force arrow from the center of the object pointing to the center of the interacting object.

b. Gravitational interactions are difficult to observe unless at least one of the objects is very massive (e.g., the Sun, planet, moon).

c. The magnitude of gravitational forces increases with the masses of the two objects and decreases with the distance between the two objects.

**M.3.4.3** Compared to magnetic and electrical interactions, the gravitational interaction is extremely weak.

**M.3.4.4** “Weight” is the everyday term for the gravitational force (pull) of Earth (or other planet or moon) on objects located on or near Earth’s surface (or surface of other planet or moon). Like all forces, gravitational forces on ordinary objects on Earth are measured with calibrated spring scales that are not moving with respect to the Earth. [SSCS, page 94]

**Learning Outcomes**

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Given a real world situation involving different objects (including people) located at the poles and/or other locations on the Earth, explain the object’s motion. Justification is based on knowledge of the direction of gravitational interactions.

- Provide evidence, gathered from investigations, print, or electronic resources, which supports the idea that a gravitational interaction is not caused by Earth’s magnetism, the Earth’s rotation, or air pressure. [SSCS, page 93]

- Given real-world situations involving gravitational interactions between two objects, and an identified object of interest (e.g., a small falling object, a planet circling a star). (a) Identify the relative masses of the objects involved and the change in motion of each object. (b) Represent the gravitational force on the object of interest by drawing a force diagram.

- Investigate the strength of the gravitational force of Earth, compared to the strength of the magnetic force and of the electrical force. [SSCS, page 93]

  - Observe and record what happens when a small magnet is held above one or more small-mass objects made of a magnetic material (e.g., paper clips) and when a charged object is held above one or more small-mass objects made of an electric insulator (e.g., small pieces of paper).

  - Represent the motion of the magnetic-material object(s) and electric-insulator objects with a motion diagram. Represent the forces acting on these object(s) by drawing force diagrams.

  - Make a claim about the magnitude of the gravitational force compared to the magnetic and electrical forces. Justification is based on the evidence of the change in motion and Newton’s second law of motion.

- Explain (qualitatively) why the gravitational forces between two objects (e.g., two pencils, a person and a car) are not noticeable. Justification is based on the defining characteristics of the gravitational interaction. [SSCS, page 93]
LEARNING OUTCOMES (5-8), continued

- Explain (qualitatively) the difference between the mass and weight of an object. Justification is based on the defining characteristics of the gravitational interaction. [SSCS, page 93]
- Analyze problems involving the gravitational interaction and the drag interaction for a defined system.
  - Identify the types of objects interacting with the object of interest, and observe/identify the changes in motion of each object.
  - Represent the forces on the object of interest by drawing a force diagram.
  - Explain the observed motion of the object of interest. Justification is based on Newton’s second law.

Grades 9 - 12

Clarification. Students are introduced to Newton’s universal Law of gravitation (they are not expected to understand the origin of the $1/r^2$ relationship).

Boundary. Situations are limited to vertical motion and uniform circular motion. Projectile motion can be developed as two, one-dimensional problems – constant motion (zero sum of forces) in the horizontal direction and constant acceleration (due to gravitational force) in the vertical direction.

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes

H.3.4.1 Gravitational, magnetic, electrical and electromagnetic interactions occur continually when objects are not touching, and they do not require an intermediate material (medium). They are called interactions at a distance, or long-range interactions. (Same as in Objective 5.1)

H.3.4.2 The force law for gravitational interaction, called Newton’s universal law of gravitation, states that the strength of the gravitational force is proportional to the product of the two masses and inversely proportional to the square of the distance between the centers of the masses $F_G = (G m_1 m_2)/r^2$. The proportionality constant is called a universal constant because it does not depend on any other properties (e.g., chemical composition) of the objects or whether the object is charged or is a magnet). [SSCS, page 148]

H.3.4.3 When an object’s distance from Earth’s surface is small compared to Earth’s radius, then a simplifying assumption is that the gravitational force on an object depends only on the mass of the object. In this case, objects fall with approximately the same acceleration: 9.8 m/sec/sec. [SSCS, page 148]

H.3.4.4 When people are in free fall (e.g., some amusement park rides, sky diving, astronaut orbiting the Earth), they feel “weightless” because people do not feel the extremely small gravitational force on each atom in their bodies. When standing, people feel the (normal) force of the ground pushing upwards on their feet, which produces the sensation of weight.

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Explain why all objects near Earth’s surface fall with approximately the same acceleration, despite having different masses and weights. Justify by using the universal law of gravitation and Newton’s second law. [SSCS page 148]
- Analyze different problems to determine whether a constant gravitational acceleration can be assumed. Justify the analysis by using the universal law of gravitation. When appropriate, calculate a gravitational force. [SSCS page 148]
LEARNING OUTCOMES (9-12), continued

- Explain why the spring scale reading for someone standing on a scale in an accelerating elevator is different from the spring scale reading when the elevator is at rest or moving with a constant speed. Justify the explanation by constructing force diagrams of the person and the scale for the different situations (moving up or down with increasing or decreasing velocities) and by using Newton’s laws. [SSCS page 148]

- Explain why an astronaut orbiting the Earth feels “weightless,” even though the gravitational force of the Earth is still acting on the astronaut. Justify using the knowledge of the human lack of sensation of gravitational forces. [SSCS page 148]

- Explain why the gravitational force on the Earth from an interacting falling object does not result in a measurable acceleration of the Earth. Justify based on the universal law of gravitation and Newton’s laws. [SSCS, page 148]

- Predict quantitatively, for the circular orbit of an object (e.g., satellite, planet, moon), the mass of an object or the distance between the objects. Justification is based on the universal law of gravitation.

- Predict algebraically how a change in distance (e.g., triple the distance) between two objects with mass and/or a change in mass (e.g., one-fourth of the mass) of one or both interacting objects changes the gravitational force on an object. Justification is based on the universal law of gravitation. [SSCS, page 148]

- Predict algebraically the position between two objects at which the vector sum of the gravitational forces (net force) on an object is zero (e.g., Earth–Moon system, planet–Sun system). Justification is based on the universal law of gravitation and Newton’s second law. [SSCS, page 148]

- Evaluate explanations using the following criteria: (a) the explanation is complete (all relevant evidence and/or scientific ideas are included); (b) the explanation is based on evidence and correct physics ideas (not opinions); (c) the explanation is clear and concisely written; and (d) the justification links the evidence and scientific ideas to the claim in a logical manner.

- Give examples of distances and times to add to a chart for the cosmic scale (> $10^{10}$). Investigate the range in sizes that can be seen with the unaided eye, visible light telescopes, and other types of telescopes.

**Objective 3.5**

**Magnetic and Electrical Interactions and Forces** (Grades 5-8 and Grades 9-12)

Students understand that both magnetic interactions and electrical interactions occur between mutually attracting or repelling objects, which can cause a change in the motion of the objects. Electrical interactions apply to point charges and are governed by a force law.

**Boundary.** Two-and three-dimensional forces and motion are excluded.

**Elementary Foundations**

By the end of grade 4, students know that:

1. Without touching them, a magnet pulls on all things made of iron and either pushes or pulls on other magnets. [BSL 4G/E2]

2. Without touching, an object that has been electrically charged by rubbing pulls on all other uncharged objects and may either push or pull other charged objects. [BSL 4G/E3*]
Grades 5 - 8

Clarification. In grades 5–8, students are introduced to the qualitative defining characteristics of magnetic and electric charge interactions, including the attraction between charged and neutral objects, and the variables that affect the magnitude of the forces between two charged objects.

Boundary. The focus should be on the observations of the magnetic and electrical interactions. A discussion of subatomic particles will occur at the 9–12 grade band. Charging by induction is excluded at the 5–8 grade band.

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes:

M.3.5.1 Magnetic interactions occur when one magnet is close to, or touching, another magnet or a magnetic material (e.g., a substance that contains iron, nickel or cobalt). The evidence of the interaction is a change in motion of one or both objects.

a. All bar magnets (e.g., a compass needle) line up in the north–south direction when freely suspended. The end of the magnet that points approximately toward the geographical north is defined as the magnet’s north end. The other end of the magnet that points approximately toward the geographical south is defined as the south end.

b. Two magnets with opposite ends near each other will move toward each other (attract). Two magnets with the same ends near each other will move away from each other (repel). A magnet and an object made of magnetic material will move toward each other (attract).

c. The magnitude of the magnet–magnetic material force and the magnet–magnet force depend on the strength of the magnet(s) (the more magnetic one or both magnets is, the greater the forces) and on the distance between the two objects (the greater the distance, the weaker the magnetic forces).

d. The magnetic force on an object points to the approximate center of the other magnet or object made of magnetic material.

M.3.5.2 Electrical interactions occur when a charged object is close to another charged object or an uncharged object. The evidence of interaction is a change in motion of one or both objects.

a. Objects are typically uncharged. Any charged object (e.g., a comb that has been rubbed on a sweater) attracts uncharged objects such as bits of paper or a thin stream of water. Objects can be charged two ways, called positively charged objects and negatively charged objects.

b. Two objects with different types of charge will move toward each other (attract). When two charged objects have the same type of charge, they move away from each other (repel). A charged object will move toward an uncharged object (attract).

c. The magnitude of the electric charge force depends on the amount of charge on one or both interacting objects and decreases with increasing distance between the charged object and the other charged or uncharged object.

d. The electrical force on an object points to the approximate center of the other charged or uncharged object.

M.3.5.3 In certain materials, charges do not appear to move as freely as charges in other materials. These observations provide evidence that some materials (i.e., conductors) allow electric charge to move easily and that some materials (i.e., insulators) do not allow electric charge to move as freely. [SSCS, page 95]

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Make a claim concerning which objects, among several objects, are magnets. Justification is based on observational evidence and the defining characteristics of magnetic interactions. If the object is a magnet, use a known magnet to label the ends of the magnet. Use the known magnet to determine which of the objects are made of a magnetic material.
LEARNING OUTCOMES (5-8), continued

- Make a claim, using simple household materials, about whether an unknown object is charged or uncharged. Justification is based on observational evidence and the defining characteristics of electrical interactions. If the object is charged, use a known charged object to determine whether the object is positively charged or negatively charged.

- Compare and contrast the magnetic and electrical interactions, based on the defining characteristics of each interaction.

- Given real-world situations involving magnetic or electrical interactions between two objects, and an identified object of interest. (a) Identify the type of objects involved in the interaction, and observe the change in motion of each object. (b) Make a claim about the type of interaction (e.g., magnetic or electrical). Claim is based on the evidence and the defining characteristics of each type of interaction. (c) Represent the force on the object of interest by drawing a force diagram. [SSCS, page 94]

- Investigate the motion of charges when different materials (metals and electric insulators) are charged by contact (touching or rubbing). (a) Predict, based on the concept of charges, whether or not charges move when certain materials are charged. (b) Follow a structured protocol for determining whether the charges move and for recording observations on data tables. (c) Analyze and represent data with diagrams. (d) Make a claim, based on the evidence, about whether or not charges move when certain materials are charged. [SSCS, page 94]

- Predict what happens to the magnetic force on an object (decreases, stays the same or increases) when the strength of the magnet changes or when the distance between the magnet and the other interacting object changes. Justification is based on a defining characteristic of magnetic interactions. [SSCS, page 94]

- Predict what happens to the electric force on an object (decreases, stays the same or increases) when the amount of charge changes or when the distance between the two interacting objects changes. Justification is based on a defining characteristic of electric charge interactions. [SSCS, page 94]

Grades 9 - 12

Clarification. Students are introduced to Coulomb’s law for point charges (students are not expected to understand the origin of the $1/r^2$ relationship), and to the atomic-scale explanation for the attraction between charged and neutral objects. Students also explore the conditions necessary for the application of Coulomb’s law to solve a problem.

Related Objectives: Electric Current Interactions and Energy (4.2); College Board Standards for College Success™: Mathematics and Statistics, A1.3.1.

Boundary. This content can be addressed in the same way as it is for students in grades 6–8, but can include more complicated situations and materials. Two- and three-dimensional forces and motion are excluded.

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes: [SSCS, page 150]

H.3.5.1 At the atomic scale, charge is a property of subatomic particles (e.g., electrons or protons) and is quantized — that is, there is an elementary unit of observable charge that is the charge of the electron.

H.3.5.2 Two charged objects, which are small compared to the distance between them, can be modeled as point charges. The forces between point charges are proportional to the product of the charges and inversely proportional to the square of the distance between the point charges $F_e = (k_e q_1 q_2)/r^2$. This force law is known as Coulomb’s law.

H.3.5.3 For ordinary-size objects, Coulomb’s law is difficult to apply. The charged objects must be approximately modeled as point charges and be far apart compared to their size. For the electrical force to be comparable in magnitude to other forces in the problem, the objects must have a small mass (e.g., small pieces of paper or foil) and be close together (e.g., a few inches apart).
H.3.5.4 All neutral materials contain equal amounts of positive and negative charge. For all methods of charging neutral objects (e.g., rubbing together two neutral materials; charging by contact and charging by induction; using a van de Graaff machine or a battery), one object/system ends up with a surplus of positive charge and the other object/system ends up with the same surplus amount of negative charge. These and other experiments support the conservation of charge law: $\Delta q_{\text{system}} = q_{\text{in}} - q_{\text{out}}$. 

H.3.5.5 Based on the atomic model, most materials have the same number of electrons and protons; therefore, the materials are electrically neutral. Charged objects can be modeled as having an unequal amount of protons and electrons. When an electrical insulator is charged, the charge “spreads out” over the surface. When an electrical conductor is charged, the excess or deficit of electrons on the surface is localized to a small area of the insulator.

H.3.5.6 The atomic model also explains why charged objects and neutral objects exert an electrical force on each other.

a. When a charged object is near a neutral metal conductor, the free electrons in the metal are attracted toward or repelled away from the external charge. As a result, one side of the conductor has an excess of electrons, and the opposite side has an electron deficit. This separation of charges on a neutral conductor causes an attractive force on the whole neutral conductor.

b. When a charged object is near a neutral insulator, the electron cloud of each insulator atom shifts position slightly so it is no longer centered on the nucleus. The separation of charge is very small, much less than the diameter of the atom. These atoms point approximately toward the external charge. The sum of all the Coulomb forces on each molecule results in an attractive force on the whole insulator.

**LEARNING OUTCOMES**

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

[SSCS, pages 149-150]

- Calculate, using the conservation of charge law, the charge on an object in simple problems.
- Investigate, and make a claim about, the mathematical relationship between the electrical force, the amount of charge of each interacting object, and the distance separating the two charged objects. Justification is based on the evidence and Newton’s laws.
- Investigate and explain the differences between charging electrical conductors and insulators by contact and charging by induction. Justification is based on the evidence, on knowledge of Newton’s second law, and on the defining characteristics of an electrical interaction.
- Explain why, when a metal is charged, the charges “spread out” on the surface of the conductor and quickly stop moving. Justify the explanation by constructing diagrams and by using Coulomb’s law, Newton’s second law, and the atomic model of charges in neutral conductors.
- Predict, using a series of diagrams, how a conductor is charged by contact and by induction in different problems. Justification is based on Coulomb’s law, Newton’s second law, the conservation of charge law, and the atomic model of charges in neutral conductors.
- Explain why there is an attraction between a charged object and a neutral insulator or conductor. Justify the explanations by constructing force diagrams and by using Coulomb’s law, Newton’s laws of motion, and the subatomic model of charges in neutral conductors or insulators.
- Analyze different problems to determine whether Coulomb’s law can be used to solve each problem. Justification is based on the conditions necessary for the application of Coulomb’s law. If appropriate, calculate the force on an object, the amount of charge on an object or the separation of two charged objects.
- Predict algebraically the change in the electrical force on a point charge in different problems where the distance between the interacting point charges changes (e.g., one-fourth of the original distance) and/or where the magnitude of the charge of one or both point charges changes (e.g., triple the original charge). Justification is based on Coulomb’s law.
**LEARNING OUTCOMES (9–12), continued**

- Predict algebraically the position in which a point charge must be placed in a line of two or three other point charges, where the vector sum of the electrical forces (net force) on the point charge is zero. Justification is based on Coulomb’s law and Newton’s laws of motion.

- Evaluate explanations using the following criteria: (a) the explanation is complete (all relevant evidence and/or scientific ideas are included); (b) the explanation is based on evidence and correct physics ideas (not opinions); (c) the explanation is clear and concisely written; and (d) the justification links the evidence and scientific ideas to the claim in a logical manner.