AP Physics 1
Grades 10, 11 & 12

Unit 1
Unit Title: Kinematics

Essential Question
- How can the idea of frames of reference allow two people to tell the truth yet have conflicting reports?
- How can we estimate the height of a very tall building with only a small rock and stopwatch?
- Why might it seem like you are moving backwards when a car passes you on the highway?
- Why is the general rule for stopping your car "when you double your speed, you must give yourself four times as much distance to stop"?

Unit Summary
Unit 1 introduces students to the study of motion and serves as a foundation for all of AP Physics 1 topics by exploring the idea of acceleration and showing students how representations can be used to model and analyze scientific information as it relates to the motion of objects.

Guiding Questions
At the end of this unit, students should be able to respond to these questions as they demonstrate understanding of key concepts, skills and relevance to their own lives.

Content:
- What is the difference between scalars and vectors?
- What are the relationships among distance, displacement, instantaneous velocity, average velocity, constant velocity, and speed, and how can they be explained?
- What is acceleration, how is it related to velocity, and how can graphs of velocity versus time be interpreted?
- How can motion be analyzed using position-time, velocity-time, and acceleration-time graphs?

- How can constant-acceleration linear motion problems be solved when provided with a description of the motion of an object in words, graphs, or experimental data?
- How can relative velocity be defined and calculated?
- How do different frames of reference affect the observed motion of an object?
- When are objects in free fall, and how can their motion be explained in terms of constant acceleration due to gravity?
- How can the motion of an object in two dimensions be described using quantities such as displacement, distance, velocity, speed, and acceleration, within an appropriate coordinate system?
- How can the displacement, velocity, and acceleration of an object or the center of mass of a system be described in terms of vectors and modeled mathematically using kinematics equations when acceleration is constant?
- What are the key features of projectile motion, and how can this type of motion be interpreted?

Process:

- How can graphs and equations be used to describe and predict motion, and why are they important for understanding kinematics?
- What is the role of vector addition in solving relative velocity problems, and how can it be applied in both one-dimensional and two-dimensional motion?
- How can dimensional analysis be used to verify the correctness of kinematic equations, and why is it important in solving motion problems?
- How can motion detectors or video analysis be used to study motion, and when are these tools most useful in experiments?
- How can the results of motion analysis be explained to others using motion diagrams, graphs, and mathematical expressions, and why is this important for clear communication?
- How can appropriate kinematic equations be selected and applied to solve problems, and what factors determine the choice of equation?
- How can integration or differentiation of position, velocity, or acceleration graphs be used to find other kinematic quantities, and when should each method be applied?
- How can experiments, such as a free-fall setup, be designed to measure acceleration due to gravity, and why is this a key measurement in motion analysis?

Reflective:

- How can kinematic equations be used to calculate the stopping distance of a car for road safety assessments?
- How can the time it takes for an emergency supply package to reach a targeted drop zone be predicted?
- How can the motion of projectiles in sports be analyzed to determine the optimal angles for throws or kicks?
- How can velocity-time graphs be integrated to estimate the distance traveled during braking in a car?
- How do simplifying assumptions, such as ignoring air resistance, affect the accuracy of predictions in projectile motion?
- How can concepts of relative velocity be applied to situations like cars passing each other or objects moving on a conveyor belt?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- 1.1.A Describe a scalar or vector quantity using magnitude and direction, as appropriate.
    - 1.1.A.1 Scalars are quantities described by magnitude only; vectors are quantities described by both magnitude and direction.
    - 1.1.A.2 Vectors can be visually modeled as arrows with appropriate direction and lengths proportional to their magnitude.
    - 1.1.A.3 Distance and speed are examples of scalar quantities, while position, displacement, velocity, and acceleration are examples of vector quantities.
        - 1.1.A.3.i Vectors are notated with an arrow above the symbol for that quantity.

$$v = v_0 + at$$

        - 1.1.A.3.ii Vector notation is not required for vector components along an axis. In one dimension, the sign of the component completely describes the direction of that component. Derived equation:

$$v_x = v_{xo} + a_x + t$$

- 1.2.A Describe a change in an object's position.
    - 1.2.A.1 When using the object model, the size, shape, and internal configuration are ignored. The object may be treated as a single point with extensive properties such as mass and charge.

- 1.2.A.2 Displacement is the change in an object's position.

- 1.2.B Describe the average velocity and acceleration of an object.
  - 1.2.B.1 Averages of velocity and acceleration are calculated considering the initial and final states of an object over an interval of time.
  - 1.2.B.2 Average velocity is the displacement of an object divided by the interval of time in which that displacement occurs.
  - 1.2.B.3 Average acceleration is the change in velocity divided by the interval of time in which that change in velocity occurs.
  - 1.2.B.4 Describe the velocity and acceleration of an object. An object is accelerating if the magnitude and/or direction of the object's velocity are changing.
  - 1.2.B.5 Calculating average velocity or average acceleration over a very small time-interval yields a value that is very close to the instantaneous velocity or instantaneous acceleration.
- **1.3.A** Describe the position, velocity, and acceleration of an object using representations of that object's motion.

  1.3.A.4.i Describe the position, velocity, and acceleration of an object using representations of that object's motion. An object's instantaneous velocity is the rate of change of the object's position, which is equal to the slope of a line tangent to a point on a graph of the object's position as a function of time.

  1.3.A.4.ii An object's instantaneous acceleration is the rate of change of the object's velocity, which is equal to the slope of a line tangent to a point on a graph of the object's velocity as a function of time.

  1.3.A.4.iii The displacement of an object during a time interval is equal to the area under the curve of a graph of the object's velocity as a function of time (i.e., the area bounded by the function and the horizontal axis for the appropriate interval).

  1.3.A.4.iv The change in velocity of an object during a time interval is equal to the area under the curve of a graph of the acceleration of the object as a function of time.

- **1.4.A** Describe the reference frame of a given observer.
  - 1.4.A.1 The choice of reference frame will determine the direction and magnitude of quantities measured by an observer in that reference frame.
- **1.4.B** Describe the motion of objects as measured by observers in different inertial reference frames.
  - 1.4.B.1 Measurements from a given reference frame may be converted to measurements from another reference frame.
  - 1.4.B.2 The observed velocity of an object results from the combination of the object's velocity and the velocity of the observer's reference frame.
    - 1.4.B.2.i Combining the motion of an object and the motion of an observer in a given reference frame involves the addition or subtraction of vectors.
    - 1.4.B.2.ii The acceleration of any object is the same as measured from all inertial reference frames.
- **1.5.A** Describe the perpendicular components of a vector.
  - 1.5.A.1 Vectors can be mathematically modeled as the resultant of two perpendicular components.
  - 1.5.A.2 Vectors can be resolved into components using a chosen coordinate system.
  - 1.5.A.3 Vectors can be resolved into perpendicular components using trigonometric functions and relationships.
- **1.5.B** Describe the motion of an object moving in two dimensions.
  - 1.5.B.1 Motion in two dimensions can be analyzed using one-dimensional kinematic relationships if the motion is separated into components.
  - 1.5.B.2 Projectile motion is a special case of two- dimensional motion that has zero acceleration in one dimension and constant, nonzero acceleration in the second dimension.

Supporting Standards

These state standards are included in the student learning experiences for this unit and may be assessed.

- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.

- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Unit 2
Unit Title: Forces and Translational Dynamics

Essential Question

- Why do seat belts and air bags save lives?
- If you stand on a bathroom scale in a moving elevator, does its reading change?
- Why is it difficult to walk on ice?
- Can a parachutist survive a fall if the parachute does not open?
- Why do we feel pulled toward Earth but not toward a pencil?
- Why do pilots sometimes black out while pulling out at the bottom of a power dive?
- Are astronauts really “weightless” while in orbit?
- Why do you tend to slide across the car seat when the car makes a sharp turn?

Unit Summary

In this unit students are introduced to the concept of force, which is an interaction between two objects or systems of objects. Part of the larger study of dynamics, forces provide the context in which students analyze and come to understand a variety of physical phenomena**.** students will learn to relate the forces acting on an object to its motion and solve a wide range of dynamics problems. Students will learn that an object moving in a circle has an acceleration toward the center, so there must be a net force toward the center as well.

Guiding Questions

Content

- What is a system, and how is its center of mass calculated?
- How can forces acting on an object be represented using free-body diagrams?
- How can you identify all the forces acting on an object in various situations?
- What is the relationship between individual forces and the net force acting on an object?
- Why does an object remain in motion or at rest unless acted upon by a net external force?

- What conditions are required for an object to remain in equilibrium?
- How does Newton’s Second Law explain the relationship between force, mass, and acceleration?
- How can you calculate an object’s acceleration when multiple forces are involved?
- What does Newton’s Third Law reveal about the interaction between two objects?
- How does centripetal force maintain circular motion, and what factors affect it?

Process

- How can free-body diagrams help solve problems involving forces?
- What methods can determine the net force acting on an object from its free-body diagram?
- Why are force sensors and motion detectors useful in analyzing force and motion relationships?
- How can vector addition and subtraction be applied to resolve forces into components?
- What strategies can simplify force analysis in systems like pulleys or inclines?
- What are the conditions for uniform circular motion, and how does centripetal force maintain it?
- How can Newton’s Law of Universal Gravitation be used to calculate gravitational force?
- What factors influence the behavior and period of motion in pendulums or objects in circular motion?

Reflective

- How does Newton's Third Law apply to scenarios like the recoil of a cannon, rocket propulsion, or a swimmer pushing off the wall?
- How does friction affect the performance of vehicle tires or athletic shoes, and how can this be justified using experimental data and principles of static and kinetic friction?
- What role do gravitational forces play in determining satellite orbits, planetary motion, and weight variations on different planets?
- How do changes in the radius or speed of an object affect the required centripetal force in circular motion?

- How do engineers design bridges or elevators by considering forces such as tension, compression, and gravitational force?
- How can it be predicted whether an object will slide down an inclined plane by evaluating the forces acting on it, including friction?
- How does centripetal force ensure safe design in curved roadways or racetracks?
- How do amusement park rides rely on concepts of circular motion and centripetal force?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- **2.1.A** Describe the properties and interactions of a system.
  - **2.1.A.1** System properties are determined by the interactions between objects within the system.
  - **2.1.A.2** If the properties or interactions of the constituent objects within a system are not important in modeling the behavior of the macroscopic system, the system can itself be treated as a single object.
  - **2.1.A.3** Systems may allow interactions between constituent parts of the system and the environment, which may result in the transfer of energy or mass.
  - **2.1.A.4** Individual objects within a chosen system may behave differently from each other as well as from the system as a whole.
  - **2.1.A.5** The internal structure of a system affects the analysis of that system.
  - **2.1.A.6** As variables external to a system are changed, the system's substructure may change.
- **2.1.B** Describe the location of a system's center of mass with respect to the system's constituent parts.
  - **2.1.B.1** For systems with symmetrical mass distributions, the center of mass is located on lines of symmetry.
  - **2.1.B.2** The location of a system's center of mass along a given axis can be calculated using the equation
  - **2.1.B.3** A system can be modeled as a singular object that is located at the system's center of mass.

- **2.2.A** Describe a force as an interaction between two objects or systems.
    - **2.2.A.1** Forces are vector quantities that describe the interactions between objects or systems.
        - **2.2.A.1.i** A force exerted on an object or system is always due to the interaction of that object with another object or system.
        - **2.2.A.1.ii** An object or system cannot exert a net force on itself.
    - **2.2.A.2** Contact forces describe the interaction of an object or system touching another object or system and are macroscopic effects of interatomic electric forces.
- **2.2.B** Describe the forces exerted on an object or system using a free-body diagram
    - **2.2.B.1** Free-body diagrams are useful tools for visualizing forces being exerted on a single object or system and for determining the equations that represent a physical situation.
    - **2.2.B.2** The free-body diagram of an object or system shows each of the forces exerted on the object by the environment.
    - **2.2.B.3** Forces exerted on an object or system are represented as vectors originating from the representation of the center of mass, such as a dot. A system is treated as though all of its mass is located at the center of mass.
    - **2.2.B.4** A coordinate system with one axis parallel to the direction of acceleration of the object or system simplifies the translation from free-body diagram to algebraic representation. For example, in a free-body diagram of an object on an inclined plane, it is useful to set one axis parallel to the surface of the incline.
- **2.3.A** Describe the interaction of two objects using Newton's third law and a representation of paired forces exerted on each object.
    - **2.3.A.1** Newton's third law describes the interaction of two objects in terms of the paired forces that each exerts on the other.
    - **2.3.A.2** Interactions between objects within a system (internal forces) do not influence the motion of a system's center of mass.
    - **2.3.A.3** Tension is the macroscopic net result of forces that segments of a string, cable, chain, or similar system exert on each other in response to an external force.
        - **2.3.A.3.i** An ideal string has negligible mass and does not stretch when under tension.

        - **2.3.A.3.ii** The tension in an ideal string is the same at all points within the string.
        - **2.3.A.3.iii** In a string with nonnegligible mass, tension may not be the same at all points within the string.
        - **2.3.A.3.iv** An ideal pulley is a pulley that has negligible mass and rotates about an axle through its center of mass with negligible friction.
- **2.4.A** Describe the conditions under which a system's velocity remains constant.
    - **2.4.A.1** The net force on a system is the vector sum of all forces exerted on the system.
    - **2.4.A.2** Translational equilibrium is a configuration of forces such that the net force exerted on a system is zero.
    - **2.4.A.3** Newton's first law states that if the net force exerted on a system is zero, the velocity of that system will remain constant.
    - **2.4.A.4** Forces may be balanced in one dimension but unbalanced in another. The system's velocity will change only in the direction of the unbalanced force.
    - **2.4.A.5** An inertial reference frame is one from which an observer would verify Newton's first law of motion.
- **2.5.A** Describe the conditions under which a system's velocity changes.
    - **2.5.A.1** Unbalanced forces are a configuration of forces such that the net force exerted on a system is not equal to zero.
    - **2.5.A.2** Newton's second law of motion states that the acceleration of a system's center of mass has a magnitude proportional to the magnitude of the net force exerted on the system and is in the same direction as that net force.
    - **2.5.A.3** The velocity of a system's center of mass will only change if a nonzero net external force is exerted on that system.
- **2.6.A** Describe the gravitational interaction between two objects or systems with mass.
    - **2.6.A.1** Newton's law of universal gravitation describes the gravitational force between two objects or systems as directly proportional to each of their masses and inversely proportional to the square of the distance between the systems' centers of mass.
        - **2.6.A.1.i** The gravitational force is attractive.

        - **2.6.A.1.ii** The gravitational force is always exerted along the line connecting the centers of mass of the two interacting systems.
        - **2.6.A.1.iii** The gravitational force on a system can be considered to be exerted on the system’s center of mass.
    - **2.6.A.2** A field models the effects of a noncontact force exerted on an object at various positions in space.
        - **2.6.A.2.i** The magnitude of the gravitational field created by a system of mass M at a point in space is equal to the ratio of the gravitational force exerted by the system on a test object of mass m to the mass of the test object.
        - **2.6.A.2.ii** If the gravitational force is the only force exerted on an object, the observed acceleration of the object (in m/s^2) is numerically equal to the magnitude of the gravitational field strength (in N/Kg) at that location.
    - **2.6.A.3** The gravitational force exerted by an astronomical body on a relatively small nearby object is called weight.
- **2.6.B** Describe situations in which the gravitational force can be considered constant.
    - **2.6.B.1** If the gravitational force between two systems’ centers of mass has a negligible change as the relative position of the two systems changes, the gravitational force can be considered constant at all points between the initial and final positions of the systems.
    - **2.6.B.2** Near the surface of Earth, the strength of the gravitational field is g=10 N/kg
- **2.6.C** Describe the conditions under which the magnitude of a system’s apparent weight is different from the magnitude of the gravitational force exerted on that system.
    - **2.6.C.1** The magnitude of the apparent weight of a system is the magnitude of the normal force exerted on the system.
    - **2.6.C.2** If the system is accelerating, the apparent weight of the system is not equal to the magnitude of the gravitational force exerted on the system.
    - **2.6.C.3** A system appears weightless when there are no forces exerted on the system or when the force of gravity is the only force exerted on the system.
    - **2.6.C.4** The equivalence principle states that an observer in a non

inertial reference frame is unable to distinguish between an object's apparent weight and the gravitational force exerted on the object by a gravitational field.

- **2.6.D** Describe inertial and gravitational mass.
  - **2.6.D.1** Objects have inertial mass, or inertia, a property that determines how much an object's motion resists changes when interacting with another object.
  - **2.6.D.2** Gravitational mass is related to the force of attraction between two systems with mass.
  - **2.6.D.3** Inertial mass and gravitational mass have been experimentally verified to be equivalent.
- **2.7.A** Describe kinetic friction between two surfaces
  - **2.7.A.1** Kinetic friction occurs when two surfaces in contact move relative to each other.
    - 2.7.A.1.i The kinetic friction force is exerted in a direction opposite to the motion of each surface relative to the other surface.
    - 2.7.A.1.ii The force of friction between two surfaces does not depend on the size of the surface area of contact.
  - **2.7.A.2** The magnitude of the kinetic friction force exerted on an object is the product of the normal force the surface exerts on the object and the coefficient of kinetic friction.
    - 2.7.A.2.i The coefficient of kinetic friction depends on the material properties of the surfaces that are in contact.
    - 2.7.A.2.ii Normal force is the perpendicular component of the force exerted on an object by the surface with which it is in contact; it is directed away from the surface.
- **2.7.B** Describe static friction between two surfaces.
  - 2.7.B.1 Static friction may occur between the contacting surfaces of two objects that are not moving relative to each other.
  - 2.7.B.2 Static friction adopts the value and direction required to prevent an object from slipping or sliding on a surface.
    - 2.7.B.2.i Slipping and sliding refer to situations in which two surfaces are moving relative to each other.
    - 2.7.B.2.ii There exists a maximum value for which static friction will prevent an object from slipping on a given surface.
  - 2.7.B.3 The coefficient of static friction is typically greater than the

coefficient of kinetic friction for a given pair of surfaces.

- **2.8.A** Describe the force exerted on an object by an ideal spring
    - 2.8.A.1 An ideal spring has negligible mass and exerts a force that is proportional to the change in its length as measured from its relaxed length.
    - 2.8.A.2 The magnitude of the force exerted by an ideal spring on an object is given by Hooke's law.
    - 2.8.A.3 The force exerted on an object by a spring is always directed toward the equilibrium position of the object–spring system.
- 2.9.A Describe the motion of an object traveling in a circular path.
    - 2.9.A.1 Centripetal acceleration is the component of an object's acceleration directed toward the center of the object's circular path.
        - 2.9.A.1.i The magnitude of centripetal acceleration for an object moving in a circular path is the ratio of the object's tangential speed squared to the radius of the circular path.
        - 2.9.A.1.ii Centripetal acceleration is directed toward the center of an object's circular path.
    - 2.9.A.2 Centripetal acceleration can result from a single force, more than one force, or components of forces exerted on an object in circular motion.
        - 2.9.A.2.i At the top of a vertical, circular loop, an object requires a minimum speed to maintain circular motion. At this point, and with this minimum speed, the gravitational force is the only force that causes the centripetal acceleration.
        - 2.9.A.2.ii Components of the static friction force and the normal force can contribute to the net force producing centripetal acceleration of an object traveling in a circle on a banked surface.
        - 2.9.A.2.iii A component of tension contributes to the net force producing centripetal acceleration experienced by a conical pendulum.
    - 2.9.A.3 Tangential acceleration is the rate at which an object's speed changes and is directed tangent to the object's circular path.
    - 2.9.A.4 The net acceleration of an object moving in a circle is the vector sum of the centripetal acceleration and tangential acceleration.
    - 2.9.A.5 The revolution of an object traveling in a circular path at a

constant speed (uniform circular motion) can be described using period and frequency.

    - 2.9.A.5.i The time to complete one full circular path, one full rotation, or a full cycle of oscillatory motion is defined as period, T.
    - 2.9.A.5.ii The rate at which an object is completing revolutions is defined as frequency, f.
    - 2.9.A.5.iii For an object traveling at a constant speed in a circular path, the period is given by the derived equation

- 2.9.B Describe circular orbits using Kepler's third law.
  - 2.9.B.1 For a satellite in circular orbit around a central body, the satellite's centripetal acceleration is caused only by gravitational attraction. The period and radius of the circular orbit are related to the mass of the central body.

Supporting Standards

These state standards are included in the student learning experiences for this unit and may be assessed.

- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.
- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
- 3.C. Justify or support a claim using evidence from experimental data,

physical representations, or physical principles or laws.

Unit 3
Unit Title: Work, Energy & Power

Essential Question

- If energy is conserved, why are we running out of it?
- Why it is impossible to build a perpetual motion machine?
- Does pushing an object always change its energy?
- Why does it seem easier to carry a large box- up a ramp rather than up a set of stairs?

Unit Summary

In this unit students are introduced to the idea of conservations as a foundational principle of physics, along with the concept of work as the primary agent of change for energy. As in earlier units, students will once again utilize both familiar and new models and representations to analyze physical situations, now with force or energy as major components. Students will be encouraged to call upon their knowledge of content and skills in unit 1 and unit 2 to determine the most appropriate technique for approaching a problem and will be challenged to understand the limiting factors of each technique.

Guiding Questions

At the end of this unit, students should be able to respond to these questions as they demonstrate understanding of key concepts, skills and relevance to their own lives.

Content

- What is work, and how can it be calculated in different physical contexts?
- What is the Work-Energy Theorem, and how does it relate to changes in kinetic energy?
- How can potential energy be described and calculated for systems with conservative forces (e.g., gravitational, elastic)?
- What is mechanical energy, and how is it conserved in the absence of non-conservative forces?
- How can energy transfers between kinetic, potential, and other forms be represented in a system?
- What is power, and how can it be calculated in terms of work done or energy

transferred over time?
- What is the relationship between power and work in energy transformations?
- How can the potential energy of a system containing more than two objects be described and calculated?

Process

What is the relationship between work, force, and displacement, and how can it be calculated?

- How does the Work-Energy Theorem relate work to changes in kinetic energy?
- When can gravitational and elastic potential energy be calculated in various systems?
- How can energy bar charts and pie charts represent energy transfers between kinetic, potential, and other forms?
- Why is total mechanical energy conserved in the absence of non-conservative forces?
- How can force vs. displacement graphs be interpreted to calculate work as the area under the curve?
- What role do non-conservative forces like friction play in energy changes?
- When can power be calculated as the rate of energy transfer or work done over time?

Reflective:

- How does the concept of work help machines like pulleys or ramps make lifting objects easier?
- Why is the Work-Energy Theorem useful for analyzing vehicle performance during acceleration and braking?
- When can the conservation of mechanical energy be applied to evaluate roller coaster designs in frictionless conditions?
- How is gravitational potential energy harnessed in systems like hydroelectric dams or energy reservoirs?
- Why is elastic potential energy important in devices such as trampolines, archery bows, or vehicle suspensions?
- How can the conservation of mechanical energy predict the motion of objects in sports like basketball shots or pole vaults?
- How do different surfaces, like grass versus asphalt, impact energy losses due to friction in real-world scenarios?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- 3.1.A Describe the translational kinetic energy of an object in terms of the object's mass and velocity.
    - 3.1.A.1 An object's translational kinetic energy is given by the equation
    - 3.1.A.2 Translational kinetic energy is a scalar quantity.
    - 3.1.A.3 Different observers may measure different values of the translational kinetic energy of an object, depending on the observer's frame of reference.
- 3.2.A Describe the work done on an object or system by a given force or collection of forces.
    - 3.2.A.1 Work is the amount of energy transferred into or out of a system by a force exerted on that system over a distance.
        - 3.2.A.1.i The work done by a conservative force exerted on a system is path-independent and only depends on the initial and final configurations of that system.
        - 3.2.A.1.ii The work done by a conservative force on a system—or the change in the potential energy of the system—will be zero if the system returns to its initial configuration.
        - 3.2.A.1.iii Potential energies are associated only with conservative forces.
        - 3.2.A.1.iv The work done by a nonconservative force is path-dependent.
    - 3.2.A.2 Work is a scalar quantity that may be positive, negative, or zero.
    - 3.2.A.3 The amount of work done on a system by aconstant force is related to the components of that force and the displacement of the point at which that force is exerted.
        - 3.2.A.3.i Only the component of the force exerted on a system that is parallel to the displacement of the point of application of the force will change the system's total energy.
        - 3.2.A.3.ii The component of the force exerted on a system perpendicular to the direction of the displacement of the system's center of mass can change the direction of the system's motion

without changing the system's kinetic energy.

- 3.2.A.4 The work-energy theorem states that the change in an object's kinetic energy is equal to the sum of the work (net work) being done by all forces exerted on the object.
    - 3.2.A.4.i An external force may change the configuration of a system. The component of the external force parallel to the displacement times the displacement of the point of application of the force gives the change in kinetic energy of the system.
    - 3.2.A.4.ii If the system's center of mass and the point of application of the force move the same distance when a force is exerted on a system, then the system may be modeled as an object, and only the system's kinetic energy can change.
    - 3.2.A.4.iii The energy dissipated by friction is typically equated to the force of friction times the length of the path over which the force is exerted
  - 3.2.A.5 Work is equal to the area under the curve of a graph of F as a function of displacement.
- 3.3.A Describe the potential energy of a system.
  - 3.3.A.1 A system composed of two or more objects has potential energy if the objects within that system only interact with each other through conservative forces.
  - 3.3.A.2 Potential energy is a scalar quantity associated with the position of objects within a system.
  - 3.3.A.3 The definition of zero potential energy for a given system is a decision made by the observer considering the situation to simplify or otherwise assist in analysis.
  - 3.3.A.4 The potential energy of common physical systems can be described using the physical properties of that system.
    - 3.3.A.4.i The elastic potential energy of an ideal spring is given by the following equation, where ✓x is the distance the spring has been stretched or compressed from its equilibrium length.
    - 3.3.A.4.ii The general form for the gravitational potential energy of a system consisting of two approximately spherical distributions of mass (e.g., moons, planets or stars) is given by the equation.
    - 3.3.A.4.iii Because the gravitational field near the surface of a planet is nearly constant, the change in gravitational potential

energy in a system consisting of an object with mass m and a planet with gravitational field of magnitude g when the object is near the surface of the planet may be approximated by the equation

   - 3.3.A.5 The total potential energy of a system containing more than two objects is the sum of the potential energy of each pair of objects within the system.
- 3.4.A Describe the energies present in a system
   - 3.4.A.1 A system composed of only a single object can only have kinetic energy.
   - 3.4.A.2 A system that contains objects that interact via conservative forces or that can change its shape reversibly may have both kinetic and potential energies.
- 3.4.B Describe the behavior of a system using conservation of mechanical energy principles.
   - 3.4.B.1 Mechanical energy is the sum of a system's kinetic and potential energies.
   - 3.4.B.2 Any change to a type of energy within a system must be balanced by an equivalent change of other types of energies within the system or by a transfer of energy between the system and its surroundings.
   - 3.4.B.3 A system may be selected so that the total energy of that system is constant.
   - 3.4.B.4 If the total energy of a system changes, that change will be equivalent to the energy transferred into or out of the system.
- 3.4.C Describe how the selection of a system determines whether the energy of that system changes.
   - 3.4.C.1 Energy is conserved in all interactions.
   - 3.4.C.2 If the work done on a selected system is zero and there are no nonconservative interactions within the system, the total mechanical energy of the system is constant.
   - 3.4.C.3 If the work done on a selected system is nonzero, energy is transferred between the system and the environment.
- 3.5.A Describe the transfer of energy into, out of, or within a system in terms of power.
   - 3.5.A.1 Power is the rate at which energy changes with respect to time,

either by transfer into or out of a system or by conversion from one type to another within a system.
- 3.5.A.2 Average power is the amount of energy being transferred or converted, divided by the time it took for that transfer or conversion to occur.
- 3.5.A.3 Because work is the change in energy of an object or system due to a force, average power is the total work done, divided by the time during which that work was done
- 3.5.A.4 The instantaneous power delivered to anobject by the component of a constant force parallel to the object's velocity can be described with the derived equation.

Annually PLCs are able to add 1-3 additional priority standards, as needed, based on their students' achievement and growth data.

Supporting Standards

These state standards are included in the student learning experiences for this unit and may be assessed.

- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.
- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws

Unit 4
Unit Title: Linear Momentum

Essential Question

- How does jet propulsion work?
- When two football players collide... who wins?
- How can you measure the speed of a bullet?

Unit Summary

Unit 4 introduces students to the relationships between force, time, impulse, and linear momentum via calculations, data analysis, designing experiments, and making predictions. Students will learn how to use new models and representations to illustrate the law of conservation of linear momentum of objects and systems while gaining proficiency using previously studied representations. Using the law of conservation of linear momentum to analyze physical situations provides students with a more complete picture of forces and opportunities to revisit misconceptions surrounding Newton's third law. Students will also have the opportunity to make connections between momentum and kinetic energy of objects or systems and see under what conditions these quantities remain constant.

Guiding Questions

Content

- What is the linear momentum of an object, and how does it differ from kinetic energy?
- How can the concepts of momentum, center of mass, and system be used to predict the behavior of objects in everyday situations?
- Under what conditions is the total momentum of a system constant, and why is total momentum conserved in a collision?
- What are the differences and similarities between elastic, inelastic, and completely inelastic collisions?
- How can the conservation of momentum and mechanical energy be applied to problems involving elastic collisions?
- How are an object's momentum change, the force causing the change, and the time over which the force is exerted related?
- How can the center of mass of a system be found, and how does the net force on a system affect the motion of the system's center of mass?

Skills

- How can force vs. time graphs be interpreted to calculate impulse and predict momentum changes?
- What insights can mass vs. velocity graphs provide about momentum changes in different systems?
- When can momentum vs. time graphs be used to determine external forces and collision dynamics?
- Why is designing experiments important to validate the impulse-momentum theorem and momentum conservation?
- How can free-body diagrams, momentum bar charts, and equations represent collision systems effectively?
- When should conservation of momentum be applied to calculate post-collision velocities in real-world scenarios?
- How does the impulse-momentum theorem explain the effects of forces in airbags, sports impacts, or similar situations?
- What role does the center of mass play in predicting motion and collision outcomes in a system?

Reflective

- How does momentum conservation explain recoil in firearms, rocket propulsion, and crash safety features?
- What is the difference between elastic and inelastic collisions, and how do they apply in sports or real-life impacts?
- Why is the concept of impulse important in reducing forces during impacts using equipment like helmets and pads?
- How can the motion of the center of mass explain stability, balance, and movement in activities like gymnastics, diving, or seesaws?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- **4.1.A** Describe the linear momentum of an object or system.
    - 4.1.A.1 Linear momentum is defined by the equation $p = mv$.
    - 4.1.A.2 Momentum is a vector quantity and has the same direction as

the velocity.

    - 4.1.A.3 Momentum can be used to analyze collisions and explosions.
        - 4.1.A.3.i A collision is a model for an interaction where the forces exerted between the involved objects in the system are much larger than the net external force exerted on those objects during the interaction.
        - 4.1.A.3.ii An explosion is a model for an interaction in which forces internal to the system move objects within that system apart.
- 4.2.A Describe the impulse delivered to an object or system.
    - 4.2.A.1 The rate of change of momentum is equal to the net external force exerted on an object or system.
    - 4.2.A.2 Impulse is defined as the product of the average force exerted on a system and the time interval during which that force is exerted on the system.
    - 4.2.A.3 Impulse is a vector quantity and has the same direction as the net force exerted on the system.
    - 4.2.A.4 The impulse delivered to a system by a net external force is equal to the area under the curve of a graph of the net external force exerted on the system as a function of time.
    - 4.2.A.5 The net external force exerted on a system is equal to the slope of a graph of the momentum of the system as a function of time.
- 4.2.B Describe the relationship between the impulse exerted on an object or a system and the change in momentum of the object or system.
    - 4.2.B.1 Change in momentum is the difference between a system's final momentum and its initial momentum.
    - 4.2.B.2 The impulse–momentum theorem relates the impulse exerted on a system and the system's change in momentum.
    - 4.2.B.3 Newton's second law of motion is a direct result of the impulse–momentum theorem applied to systems with constant mass.
- 4.3.A Describe the behavior of a system using conservation of linear momentum.
    - 4.3.A.1 A collection of objects with individual momenta can be described as one system with one center-of-mass velocity.
        - 4.3.A.1.i For a collection of objects, the velocity of a system's center of mass can be calculated using the equation
        - 4.3.A.1.ii The velocity of a system's center of mass is constant in

the absence of a net external force.

    - 4.3.A.2 The total momentum of a system is the sum of the momenta of the system’s constituent parts.
    - 4.3.A.3 In the absence of net external forces, any change to the momentum of an object within a system must be balanced by an equivalent and opposite change of momentum elsewhere within the system. Any change to the momentum of a system is due to a transfer of momentum between the system and its surroundings.
        - 4.3.A.3.i The impulse exerted by one object on a second object is equal and opposite to the impulse exerted by the second object on the first. This is a direct result of Newton’s third law.
        - 4.3.A.3.ii A system may be selected so that the total momentum of that system is constant.
        - 4.3.A.3.iii If the total momentum of a system changes, that change will be equivalent to the impulse exerted on the system.
    - 4.3.A.4 Correct application of conservation of momentum can be used to determine the velocity of a system immediately before and immediately after collisions or explosions.
- 4.3.B Describe how the selection of a system determines whether the momentum of that system changes.
    - 4.3.B.1 Momentum is conserved in all interactions.
    - 4.3.B.2 If the net external force on the selected system is zero, the total momentum of the system is constant.
    - 4.3.B.3 If the net external force on the selected system is nonzero, momentum is transferred between the system and the environment.
- 4.4.A Describe whether an interaction between objects is elastic or inelastic.
    - 4.4.A.1 An elastic collision between objects is one in which the initial kinetic energy of the system is equal to the final kinetic energy of the system.
    - 4.4.A.2 In an elastic collision, the final kinetic energies of each of the objects within the system may be different from their initial kinetic energies.
    - 4.4.A.3 An inelastic collision between objects is one in which the total kinetic energy of the system decreases.
    - 4.4.A.4 In an inelastic collision, some of the initial kinetic energy is not restored to kinetic energy but is transformed by nonconservative forces

into other forms of energy.

- 4.4.A.5 In a perfectly inelastic collision, the objects stick together and move with the same velocity after the collision.

Annually PLCs are able to add 1-3 additional priority standards, as needed, based on their students' achievement and growth data.

Supporting Standards

These state standards are included in the student learning experiences for this unit and may be assessed.

- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.
- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Unit 5
Unit Title: Torque and Rotational Dynamics

Essential Question

- Why does it matter where a door handle is placed?
- Why are long wrenches more effective?
- Why is it best to lift heavy objects with your knees bent and the object near your body?
- What do mobiles have in common with the Grand Canyon Skywalk?
- Why does a tightrope walker use a long pole?

Unit Summary

Unit 5 reinforces force and linear motion by introducing students to their rotational analogs – torque and rotational motion. Although these topics present more complex scenarios, the tools of analysis remain the same. During their study of torque and rotational motion, students will be introduced to different ways of modeling forces. Throughout units 5 & 6, students will compare and connect their understanding of linear and rotational motion, dynamics, energy, and momentum to develop holistic models to evaluate physical phenomena.

Guiding Questions

Content

- What is angular displacement, angular velocity, and angular acceleration, and how do they differ from linear motion quantities?
- How can rotational kinematic equations be used to explain the relationships between angular quantities and time?
- What is the analogy between linear and rotational kinematics, and how can rotational motion graphs be interpreted?
- What is the relationship between linear and angular velocity, and what factors, such as the radius of rotation, affect it?
- How can linear motion quantities (displacement, velocity, acceleration) be calculated from angular parameters?
- What is torque, how does it differ from force, and how can net torque be calculated in various situations?
- What factors affect torque, including force magnitude, direction, and lever arm distance?

- What is rotational inertia, how does it depend on mass distribution, and how does it compare for different shapes?
- How can rotational equilibrium be analyzed by applying Newton's First Law in rotational form?
- How can Newton's Second Law in rotational form be applied to calculate angular acceleration using torque and rotational inertia?

Process

- How can qualitative sketches of angular velocity and angular displacement vs. time graphs be created for different rotational scenarios?
- What symbolic relationships describe angular displacement, velocity, acceleration, and time in rotational kinematics?
- When should you compare angular quantities between multiple rotating objects under different conditions?
- How can you derive a symbolic expression for linear velocity using angular velocity and radius?
- Why does mass distribution affect rotational inertia, and how can you compare rotational inertia in objects like disks and hoops?
- How can net torque be calculated and compared in systems with varying force magnitudes, lever arms, and angles of application?
- Why is analyzing torque and force balance important in determining rotational equilibrium?

Reflective

- How do torque, rotational inertia, and radius of rotation improve the efficiency and motion of tools and systems like wrenches, drills, and fans?
- How can principles of rotational equilibrium and mass distribution ensure stability and control in structures like cranes, seesaws, and baseball bats?
- How do rotational inertia and angular acceleration affect the design of systems such as flywheels, gears, and figure skaters' spins?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- 5.1.A Describe the rotation of a system with respect to time using angular displacement, angular velocity, and angular acceleration

- 5.1.A.1 Angular displacement is the measurement of the angle, in radians, through which a point on a rigid system rotates about a specified axis.
  - 5.1.A.1.i A rigid system is one that holds its shape but in which different points on the system move in different directions during rotation.
  - 5.1.A.1.ii One direction of angular displacement about an axis of rotation—clockwise or counterclockwise—is typically indicated as mathematically positive, with the other direction becoming mathematically negative.
  - 5.1.A.1.iii If the rotation of a system about an axis may be well described using the motion of the system's center of mass, the system may be treated as a single object. For example, the rotation of Earth about its axis may be considered negligible when considering the revolution of Earth about the center of mass of the Earth–Sun system.
- 5.1.A.2 Average angular velocity is the average rate at which angular position changes with respect to time.
- 5.1.A.3 Average angular acceleration is the average rate at which the angular velocity changes with respect to time.
- 5.1.A.4 Angular displacement, angular velocity, and angular acceleration around one axis are analogous to linear displacement, velocity, and acceleration in one dimension and demonstrate the same mathematical relationships.
  - 5.1.A.4.i For constant angular acceleration, the mathematical relationships between angular displacement, angular velocity, and angular acceleration can be described using rotational kinematics equations.
  - 5.1.A.4.ii Graphs of angular displacement, angular velocity, and angular acceleration as functions of time can be used to find the relationships between those quantities.

- **5.2.A** Describe the linear motion of a point on a rotating rigid system that corresponds to the rotational motion of that point, and vice versa.
  - 5.2.A.1 For a point at a distance r from a fixed axis of rotation, the linear distance s traveled by the point as the system rotates through an angle

- 5.2.A.2 Derived relationships of linear velocity and of the tangential component of acceleration to their respective angular quantities are given by the following equations
- 5.2.A.3 For a rigid system, all points within that system have the same angular velocity and angular acceleration.

- 5.3.A Identify the torques exerted on a rigid system.
  - 5.3.A.1 Torque results only from the force component perpendicular to the position vector from the axis of rotation to the point of application of the force.
  - 5.3.A.2 The lever arm is the perpendicular distance from the axis of rotation to the line of action of the exerted force.
- 5.3.B Describe the torques exerted on a rigid system.
  - 5.3.B.1 Torques can be described using force diagrams.
    - 5.3.B.1.i Force diagrams are similar to free-body diagrams and are used to analyze the torques exerted on a rigid system.
    - 5.3.B.1.ii Similar to free-body diagrams, force diagrams represent the relative magnitude and direction of the forces exerted on a rigid system. Force diagrams also depict the location at which those forces are exerted relative to the axis of rotation.
  - 5.3.B.2 The magnitude of the torque exerted on a rigid system by a force is described by the following equation, where theta is the angle between the force vector and the position vector from the axis of rotation to the point of application of the force.
- 5.4.A Describe the rotational inertia of a rigid system relative to a given axis of rotation.
  - 5.4.A.1 Rotational inertia measures a rigid system's resistance to changes in rotation and is related to the mass of the system and the distribution of that mass relative to the axis of rotation.
  - 5.4.A.2 The rotational inertia of an object rotating a perpendicular distance r from an axis is described by the equation.
  - 5.4.A.3 The total rotational inertia of a collection of objects about an axis is the sum of the rotational inertias of each object about that axis
- 5.4.B Describe the rotational inertia of a rigid system rotating about an axis that does not pass through the system's center of mass.
  - 5.4.B.1 A rigid system's rotational inertia in a given plane is at a minimum when the rotational axis passes through the system's center

of mass.

    - 5.4.B.2 The parallel axis theorem uses the following equation to relate the rotational inertia of a rigid system about any axis that is parallel to an axis through its center of mass:
- 5.5.A Describe the conditions under which a system's angular velocity remains constant.
    - 5.5.A.1 A system may exhibit rotational equilibrium (constant angular velocity) without being in translational equilibrium, and vice versa.
        - 5.5.A.1.i Free-body and force diagrams describe the nature of the forces and torques exerted on an object or rigid system.
        - 5.5.A.1.ii Rotational equilibrium is a configuration of torques such that the net torque exerted on the system is zero
        - 5.5.A.1.iii The rotational analog of Newton's first law is that a system will have a constant angular velocity only if the net torque exerted on the system is zero.
    - 5.5.A.2 A rotational corollary to Newton's second law states that if the torques exerted on a rigid system are not balanced, the system's angular velocity must be changing.
- 5.6.A Describe the conditions under which a system's angular velocity changes.
    - 5.6.A.1 Angular velocity changes when the net torque exerted on the object or system is not equal to zero.
    - 5.6.A.2 The rate at which the angular velocity of a rigid system changes is directly proportional to the net torque exerted on the rigid system and is in the same direction. The angular acceleration of the rigid system is inversely proportional to the rotational inertia of the rigid system.
    - 5.6.A.3 To fully describe a rotating rigid system, linear and rotational analyses may need to be performed independently.

Annually PLCs are able to add 1-3 additional priority standards, as needed, based on their students' achievement and growth data.

Supporting Standards

These state standards are included in the student learning experiences for this unit and may be assessed.

- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.
- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Unit 6
Unit Title: Energy and Momentum of Rotating Systems

Essential Question

- Why do planets move faster when they travel closer to the sun?
- What do ice skaters do with their arms when they want to spin faster? Why?
- Why is it more difficult to balance on a stopped bike than on a moving bike?
- How does a diver control her rotation rate during a dive?

Unit Summary

In unit 6, students will apply their knowledge of energy and momentum to rotating systems. Similar to the approach used for translational energy and momentum concepts in Unit 3 and 4, it is important that students have conceptual understanding of how angular momentum and rotational energy change due to external torque(s) on a system. Additionally, articulating the conditions under which the rotational energy and/or angular momentum of a system remains constant is foundational to working through more complex scenarios. Students will use the content and skills presented in both Units 5 and 6 to further study the motion of orbiting satellites and rolling without slipping in this unit.

Guiding Questions

Content

- What is the relationship between rotational kinetic energy and translational kinetic energy in rolling objects?
- What factors affect rotational kinetic energy, including moment of inertia and angular velocity?
- How can the total kinetic energy of a system with both rotational and translational motion be calculated?
- How do changes in angular velocity impact rotational kinetic energy?
- What is angular momentum, and what variables does it depend on?
- How can angular impulse be applied to changes in angular momentum?
- How does changing the moment of inertia affect angular momentum?
- What is the role of torque in rotational motion compared to force in linear motion?
- How can conservation of angular momentum be applied to real-world phenomena like a spinning figure skater or orbiting satellites?

Process

- How can a graph of rotational kinetic energy versus angular velocity be constructed, and why is it justified using energy conservation principles?
- What factors should be considered when comparing rotational and translational kinetic energy, and how can differences be justified using moments of inertia?
- When analyzing a rolling object, how can the forces and torques be diagrammed to determine the conditions for rolling without slipping, and why is this important?
- How can orbital speeds and periods for satellites at different radii be calculated using Newton's laws, and when is this useful?
- How can angular momentum be determined from given quantities, and why is this calculation justified by physical principles?
- How can angular momentum conservation principles be applied to compare angular velocities before and after a change in moment of inertia, and when should this approach be used?

Reflective

- How do moment of inertia and angular velocity influence the performance of machinery like wind turbines or flywheels?
- How is total kinetic energy calculated in systems with both rotational and translational motion, and how does this apply to rolling objects like wheels or bowling balls?
- How do changes in moment of inertia and angular velocity affect devices like electric motors, spinning hard drives, or a skater pulling in their arms?
- How are the principles of angular momentum used to stabilize bicycles, spacecraft, and sports like gymnastics or figure skating?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- 6.1.A Describe the rotational kinetic energy of a rigid system in terms of the rotational inertia and angular velocity of that rigid system.
  - 6.1.A.1 The rotational kinetic energy of an object or rigid system is related to the rotational inertia and angular velocity of the rigid system and is given by the equation

- 6.1.A.1.i The rotational inertia of an object about a fixed axis can be used to show that the rotational kinetic energy of that object is equivalent to its translational kinetic energy, which is its total kinetic energy.
- 6.1.A.1.ii The total kinetic energy of a rigid system is the sum of its rotational kinetic energy due to its rotation about its center of mass and the translational kinetic energy due to the linear motion of its center of mass.

- 6.1.A.2 A rigid system can have rotational kinetic energy while its center of mass is at rest due to the individual points within the rigid system having linear speed and, therefore, kinetic energy.
- 6.1.A.3 Rotational kinetic energy is a scalar quantity.

- 6.2.A Describe the work done on a rigid system by a given torque or collection of torques.
  - 6.2.A.1 A torque can transfer energy into or out of an object or rigid system if the torque is exerted over an angular displacement.
  - 6.2.A.2 The amount of work done on a rigid system by a torque is related to the magnitude of that torque and the angular displacement through which the rigid system rotates during the interval in which that torque is exerted.
  - 6.2.A.3 Work done on a rigid system by a given torque can be found from the area under the curve of a graph of torque as a function of angular position.
- 6.3.A Describe the angular momentum of an object or rigid system.
  - 6.3.A.1 The magnitude of the angular momentum of a rigid system about a specific axis can be described with the equation
  - 6.3.A.2 The magnitude of the angular momentum of an object about a given point is
    - 6.3.A.2.i The selection of the axis about which an object is considered to rotate influences the determination of the angular momentum of that object.
    - 6.3.A.2.ii The measured angular momentum of an object traveling in a straight line depends on the distance between the reference point and the object, the mass of the object, the speed of the object, and the angle between the radial distance and the velocity of the object.

- 6.3.B Describe the angular impulse delivered to an object or rigid system by a torque.
    - 6.3.B.1 Angular impulse is defined as the product of the torque exerted on an object or rigid system and the time interval during which the torque is exerted.
    - 6.3.B.2 Angular impulse has the same direction as the torque exerted on the object or system.
    - 6.3.B.3 The angular impulse delivered to an object or rigid system by a torque can be found from the area under the curve of a graph of the torque as a function of time.
- 6.3.C Relate the change in angular momentum of an object or rigid system to the angular impulse given to that object or rigid system.
    - 6.3.C.1 The magnitude of the change in angular momentum can be described by comparing the magnitudes of the final and initial angular momenta of the object or rigid system:
    - 6.3.C.2 A rotational form of the impulse–momentum theorem relates the angular impulse delivered to an object or rigid system and the change in angular momentum of that object or rigid system.
        - 6.3.C.2.i The angular impulse exerted on an object or rigid system is equal to the change in angular momentum of that object or rigid system.
        - 6.3.C.2.ii The rotational form of the impulse–momentum theorem is a direct result of the rotational form of Newton's second law of motion for cases in which rotational inertia is constant:
    - 6.3.C.3 The net torque exerted on an object is equal to the slope of the graph of the angular momentum of an object as a function of time.
    - 6.3.C.4 The angular impulse delivered to an object is equal to the area under the curve of a graph of the net external torque exerted on an object as a function of time.
- 6.4.A Describe the behavior of a system using conservation of angular momentum.
    - 6.4.A.1 The total angular momentum of a system about a rotational axis is the sum of the angular momenta of the system's constituent parts about that axis.
    - 6.4.A.2 Any change to a system's angular momentum must be due to an interaction between the system and its surroundings.

        - 6.4.A.2.i The angular impulse exerted by one object or system on a second object or system is equal and opposite to the angular impulse exerted by the second object or system on the first. This is a direct result of Newton's third law.
        - 6.4.A.2.ii A system may be selected so that the total angular momentum of that system is constant.
        - 6.4.A.2.iii The angular speed of a nonrigid system may change without the angular momentum of the system changing if the system changes shape by moving mass closer to or further from the rotational axis.
        - 6.4.A.2.iv If the total angular momentum of a system changes, that change will be equivalent to the angular impulse exerted on the system.
- 6.4.B Describe how the selection of a system determines whether the angular momentum of that system changes.
    - 6.4.B.1 Angular momentum is conserved in all interactions.
    - 6.4.B.2 If the net external torque exerted on a selected object or rigid system is zero, the total angular momentum of that system is constant.
    - 6.4.B.3 If the net external torque exerted on a selected object or rigid system is nonzero, angular momentum is transferred between the system and the environment.
- 6.5.A Describe the kinetic energy of a system that has translational and rotational motion.
    - 6.5.A.1 The total kinetic energy of a system is the sum of the system's translational and rotational kinetic energies.
- 6.5.B Describe the motion of a system that is rolling without slipping.
    - 6.5.B.1 While rolling without slipping, the translational motion of a system's center of mass is related to the rotational motion of the system itself with the equations.
    - 6.5.B.2 For ideal cases, rolling without slipping implies that the frictional force does not dissipate any energy from the rolling system.
- 6.5.C Describe the motion of a system that is rolling while slipping.
    - 6.5.C.1 When slipping, the motion of a system's center of mass and the system's rotational motion cannot be directly related.
    - 6.5.C.2 When a rotating system is slipping relative to another surface, the point of application of the force of kinetic friction exerted on the

system moves with respect to the surface, so the force of kinetic friction will dissipate energy from the system.

- 6.6.A Describe the motions of a system consisting of two objects interacting only via gravitational forces.
    - 6.6.A.1 In a system consisting only of a massive central object and an orbiting satellite with mass that is negligible in comparison to the central object's mass, the motion of the central object itself is negligible.
    - 6.6.A.2 The motion of satellites in orbits is constrained by conservation laws.
        - 6.6.A.2.i In circular orbits, the system's total mechanical energy, the system's gravitational potential energy, and the satellite's angular momentum and kinetic energy are constant.
        - 6.6.A.2.ii In elliptical orbits, the system's total mechanical energy and the satellite's angular momentum are constant, but the system's gravitational potential energy and the satellite's kinetic energy can each change.
        - 6.6.A.2.iii The gravitational potential energy of a system consisting of a satellite and a massive central object is defined to be zero when the satellite is an infinite distance from the central object.
    - 6.6.A.3 The escape velocity of a satellite is the satellite's velocity such that the mechanical energy of the satellite–central-object system is equal to zero.
        - 6.6.A.3.i When the only force exerted on a satellite is gravity from a central object, a satellite that reaches escape velocity will move away from the central body until its speed reaches zero at an infinite distance from the central body.
        - 6.6.A.3.ii The escape velocity of a satellite from a central body of mass M can be derived using conservation of energy laws.

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Supporting Standards

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- 1.A. Create diagrams, tables, charts, or schematics to represent physical situations.

- 1B. Create quantitative graphs with appropriate scales and units, including plotting data.
- 1C. Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.
- 2A. Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.
- 2B. Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.
- 2.C. Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.
- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
- 3.B. Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Unit 7
Unit Title: Oscillations

Essential Question

- Why should soldiers not march in step when they go over a bridge?
- What do a child on a swing, a beating heart, and a metronome have in common?
- How can an astronaut be "weighed" in space?
- How could you measure the length of a long string with a stopwatch?

Unit Summary

In unit 7, students will apply previously – encountered models and methods of analysis to simple harmonic motion. They will also be reminded that, even in new situations, the fundamental laws of physics remain the same. Because this unit is the first in which students possess all the tools of force, energy, and momentum conservation – such as energy bar, charts, free – body diagrams, and momentum diagrams – scaffolding lessons will enhance student understanding of fundamental physics principles and their limitations, as they relate to oscillating systems. Students will also use the skills and knowledge they have gained to make and justify claims, as well as connect new concepts with those learned in previous topics.

Guiding Questions

Content

- What is simple harmonic motion (SHM), and what conditions are required for it to occur?
- How is the restoring force in SHM described, and how does SHM differ from other types of oscillatory motion?
- What are examples of real-world systems that exhibit SHM, such as mass-spring systems and pendulums?
- What are frequency and period in SHM, and how are they related?
- How can the period and frequency of SHM be calculated, given parameters like mass, spring constant, and length of a pendulum?
- How do changes in mass or spring constant affect the period and frequency of a mass-spring system?
- How can SHM be represented graphically by plotting displacement, velocity, and acceleration as functions of time, and what are the key features of these

graphs?

- What are the potential and kinetic energy of a simple harmonic oscillator, and how is energy conserved in SHM?

Process

- What parameters should be considered when comparing the periods and frequencies of different simple harmonic oscillators (mass-spring system vs. pendulum), and why do these differences occur?
- How can the period and frequency of a mass-spring system be calculated, and what steps are involved in applying the formula with mass and spring constant?
- How can a chart illustrating potential and kinetic energy in a simple harmonic oscillator be created, and why is energy transferred between these forms during oscillation?
- What is the process for estimating the period of a simple pendulum, and why does varying the length of the string affect the period?
- How can the maximum velocity in simple harmonic motion be calculated, and why is this relationship significant in understanding the system's behavior?
- What factors affect the energy distribution (kinetic and potential) at different points in SHM, and how do these factors impact the energy during oscillation?

Reflective

- How are SHM principles applied in the design of clocks, and why are oscillations used to keep accurate time and maintain consistent motion in mechanical clockworks?
- How do SHM principles help in the design of shock absorbers in vehicles, and why is it important for oscillations to absorb and dissipate energy from road impacts to improve comfort and safety?
- How is SHM applied in the design of suspension systems in vehicles, and why does minimizing forces acting on the vehicle's body ensure a smoother ride and better control during motion?
- How does the role of restoring force in SHM influence the design of spring-based scales, and why is restoring force crucial for ensuring accurate weight measurements by linking displacement to the force applied to the spring?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- 7.1.A Describe simple harmonic motion.
  - 7.1.A.1 Simple harmonic motion is a special case of periodic motion.
  - 7.1.A.2 SHM results when the magnitude of the restoring force exerted on an object is proportional to that object's displacement from its equilibrium position.
    - 7.1.A.2.i A restoring force is a force that is exerted in a direction opposite to the object's displacement from an equilibrium position.
    - 7.1.A.2.ii An equilibrium position is a location at which the net force exerted on an object or system is zero.
    - 7.1.A.2.iii The motion of a pendulum with a small angular displacement can be modeled as simple harmonic motion because the restoring torque is proportional to the angular displacement.
- 7.2.A Describe the frequency and period of an object exhibiting SHM.
  - 7.2.A.1 The period of SHM is related to the frequency f of the object's motion by the following equation:
    - 7.2.A.1.i The period of an object - ideal spring oscillator is given by the equation
    - 7.2.A.1.ii The period of a simple pendulum displaced by a small angle is given by the equation
- 7.3.A Describe the displacement, velocity, and acceleration of an object exhibiting SHM.
  - 7.3.A.1 For an object exhibiting SHM, the displacement of that object measured from its equilibrium position can be represented by the equations
    - 7.3.A.1.i Minima, maxima, and zeros of displacement, velocity, and acceleration are features of harmonic motion.
    - 7.3.A.1.ii Recognizing the positions or times at which the displacement, velocity, and acceleration for SHM have extrema or zeros can help in qualitatively describing the behavior of the motion.
  - 7.3.A.2 Changing the amplitude of a system exhibiting SHM will not

        change the period of that system.
    - 7.3.A.3 Properties of SHM can be determined and analyzed using graphical representations
- 7.4.A Describe the mechanical energy of a system exhibiting SHM.
    - 7.4.A.1 The total energy of a system exhibiting SHM is the sum of the system's kinetic and potential energies.
    - 7.4.A.2 Conservation of energy indicates that the total energy of a system exhibiting SHM is constant.
    - 7.4.A.3 The kinetic energy of a system exhibiting SHM is at a maximum when the system's potential energy is at a minimum.
    - 7.4.A.4 The potential energy of a system exhibiting SHM is at a maximum when the system's kinetic energy is at a minimum.
        - 7.4.A.4.i The minimum kinetic energy of a system exhibiting SHM is zero.
        - 7.4.A.4.ii Changing the amplitude of a systemexhibiting SHM will change the maximum potential energy of the system and, therefore, the total energy of the system

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Supporting Standards

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- 2D. Predict new values or factors of change of physical quantities using functional dependence between variables.
- 3A. Create experimental procedures that are appropriate for a given scientific question.
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- 3.C. Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Unit 8
Unit Title: Fluids

Essential Question

- Why does a 15-g nail sink in water and a cargo ship float?
- How can a hot air balloon travel for hours in the sky?
- Why is it dangerous for scuba divers to ascend to the surface quickly from a deep- sea dive?

Unit Summary

In unit 8, students consider how the forces and conservation laws studied in units 1 through 4 can be applied to the study of ideal fluids. Unit 8 ties together the thematic threads that have been woven throughout the course, including the interactions between systems and the conservation of fundamental quantities.

Guiding Questions

Content

- What is the relationship between mass, volume, and density in a fluid, and how do these properties affect its behavior?
- How can we compare the density of different fluids, and why does this affect buoyancy and floating?
- How do changes in the internal structure of a fluid, like its composition or phase, influence its density and behavior?
- What is pressure, and how is it distributed in a fluid at rest?
- How does pressure change with depth in a fluid, and when does this concept help calculate forces at different depths?
- How do external forces affect pressure in a fluid, and what is the relationship between pressure and surface area?
- Why does pressure in fluids arise from molecular collisions, and how is it influenced by the fluid's properties?
- How can Newton's laws predict fluid motion, and how do external forces affect the fluid's velocity and pressure?
- How can the continuity equation be applied to analyze the flow rate of fluids through varying cross-sectional areas in a pipe system?
- How does the principle of conservation of energy apply to fluids, particularly in relation to Bernoulli's principle?

Process

- What is the relationship between pressure, depth, and fluid behavior, and how does this help justify claims in fluid dynamics?
- How do free body diagrams help describe forces on an object submerged in a fluid, and why are they useful for calculating buoyant force?
- How can Archimedes' principle estimate buoyant force, and what impact do fluid density and object volume have on it?
- How are energy bar charts used to represent energy distribution in fluid systems, and why is it important to analyze energy transformations?
- What role do equations like Bernoulli's principle and the continuity equation play in explaining fluid behavior, and why are they useful?
- How do discrepancies between predicted and observed results help refine experimental methods in fluid dynamics, and why is this important?

Reflective

- How does understanding fluid pressure help engineers design safe underwater systems and optimize functionality?
- How do fluid dynamics principles like the continuity equation improve the performance of pipes and water systems?
- How do fluid dynamics and buoyancy principles apply to the design of medical devices and sports equipment for safety and performance?

Power Standards

These state standards have been identified as critical to students' long-term learning progression in this discipline. They are assessed within the scope of this unit.

- **8.1.A** Describe the properties of a fluid.
    - 8.1.A.1 Distinguishing properties of solids, liquids, and gases stem from the varying interactions between atoms and molecules.
    - 8.1.A.2 A fluid is a substance that has no fixed shape.
    - 8.1.A.3 Fluids can be characterized by their density. Density is defined as a ratio of mass to volume.
    - 8.1.A.4 An ideal fluid is incompressible and has no viscosity.
- 8.2.A Describe the pressure exerted on a surface by a given force.
    - 8.2.A.1 Pressure is defined as the magnitude of the perpendicular force

component exerted per unit area over a given surface area, as described by the equation.

    - 8.2.A.2 Pressure is a scalar quantity.
    - 8.2.A.3 The volume and density of a given amount of an incompressible fluid is constant regardless of the pressure exerted on that fluid.
- 8.2.B Describe the pressure exerted by a fluid.
    - 8.2.B.1 The pressure exerted by a fluid is the result of the entirety of the interactions between the fluid's constituent particles and the surface with which those particles interact.
    - 8.2.B.2 The absolute pressure of a fluid at a given point is equal to the sum of a reference pressure P_0, such as the atmospheric pressure P_{atm}, and the gauge pressure gauge.
    - 8.2.B.3 The gauge pressure of a vertical column of fluid is described by the equation.
- 8.3.A Describe the conditions under which a fluid's velocity changes.
    - 8.3.A.1 Newton's laws can be used to describe the motion of particles within a fluid.
    - 8.3.A.2 The macroscopic behavior of a fluid is a result of the internal interactions between the fluid's constituent particles and external forces exerted on the fluid.
- 8.3.B Describe the buoyant force exerted on an object interacting with a fluid.
    - 8.3.B.1 The buoyant force is a net upward force exerted on an object by a fluid.
    - 8.3.B.2 The buoyant force exerted on an object by a fluid is a result of the collective forces exerted on the object by the particles making up the fluid.
    - 8.3.B.2 The magnitude of the buoyant force exerted on an object by a fluid is equivalent to the weight of the fluid displaced by the object.
- 8.4.A Describe the flow of an incompressible fluid through a cross-sectional area by using mass conservation.
    - 8.4.A.1 A difference in pressure between two locations causes a fluid to flow.
        - 8.4.A.1.i The rate at which matter enters a fluid-filled tube open at both ends must equal the rate at which matter exits the tube.
        - 8.4.A.1.ii The rate at which matter flows into a location is proportional to the cross- sectional area of the flow and the

speed at which the fluid flows.
    - 8.4.A.2 The continuity equation for fluid flow describes conservation of mass flow rate in incompressible fluids.
- 8.4.B Describe the flow of a fluid as a result of a difference in energy between two locations within the fluid– Earth system.
    - 8.4.B.1 A difference in gravitational potential energies between two locations in a fluid will result in a difference in kinetic energy and pressure between those two locations that is described by conservation laws.
    - 8.4.B.2 Bernoulli's equation describes the conservation of mechanical energy in fluid flow.
    - 8.4.B.3 Torricelli's theorem relates the speed of a fluid exiting an opening to the difference in height between the opening and the top surface of the fluid and can be derived from conservation of energy principles.

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