AP Physics 2
Grade 11 & 12

Unit 9
Unit Title: Thermodynamics

Essential Question
- Why does the tile floor in the bathroom feel so much colder than the bathroom mat?
- How cold can something get?
- How would our lives be different without heat engines?
- How do the laws of thermodynamics help us understand the limitations in function and efficiency of technological systems?

Unit Summary
In this unit, students investigate what they cannot see by examining the properties of ideal gases. This unit's focus is the study of relationships and change, so it is important that students can discuss—and describe mathematically—what happens when a physical scenario changes, such as the consequences of heating or cooling a system. Students will use the first law of thermodynamics and PV diagrams to represent and analyze thermodynamic processes. Thermal energy transfer and material properties such as specific heat and thermal conductivity will be studied. This unit also acquaints students with the second law of thermodynamics, including entropy.

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 implied when a gas is treated like an "ideal gas"?
- How can the application of the ideal gas law and kinetic molecular theory help us understand the behaviors and changes in an ideal gas system?

- How do heat transfer processes (conduction, convection, radiation) work, and how can you calculate energy flow?
- How can the first law of thermodynamics be applied to analyze changes in heat, work, and internal energy?
- What are entropy changes, and how can the second law of thermodynamics be applied to reversible and irreversible processes?

Process

- How can the relationships between pressure, volume, temperature, and energy be used to determine the changes in an ideal gas system?
- How can energy conservation principles be used to analyze heat engines and refrigerators?
- How can PV diagrams be interpreted, and how do you calculate the work done by or on a system?

Reflective

- What are the environmental implications of energy transformations and efficiency?
- How do thermodynamic principles apply to the design of sustainable energy systems?

Power Standards

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

- 9.1.A. Describe the pressure a gas exerts on its container in terms of atomic motion within that gas.
  - 9.1.A.1. Atoms in a gas collide with and exert forces on other atoms in the gas and with the container in which the gas is contained.
    - 9.1.A.1.i. Collisions involving pairs of atoms or an atom and a fixed object, can be described and analyzed using conservation of momentum principles.
    - 9.1.A.1.ii. The pressure exerted by a gas on a surface is the ratio of the sum of the magnitudes of the perpendicular components of the forces exerted by the gas's atoms on the surface to the area of the surface. Relevant Equation $P = F/A$

- 9.1.A.1.iii. Pressure exists throughout the gas itself, not just at the boundary between the gas and the container.

- 9.1.B. Describe the temperature of a system in terms of the atomic motion within that system.
  - 9.1.B.1. The temperature of a system is characterized by the average kinetic energy of the atoms within that system.
    - 9.1.B.1.i. The Maxwell–Boltzmann distribution provides a graphical representation of the energies and speeds of atoms at a given temperature.
    - 9.1.B.1.ii. The root-mean-square speed corresponding to the average kinetic energy for an ideal gas is related to the temperature of the gas by $K = 3/2\, k_b T = ½\, m v_{rms}^2$
- 9.2.A. Describe the properties of an ideal gas.
  - 9.2.A.1. The classical model of an ideal gas assumes that the instantaneous velocities of atoms are random, the volumes of the atoms are negligible compared to the total volume occupied by the gas, the atoms collide elastically, and the only appreciable forces on the atoms are those that occur during collisions.
  - 9.2.A.2. An ideal gas is one in which the relationships between pressure, volume, the number of moles or number of atoms, and temperature of a gas can be modeled using the equation $PV = nRT = Nk_bT$.
  - 9.2.A.3. Graphs modeling the pressure, temperature, and volume of gases can be used to describe or determine properties of that gas.
  - 9.2.A.4. A temperature at which an ideal gas has zero pressure can be extrapolated from a graph of pressure as a function of temperature.
- 9.3.A. Describe the transfer of energy between two systems in thermal contact due to temperature differences of those two systems.
  - 9.3.A.1. Two systems are in thermal contact if the systems may transfer energy by thermal processes.
    - 9.3.A.1.i. Heating is the transfer of energy into a system by thermal processes.
    - 9.3.A.1.ii. Cooling is the transfer of energy out of a system by thermal processes.
  - 9.3.A.2. The thermal processes by which energy may be transferred between systems at different temperatures are conduction, convection, and radiation.

- 9.3.A.3. Energy is transferred through thermal processes spontaneously from a higher-temperature system to a lower-temperature system.
    - 9.3.A.3.i. In collisions between atoms from different systems, energy is most likely to be transferred from higher-energy atoms to lower-energy atoms.
    - 9.3.A.3.ii. After many collisions of atoms from different systems, the most probable state is one in which both systems have the same temperature.
- 9.3.A.4. Thermal equilibrium results when no net energy is transferred by thermal processes between two systems in thermal contact with each other

- 9.4.A. Describe the pressure a gas exerts on its container in terms of atomic motion within that gas.
  - 9.4.A.1. The internal energy of a system is the sum of the kinetic energy of the objects that make up the system and the potential energy of the configuration of those objects.
    - 9.4.A.1.i. The atoms in an ideal gas do not interact with each other via conservative forces, and the internal structure is not considered. Therefore, an ideal gas does not have internal potential energy.
    - 9.4.A.1.ii. The internal energy of an ideal monatomic gas is the sum of the kinetic energies of the constituent atoms in the gas. Relevant equation: $U = nRT = 3/2\ Nk_bT$
  - 9.4.A.2. Changes to a system's internal energy can result in changes to the internal structure and internal behavior of that system without changing the motion of the system's center of mass.
- 9.4.B. Describe the behavior of a system using thermodynamic processes.
  - 9.4.B.1. The first law of thermodynamics is a restatement of conservation of energy that accounts for energy transferred into or out of a system by work, heating, or cooling.
    - 9.4.B.1.i. For an isolated system, the total energy is constant.
    - 9.4.B.1.ii. For a closed system, the change in internal energy is the sum of energy transferred to or from the system by heating, or work done on the system. Relevant equation: $\Delta U = Q + W$
    - 9.4.B.1.iii. The work done on a system by a constant or average external pressure that changes the volume of that system (for

example, a piston compressing a gas in a container) is defined as $W = -P \Delta V$.

- 9.4.B.2. Pressure-volume graphs (also known as PV diagrams) are representations used to represent thermodynamic processes.
  - 9.4.B.2.i. Lines of constant temperature on a PV diagram are called isotherms.
  - 9.4.B.2.ii. The absolute value of the work done on a gas when the gas expands or compresses is equal to the area underneath the curve of a plot of pressure vs. volume for the gas.
- 9.4.B.3. Special cases of thermal processes depend on the relationship between the configuration of the system, the nature of the work done on the system, and the system's surroundings. These include constant volume (isovolumetric), constant temperature (isothermal), and constant pressure (isobaric), as well as processes where no energy is transferred to or from the system through thermal processes (adiabatic).

- 9.5.A. Describe the energy required to change the temperature of an object by a certain amount.
  - 9.5.A.1. The amount of energy required to change the temperature of a material is related to the material's specific heat. Relevant equation: $Q = mc\Delta T$
  - 9.5.A.2. The specific heat of a material is an intrinsic property of that material that depends on the arrangement and interactions of the atoms that make up the material.
- 9.5.B. Describe the rate at which energy is transferred by conduction through a given material.
  - 9.5.B.1. The rate at which energy is transferred by conduction through a given material is related to the thermal conductivity, the physical dimensions of the material, and the temperature difference across the material. Relevant equation: $Q / \Delta t = kA \Delta T / L$
  - 9.5.B.2. The thermal conductivity of a material is an intrinsic property of that material that depends on the arrangement and interactions of the atoms that make up the material.
- 9.6.A. Describe the change in entropy for a given system over time.

- 9.6.A.1. The second law of thermodynamics states that the total entropy of an isolated system can never decrease and is constant only when all processes the system undergoes are reversible.
- 9.6.A.2. Entropy can be qualitatively described as the tendency of energy to spread or the unavailability of some of the system's energy to do work.
  - 9.6.A.2.i. Localized energy will tend to disperse and spread out.
  - 9.6.A.2.ii. Entropy is a state function and therefore only depends on the current state or configuration of a system, not how the system reached that state.
  - 9.6.A.2.iii. Maximum entropy occurs when a system is in thermodynamic equilibrium.
- 9.6.A.3. The change in a system's entropy is determined by the system's interactions with its surroundings.
  - 9.6.A.3.i. Closed systems spontaneously move toward thermodynamic equilibrium.
  - 9.6.A.3.ii. The entropy of a closed system never decreases, but the entropy of an open system can decrease because energy can be transferred into or out of the system.

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 10
Unit Title: Electric Force, Field and Potential

Essential Question

- Why can you suspend a charged water droplet in the air?
- Since balloons are made of rubber, how can they get “charged” so that they stick to the wall?
- Where is the safest place to be in a lightning storm?
- How can you protect your electronics from an EMP?

Unit Summary

Unit 10 begins the study of electrostatic phenomena at a fundamental level, introducing students to the model of field forces. Despite the topical shift from gases to charged particles, this unit continues the study of interactions and change. Unit 10 reinforces the idea that interactions can be described by forces, and that the electric force, like the other forces introduced in AP Physics 1, can be described with Newton’s laws. Students are encouraged to apply fundamental physics principles studied in AP Physics 1 when learning about fields (gravitational and electric) and the forces experienced by objects in a field.

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 electric force and electric field, and how are they related?
- How does Coulomb’s law describe the interaction between charged particles?
- What is the relationship between electric field strength and electric potential, and how can one be derived from the other?
- How does the principle of superposition apply to electric forces, fields, and potentials?
- How do conductors and insulators behave in the presence of an electric field?

Process

- How can you use vector addition to determine the net electric force acting on a charge?
- What strategies can be used to draw and interpret electric field diagrams for different charge distributions?
- What problem-solving techniques can help determine the electric potential at a point due to multiple charges?
- How can experimental data be used to verify the relationship between electric potential and electric field?

Reflective

- How does understanding electric forces and fields help explain everyday phenomena like lightning or static electricity?
- In what ways is electric potential similar to gravitational potential, and how are they different?
- How do the concepts of electric fields and potentials apply to real-world technologies such as capacitors or medical imaging devices?
- What ethical and environmental considerations arise from the generation and use of electric fields in modern technology?
- How has the study of electric forces and fields influenced the development of modern physics and engineering?

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.

- 10.1.A. Describe the electric force that results from the interactions between charged objects or systems.
    - 10.1.A.1. Charge is a fundamental property of all matter.
        - 10.1.A.1.i. Charge is described as positive or negative.
        - 10.1.A.1.ii. The magnitude of the charge of a single electron or proton, the elementary charge e, can be considered to be the smallest indivisible amount of charge.
        - 10.1.A.1.iii. The charge of an electron is -e, the charge of a proton is +e, and a neutron has no electric charge.
        - 10.1.A.1.iv. A point charge is a model in which the physical size of a

charged object or system is negligible in the context of the situation being analyzed.

- 10.1.A.2. Coulomb's law describes the electrostatic force between two charged objects as directly proportional to the magnitude of each of the charges and inversely proportional to the square of the distance between the objects. Relevant equation: $F_E = 1/4\pi\varepsilon_0 \, q_1q_2/r^2 = k \, q_1q_2/r^2$
- 10.1.A.3. The direction of the electrostatic force depends on the signs of the charges of the interacting objects and is parallel to the line of separation between the objects.
  - 10.1.A.3.i. Two objects with charges of the same sign exert repulsive forces on each other.
  - 10.1.A.3.ii. Two objects with charges of opposite signs exert attractive forces on each other.
- 10.1.A.4. Electric forces are responsible for some of the macroscopic properties of objects in everyday experiences. However, the large number of particle interactions that occur make it more convenient to treat everyday forces in terms of nonfundamental forces called contact forces, such as normal force, friction, and tension.

- 10.1.B. Describe the electric and gravitational forces that result from interactions between charged objects with mass.
  - 10.1.B.1. Electrostatic forces can be attractive or repulsive, while gravitational forces are always attractive.
  - 10.1.B.2. For any two objects that have mass and electric charge, the magnitude of the gravitational force is usually much smaller than the magnitude of the electrostatic force.
  - 10.1.B.3. Gravitational forces dominate at larger scales even though they are weaker than electrostatic forces, because systems at large scales tend to be electrically neutral.
- 10.1.C. Describe the electric permittivity of a material or medium.
  - 10.1.C.1. Electric permittivity is a measurement of the degree to which a material or medium is polarized in the presence of an electric field.
  - 10.1.C.2. Electric polarization can be modeled as the induced rearrangement of electrons by an external electric field, resulting in a separation of positive and negative charges within a material or medium.
  - 10.1.C.3. Free space has a constant value of electric permittivity, ε_0, that

appears in physical relationships

  - 10.1.C.4. The permittivity of matter has a value different from that of free space that arises from the matter's composition and arrangement.
    - 10.1.C.4.i. In a given material, electric permittivity is determined by the ease with which electrons can change configurations within the material.
    - 10.1.C.4.ii. Conductors are made from electrically conducting materials in which charge carriers move easily; insulators are made from electrically nonconducting materials in which charge carriers cannot move easily.
- 10.2.A. Describe the behavior of a system using conservation of charge.
  - 10.2.A.1. The net charge or charge distribution of a system can change in response to the presence of, or changes in, the net charge or charge distribution of other systems.
    - 10.2.A.1.i. The net charge of a system can change due to friction or contact between systems.
    - 10.2.A.1.ii. Induced charge separation occurs when the electrostatic force between two systems alters the distribution of charges within the systems, resulting in the polarization of one or both systems.
    - 10.2.A.1.iii. Induced charge separation can occur in neutral systems.
  - 10.2.A.2. Any change to a system's net charge is due to a transfer of charge between the system and its surroundings.
    - 10.2.A.2.i. The charging of a system typically involves the transfer of electrons to and from the system.
    - 10.2.A.2.ii. The net charge of a system will be constant unless there is a transfer of charge to or from the system.
  - 10.2.A.3. Grounding involves electrically connecting a charged system to a much larger and approximately neutral system (e.g., Earth).
- 10.3.A. Describe the electric field produced by a charged object or configuration of point charges.
  - 10.3.A.1. Electric fields may originate from charged objects
  - 10.3.A.2. The electric field at a given point is the ratio of the electric force exerted on a test charge at that point to the charge of the test charge. Relevant equation: $E = F_E/q$

- 10.3.A.2.i. A test charge is a point charge of small enough magnitude such that its presence does not significantly affect an electric field in its vicinity.
- 10.3.A.2.ii. An electric field points away from isolated positive charges and toward isolated negative charges.
- 10.3.A.2.iii. The electric force exerted on a positive test charge by an electric field is in the same direction as the electric field.

- 10.3.A.3. The electric field is a vector quantity and can be represented in space using vector field maps.
  - 10.3.A.3.i. The net electric field at a given location is the vector sum of individual electric fields created by nearby charged objects.
  - 10.3.A.3.ii. Electric field maps use vectors to depict the magnitude and direction of the electric field at many locations within a given region.
  - 10.3.A.3.iii. Electric field line diagrams are simplified models of electric field maps and can be used to determine the relative magnitude and direction of the electric field at any position in the diagram.
- 10.3.B. Describe the electric field generated by charged conductors or insulators.
  - 10.3.B.1. While in electrostatic equilibrium, the excess charge of a solid conductor is distributed on the surface of the conductor, and the electric field within the conductor is zero.
    - 10.3.B.1.i. At the surface of a charged conductor, the electric field is perpendicular to the surface.
    - 10.3.B.1.ii. The electric field outside an isolated sphere with spherically symmetric charge distribution is the same as the electric field due to a point charge with the same net charge as the sphere located at the center of the sphere.
  - 10.3.B.2. While in electrostatic equilibrium, the excess charge of an insulator is distributed throughout the interior of the insulator as well as at the surface, and the electric field within the insulator may have a nonzero value.
- 10.4.A. Describe the electric potential energy of a system.
  - 10.4.A.1. The electric potential energy of a system of two point charges

equals the amount of work required for an external force to bring the point charges to their current positions from infinitely far away.

- 10.4.A.2. The general form for the electric potential energy of two charged objects is given by the equation $U = 1/4\pi\varepsilon_0 \; q_1q_2/r = k\,q_1q_2/r$
- 10.4.A.3. The total electric potential energy of a system can be determined by finding the sum of the electric potential energies of the individual interactions between each pair of charged objects in the system.

- 10.5.A. Describe the electric potential due to a configuration of charged objects.
  - 10.5.A.1. Electric potential describes the electric potential energy per unit charge at a point in space.
  - 10.5.A.2. The electric potential due to multiple point charges can be determined by the principle of scalar superposition of the electric potential due to each of the point charges. Relevant equation: $V = 1/4\pi\varepsilon_0 \sum q_i/r_i$
  - 10.5.A.3. The electric potential difference between two points is the change in electric potential energy per unit charge when a test charge is moved between the two points. Relevant equation: $\Delta V = \Delta U_E/q$
    - 10.5.A.3.i. Electric potential difference may also result from chemical processes that cause positive and negative charges to separate, such as in a battery.
  - 10.5.A.4. When conductors are in electrical contact, electrons will be redistributed such that the surfaces of the conductors are at the same electric potential.
- 10.5.B. Describe the relationship between electric potential and electric field.
  - 10.5.B.1. The average electric field between two points in space is equal to the electric potential difference between the two points divided by the distance between the two points. Relevant equation: $E = \Delta V/\Delta r$
  - 10.5.B.2. Electric field vector maps and equipotential lines are tools to describe the field produced by a charge or configuration of charges and can be used to predict the motion of charged objects in the field.
    - 10.5.B.2.i. Equipotential lines represent lines of equal electric potential in space. These lines are also referred to as isolines of electric potential.
    - 10.5.B.2.ii. Isolines are perpendicular to electric field vectors. An

isoline map of electric potential can be constructed from an electric field vector map, and an electric field map may be constructed from an isoline map.

        - 10.5.B.2.iii. An electric field vector points in the direction of decreasing potential.
        - 10.5.B.2.iv. There is no component of an electric field along an isoline.
- 10.6.A. Describe the physical properties of a parallel-plate capacitor.
    - 10.6.A.1. A parallel-plate capacitor consists of two separated parallel conducting surfaces that can hold equal amounts of charge with opposite signs.
    - 10.6.A.2. Capacitance relates the magnitude of the charge stored on each plate to the electric potential difference created by the separation of those charges. Relevant equation: $C = Q/\Delta V$
        - 10.6.A.2.i. The capacitance of a capacitor depends only on the physical properties of the capacitor, such as the capacitor's shape and the material used to separate the plates.
        - 10.6.A.2.ii. The capacitance of a parallel-plate capacitor is proportional to the area of one of its plates and inversely proportional to the distance between its plates. The constant of proportionality is the product of the dielectric constant, κ, of the material between the plates and the electric permittivity of free space, ε_0. Relevant equation: $C = \kappa\varepsilon_0 A/d$
    - 10.6.A.3. The electric field between two charged parallel plates with uniformly distributed electric charge, such as in a parallel-plate capacitor, is constant in both magnitude and direction, except near the edges of the plates.
        - 10.6.A.3.i. The magnitude of the electric field between two charged parallel plates, where the plate separation is much smaller than the dimensions of the plates, can be described with the equation $E_C = Q/\kappa\varepsilon_0 A$.
        - 10.6.A.3.ii. A charged particle between two oppositely charged parallel plates undergoes constant acceleration and therefore its motion shares characteristics with the projectile motion of an object with mass in the gravitational field near Earth's surface.
    - 10.6.A.4. The electric potential energy stored in a capacitor is equal to

the work done by an external force to separate that amount of charge on the capacitor.

- 10.6.A.5. The electric potential energy stored in a capacitor is described by the equation $U_C = 1/2\ Q\ \Delta V$
- 10.6.A.6. Adding a dielectric between two plates of a capacitor changes the capacitance of the capacitor and induces an electric field in the dielectric in the opposite direction to the field between the plates.

- 10.7.A. Describe changes in energy in a system due to a difference in electric potential between two locations.
  - 10.7.A.1. When a charged object moves between two locations with different electric potentials, the resulting change in the electric potential energy of the object-field system is given by the following equation. Relevant equation: $\Delta U_E = q\ \Delta V$
  - 10.7.A.2. The movement of a charged object between two points with different electric potentials results in a change in kinetic energy of the object consistent with the conservation of energy.Bulleted list with standards notation

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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 11
Unit Title: Electric Circuits

Essential Question
- Why do lights on electronics dim slowly and then go out when unplugged?
- Why do several bulbs on a string of lights go out when one bulb is unplugged?
- How can we effectively store electrical energy to use later?
- How can you make a 120 Watt bulb brighter than a 40 Watt bulb?

Unit Summary
Unit 11 revisits the behavior of charged particles to deepen students' understanding of the law of conservation of energy and its application to electric circuits. This unit requires more than calculating currents, resistances, and potential differences in a simple circuit. For example, students must be able to articulate the impact of a light bulb being removed from a circuit. They should also practice designing an experiment, for example, to test if a light bulb is ohmic or justify how and why circuit elements in series and parallel affect the properties of a circuit.

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 are the differences between series and parallel circuits in terms of voltage, current, and resistance?
- How do Kirchhoff's laws help describe the conservation of charge and energy in circuits?
- What factors affect the resistance of a conductor, and how is resistance mathematically related to voltage and current?
- How do capacitors behave in DC circuits, and what is their role in storing electrical energy?
- What is the relationship between power, current, voltage, and resistance in an electrical circuit?

Process
- How can you use Kirchhoff's rules to analyze complex circuits?

- What steps are necessary to construct a circuit diagram from a verbal or written description?
- How can you experimentally determine the equivalent resistance of series and parallel resistor combinations?
- What methods can be used to measure current, voltage, and resistance in a circuit accurately?
- How can energy conservation principles be applied to analyze power dissipation in electrical circuits?

Reflective

- How do the principles of electric circuits apply to the design and functioning of household electrical systems?
- What safety considerations should be taken into account when designing or working with electrical circuits?
- How do the concepts of resistance and power dissipation impact the efficiency of electrical devices?
- How has the study of electric circuits influenced technological advancements in modern electronics?
- In what ways do electric circuits play a role in renewable energy systems, such as solar panels and wind turbines?

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.

- 11.1.A. Describe the movement of electric charges through a medium.
  - 11.1.A.1. Current is the rate at which charge passes through a cross-sectional area of a wire. Relevant equation: $I = \Delta q / \Delta t$
    - 11.A.1.i. Electric charge moves in a circuit in response to an electric potential difference, sometimes referred to as electromotive force, or emf (ε).
    - 11.A.1.ii. If the current is zero in a section of wire, the net motion of charge carriers in the wire is also zero, although individual charge carriers will not have zero speed.
  - 11.1.A.2. Although current is not a vector quantity, it does have a direction. The direction of current is associated with what the motion of

positive charge would be but not with any coordinate system in space.

- 11.1.A.2.i. The direction of conventional current is chosen to be the direction in which positive charge would move.
- 11.1.A.2.ii. In common circuits, current is actually due to the movement of electrons (negative charge carriers).

- 11.2.A. Describe the behavior of a circuit.
  - 11.2.A.1. A circuit is composed of electrical loops, which may include circuit elements such as wires, batteries, resistors, lightbulbs, capacitors, switches, ammeters, and voltmeters.
  - 11.2.A.2. A closed electrical loop is a closed path through which charges may flow.
    - 11.2.A.2.i. A closed circuit is one in which charges would be able to flow.
    - 11.2.A.2.ii. An open circuit is one in which charges would not be able to flow.
    - 11.2.A.2.iii. A short circuit is one in which charges would be able to flow with no change in potential difference.
  - 11.2.A.3. A single circuit element may be part of multiple electrical loops.
  - 11.2.A.4. Circuit schematics are representations used to describe and analyze electric circuits.
    - 11.2.A.4.i. The properties of an electric circuit are dependent on the physical arrangement of its constituent elements.
    - 11.2.A.4.ii. Circuit elements have common symbols that are used to create schematic diagrams. Variable elements are indicated by a diagonal strikethrough arrow across the standard symbol for that element. Standard circuit elements are Battery, Bulb, Switch, Capacitor, Resistor, Ammeter, and Voltmeter.
- 11.3.A. Describe the resistance of an object using physical properties of that object.
  - 11.3.A.1. Resistance is a measure of the degree to which an object opposes the movement of electric charge.
  - 11.3.A.2. The resistance of a resistor with uniform geometry is proportional to its resistivity and length and is inversely proportional to its cross-sectional area. Relevant equation: $R = \rho l/A$
    - 11.3.A.2.i. Resistivity is a fundamental property of a material that depends on its atomic and molecular structure and quantifies

how strongly the material opposes the motion of electric charge.

    - 11.3.A.2.ii. The resistivity of a conductor typically increases with temperature.
- 11.3.B. Describe the electrical characteristics of elements of a circuit.
  - 11.3.B.1. Ohm's law relates current, resistance, and potential difference across a conductive element of a circuit. Relevant equation: $I = \Delta V/R$
    - 11.3.B.1.i. Materials that obey Ohm's law have constant resistance for all currents and are called ohmic materials.
    - 11.3.B.1.ii. The resistivity of an ohmic material is constant regardless of temperature.
    - 11.3.B.1.iii. Resistors can also convert electrical energy to thermal energy, which may change the temperature of both the resistor and the resistor's environment.
    - 11.3.B.1.iv. The resistance of an ohmic circuit element can be determined from the slope of a graph of the current in the element as a function of the potential difference across the element.
- 11.4.A. Describe the transfer of energy into, out of, or within an electric circuit, in terms of power.
  - 11.4.A.1. The rate at which energy is transferred, converted, or dissipated by a circuit element depends on the current in the element and the electric potential difference across it. Relevant equation: $P=I\Delta V$ Derived equations: $P= I^2R= (\Delta V)^2/R$
  - 11.4.A.2. The brightness of a bulb increases with power, so power can be used to qualitatively predict the brightness of bulbs in a circuit.
- 11.5.A. Describe the equivalent resistance of multiple resistors connected in a circuit.
  - 11.5.A.1. Circuit elements may be connected in series and/or in parallel.
    - 11.5.A.1.i. A series connection is one in which any charge passing through one circuit element must proceed through all elements in that connection and has no other path available. The current in each element in series must be the same.
    - 11.5.A.1.ii. A parallel connection is one in which charges may flow through one of two or more paths. Across each path, the potential difference is the same.
  - 11.5.A.2. A collection of resistors in a circuit may be analyzed as though it

were a single resistor with an equivalent resistance R_{eq}.

- 11.5.A.2.i. The equivalent resistance of a set of resistors in series is the sum of the individual resistances.
- 11.5.A.2.ii. The inverse of the equivalent resistance of a set of resistors connected in parallel is equal to the sum of the inverses of the individual resistances.
- 11.5.A.2.iii. When resistors are connected in parallel, the number of paths available to charges increases, and the equivalent resistance of the group of resistors decreases.

- 11.5.B. Describe a circuit with resistive wires and a battery with internal resistance.
  - 11.5.B.1. Ideal batteries have negligible internal resistance. Ideal wires have negligible resistance.
    - 11.5.B.1.i. The resistance of wires that are good conductors may normally be neglected, because their resistance is much smaller than that of other elements of a circuit.
    - 11.5.B.1.ii. The resistance of wires may only be neglected if the circuit contains other elements that do have resistance.
    - 11.5.B.1.iii. The potential difference a battery would supply if it were ideal is the potential difference measured across the terminals when there is no current in the battery and is sometimes referred to as its emf (ε).
  - 11.5.B.2. The internal resistance of a nonideal battery may be treated as the resistance of a resistor in series with an ideal battery and the remainder of the circuit.
  - 11.5.B.3. When there is current in a nonideal battery with internal resistance r, the potential difference across the terminals of the battery is reduced relative to the potential difference when there is no current in the battery. Derived equation: $\Delta V = \varepsilon - Ir$
- 11.5.C. Describe the measurement of current and potential difference in a circuit.
  - 11.5.C.1. Ammeters are used to measure current at a specific point in a circuit.
    - 11.5.C.1.i. Ammeters must be connected in series with the element in which current is being measured.
    - 11.5.C.1.ii. Ideal ammeters have zero resistance so that they do not

affect the current in the element that they are in series with.
    - 11.5.C.2. Voltmeters are used to measure electric potential difference between two points in a circuit.
        - 11.5.C.2.i. Voltmeters must be connected in parallel with the element across which potential difference is being measured.
        - 11.5.C.2.ii. Ideal voltmeters have an infinite resistance so that no charge flows through them.
    - 11.5.C.3. Nonideal ammeters and voltmeters will change the properties of the circuit being measured.
- 11.6.A. Describe a circuit or elements of a circuit by applying Kirchhoff's loop rule.
    - 11.6.A.1. Energy changes in simple electrical circuits may be represented in terms of charges moving through electric potential differences within circuit elements. Relevant equation: $\Delta U_E = q\Delta V$
    - 11.6.A.2. Kirchhoff's loop rule is a consequence of the conservation of energy.
    - 11.6.A.3. Kirchhoff's loop rule states that the sum of potential differences across all circuit elements in a single closed loop must equal zero. Relevant equation: $\Sigma\Delta V = 0$
    - 11.6.A.4. The values of electric potential at points in a circuit can be represented by a graph of electric potential as a function of position within a loop.
- 11.7.A. Describe a circuit or elements of a circuit by applying Kirchhoff's junction rule.
    - 11.7.A.1. Kirchhoff's junction rule is a consequence of the conservation of electric charge.
    - 11.7.A.2. Kirchhoff's junction rule states that the total amount of charge entering a junction per unit time must equal the total amount of charge exiting that junction per unit time. Relevant equation: $\Sigma I_{in} = \Sigma I_{out}$
- 11.8.A. Describe the equivalent capacitance of multiple capacitors.
    - 11.8.A.1. A collection of capacitors in a circuit may be analyzed as though it were a single capacitor with an equivalent capacitance C_{eq}.
        - 11.8.A.1.i. The inverse of the equivalent capacitance of a set of capacitors connected in series is equal to the sum of the inverses of the individual capacitances. Relevant equation: $1/C_{eq,s} = \Sigma\, 1/C_i$
        - 11.8.A.1.ii. The equivalent capacitance of a set of capacitors in

series is less than the capacitance of the smallest capacitor.

    - 11.8.A.1.iii. The equivalent capacitance of a set of capacitors in parallel is the sum of the individual capacitances. Relevant equation: $C_{eq,p} = \Sigma C_i$
  - 11.8.A.2. As a result of conservation of charge, each of the capacitors in series must have the same magnitude of charge on each plate.
- 11.8.B. Describe the behavior of a circuit containing combinations of resistors and capacitors.
  - 11.8.B.1. The time constant τ is a significant feature of an RC circuit.
    - 11.8.B.1.i. The time constant of an RC circuit is a measure of how quickly the capacitor will charge or discharge and is defined as $\tau = R_{eq} C_{eq}$
    - 11.8.B.1.ii. For a charging capacitor, the time constant represents the time required for the capacitor's charge to increase from zero to approximately 63 percent of its final asymptotic value.
    - 11.8.B.1.iii. For a discharging capacitor, the time constant represents the time required for the capacitor's charge to decrease from fully charged to approximately 37 percent of its initial value.
  - 11.8.B.2. The potential difference across a capacitor and the current in the branch of the circuit containing the capacitor each change over time as the capacitor charges and discharges, but both will reach a steady state after a long time interval.
    - 11.8.B.2.i. Immediately after being placed in a circuit, an uncharged capacitor acts like a wire, and charge can easily flow to or from the plates of the capacitor.
    - 11.8.B.2.ii. As a capacitor charges, changes to the potential difference across the capacitor affect the charge on the plates of the capacitor, the current circuit branch in which the capacitor is located, and the electric potential energy stored in the capacitor.
    - 11.8.B.2.iii. The potential difference across a capacitor, the current in the circuit branch in which the capacitor is located, and the electric potential energy stored in the capacitor all change with respect to time and asymptotically approach steady state conditions.

- 11.8.B.2.iv. After a long time, a charging capacitor approaches a state of being fully charged, reaching a maximum potential difference at which there is zero current in the circuit branch in which the capacitor is located.
- 11.8.B.2.v. Immediately after a charged capacitor begins discharging, the amount of charge on the capacitor plates and the energy stored in the capacitor begin to decrease.
- 11.8.B.2.vi. As a capacitor discharges, the amount of charge on the capacitor, the potential difference across the capacitor, and the current in the circuit branch in which the capacitor is located all decrease until a steady state is reached.
- 11.8.B.2.vii. After either charging or discharging for times much greater than the time constant, the capacitor and the relevant circuit branch may be modeled using steady-state conditions.

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 12
Unit Title: Magnetism and Electromagnetism

Essential Question

- How does an induction stovetop heat a pan without heating the cooktop?
- How would our world look different without induction?
- How would modern medicine be different without powerful magnets?
- How does an electric motor work?

Unit Summary

In this unit, students will build upon their knowledge of electrostatic forces, fields, free charges, and circuits by exploring the relationships between moving charges, the magnetic fields they generate, and the magnetic forces that act on other moving charges in those fields. Students will discover the natural symmetry between electricity and magnetism and how electromagnetic induction powers technology in modern society.

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 relationship between moving charges and the creation of magnetic fields?
- How do the right-hand rules help determine the direction of magnetic forces and fields?
- How do electric and magnetic fields interact in electromagnetic induction?
- What are the fundamental principles behind Faraday's Law and Lenz's Law?
- How do Maxwell's equations describe the relationship between electricity and magnetism?

Process

- How can you use vector analysis to determine the force on a moving charge in a magnetic field?
- What experimental techniques can be used to investigate the effects of

magnetic fields on current-carrying wires?
- How can you apply Faraday's Law to calculate the induced EMF in a changing magnetic field?
- What steps are needed to analyze the behavior of a charged particle moving through perpendicular electric and magnetic fields?
- How can you use the concept of electromagnetic waves to explain their behavior and propagation in space?Student is able to use graphs and equations to describe and predict motion

Reflective

- How does our understanding of electromagnetism influence the design and function of everyday technologies such as electric motors and generators?
- In what ways do electromagnetic waves impact communication technologies, such as radio, television, and Wi-Fi?
- How do the principles of electromagnetism apply to medical imaging technologies like MRI?
- What role does electromagnetism play in the development of sustainable energy solutions, such as wind and hydroelectric power generation?
- How has the unification of electricity and magnetism through Maxwell's equations shaped our modern understanding of physics and technological innovation?

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.

- 12.1.A. Describe the properties of a magnetic field.
    - 12.1.A.1. A magnetic field is a vector field that can be used to determine the magnetic force exerted on moving electric charges, electric currents, or magnetic materials.
        - 12.1.A.1.i. Magnetic fields can be produced by magnetic dipoles or combinations of dipoles, but never by monopoles.
        - 12.1.A.1.ii. Magnetic dipoles have north and south polarity.
    - 12.1.A.2. A magnetic field is a vector quantity and can be represented using vector field maps.
        - 12.1.A.2.i. Magnetic field lines form closed loops.

- 12.1.A.2.ii. Magnetic fields in a bar magnet form closed loops, with the external magnetic field pointing away from one end (defined as the north pole) and returning to the other end (defined as the south pole).

- 12.1.B. Describe the magnetic behavior of a material as a result of the configuration of magnetic dipoles in the material.
  - 12.1.B.1. Magnetic dipoles result from the circular or rotational motion of electric charges. In magnetic materials, this can be the motion of electrons.
    - 12.1.B.1.i. Permanent magnetism and induced magnetism are system properties that both result from the alignment of magnetic dipoles within a system.
    - 12.1.B.1.ii. No magnetic north pole is ever found in isolation from a south pole. For example, if a bar magnet is broken in half, both halves are magnetic dipoles.
    - 12.1.B.1.iii. Magnetic poles of the same polarity will repel; magnetic poles of opposite polarity will attract
    - 12.1.B.1.iv. The magnitude of the magnetic field from a magnetic dipole decreases with increasing distance from the dipole.
  - 12.1.B.2. A magnetic dipole, such as a magnetic compass, placed in a magnetic field will tend to align with the magnetic field.
  - 12.1.B.3. A material's composition influences its magnetic behavior in the presence of an external magnetic field.
    - 12.1.B.3.i. Ferromagnetic materials such as iron, nickel, and cobalt can be permanently magnetized by an external field that causes the alignment of magnetic domains or atomic magnetic dipoles.
    - 12.1.B.3.ii. Paramagnetic materials such as aluminum, titanium, and magnesium interact weakly with an external magnetic field, in that the magnetic dipoles of the material do not remain aligned after the external field is removed.
    - 12.1.B.3.iii. All materials have the property of diamagnetism, in that their electronic structure creates a usually weak alignment of the dipole moments of the material opposite the external magnetic field
  - 12.B.4. Earth's magnetic field may be approximated as a magnetic dipole.

- 12.1.C. Describe the magnetic permeability of a material.
  - 12.1.C.1. Magnetic permeability is a measurement of the amount of magnetization in a material in response to an external magnetic field.
  - 12.1.C.2. Free space has a constant value of magnetic permeability, known as the vacuum permeability μ_0, that appears in equations representing physical relationships.
  - 12.1.C.3. The permeability of matter has values different from that of free space and arises from the matter's composition and arrangement. It is not a constant for a material and varies based on many factors, including temperature, orientation, and strength of the external field.
- 12.2.A. Describe the magnetic field produced by moving charged objects.
  - 12.2.A.1. A single moving charged object produces a magnetic field.
    - 12.2.A.1.i. The magnetic field at a particular point produced by a moving charged object depends on the object's velocity and the distance between the point and the object.
    - 12.2.A.1.ii. At a point in space, the direction of the magnetic field produced by a moving charged object is perpendicular to both the velocity of the object and the position vector from the object to that point in space and can be determined using the right-hand rule.
    - 12.2.A.1.iii. The magnitude of the magnetic field is a maximum when the velocity vector and the position vector from the object to that point in space are perpendicular.
- 12.2.B. Describe the force exerted on moving charged objects by a magnetic field
  - 12.2.B.1. Magnetic forces describe interactions between moving charged objects.
  - 12.2.B.2. A magnetic field may exert a force on a charged object moving in that field.
    - 12.2.B.2.i. The magnitude of the force exerted by a magnetic field on a moving charged object is proportional to the magnitude of the charge, the magnitude of the charged object's velocity, and the magnitude of the magnetic field and also depends on the angle between the velocity and magnetic field vectors. Relevant equation: $F = qvB\sin\theta$
    - 12.2.B.2.ii. The direction of the force exerted by a magnetic field on

a moving charged object is perpendicular to both the direction of the magnetic field and the velocity of the charge, as defined by the right-hand rule.

- 12.2.B.3. In a region containing both a magnetic field and an electric field, a moving charged object will experience independent forces from each field.
- 12.2.B.4. The Hall effect describes the potential difference created in a conductor by an external magnetic field that has a component perpendicular to the direction of charges moving in the conductor.

- 12.3.A. Describe the magnetic field produced by a current-carrying wire.
  - 12.3.A.1. A current-carrying wire produces a magnetic field.
    - 12.3.A.1.i. The magnetic field vectors around a long, straight, current-carrying wire are tangent to concentric circles centered on that wire. The field has no component toward, away from, or parallel to the long, straight, current-carrying wire.
    - 12.3.A.1.ii. At a point in space, the magnitude of the magnetic field due to a long, straight, current-carrying wire is proportional to the magnitude of the current in the wire and inversely proportional to the perpendicular distance from the central axis of the wire to the point. Relevant equation: $B = \mu_0 I/2\pi r$
    - 12.3.A.1.iii. The direction of the magnetic field created by a current-carrying wire is determined with the right-hand rule.
    - 12.3.A.1.iv. The direction of the magnetic field at the center of a current-carrying loop is directed along the axis of the loop and can be found using the right-hand rule.
    - 12.3.A.1.v. The magnetic field at a location near two or more current-carrying wires can be determined using vector addition principles.
- 12.3.B. Describe the force exerted on a current-carrying wire by a magnetic field.
  - 12.3.B.1. A magnetic field may exert a force on a current-carrying wire.
    - 12.3.B.1.i. The magnitude of the force exerted by a magnetic field on a current-carrying wire is proportional to the current, the length of the portion of the wire within the magnetic field, and the magnitude of the magnetic field, and also depends on the angle between the direction of the current in the wire and the direction

of the magnetic field. Relevant equation: $F = IlB\sin\theta$

- 12.3.B.1.ii. The direction of the force exerted by the magnetic field on a current-carrying wire is determined by the right-hand rule.

- 12.4.A. Describe the induced electric potential difference resulting from a change in magnetic flux.
  - 12.4.A.1. Magnetic flux is a description of the amount of the component of a magnetic field that is perpendicular to a cross-sectional area.
  - 12.4.A.2. Magnetic flux through a surface is proportional to the magnitude of the component of the magnetic field perpendicular to the surface and to the cross-sectional area of the surface. Relevant equation: $\Phi_B = BA\cos\theta$
    - 12.4.A.2.i. The area vector is defined to be perpendicular to the plane of the surface and directed outward from a closed surface.
    - 12.4.A.2.ii. The sign of the magnetic flux indicates whether the magnetic field is parallel to or antiparallel to the area vector.
  - 12.4.A.3. Faraday's law describes the relationship between changing magnetic flux and the resulting induced emf in a system. Relevant equation: $\varepsilon = \Delta\Phi / \Delta t$
  - 12.4.A.4. Lenz's law is used to determine the direction of an induced emf resulting from a changing magnetic flux. Relevant equation: $\varepsilon = -\Delta\Phi / \Delta t = \Delta(BA\cos\theta) / \Delta t$
    - 12.4.A.4.i. An induced emf generates a current that creates a magnetic field that opposes the change in magnetic flux.
    - 12.4.A.4.ii. The right-hand rule is used to determine the relationships between current, emf, and magnetic flux.
  - 12.4.A.5. A common example of electromagnetic induction is a conducting rod on conducting rails in a region with a uniform magnetic field. Derived equation: $\varepsilon = Blv$

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 13
Unit Title: Geometric Optics

Essential Question

- Why can't a flat lens focus light?
- Why does a mirror flip words?
- How can we make things invisible?
- Why does a straw in a glass of water look bent?

Unit Summary

Unit 13 demonstrates another distinct shift in both content and the models used to analyze physical scenarios. In this unit, students will be introduced to the different ways of thinking about and modeling light. This unit will focus on using the ray model of light to determine the images formed by mirrors as a result of reflection and the images formed by lenses as a result of refraction. Students will be challenged to confront their misconceptions about light, including why objects are not always located where they are seen.

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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

- How do the laws of reflection and refraction govern the behavior of light at boundaries between different media?
- What is Snell's Law, and how does it describe the bending of light as it passes through different materials?
- How do concave and convex mirrors form images, and how can ray diagrams be used to predict image characteristics?
- What are the differences between real and virtual images, and how do they form in mirrors and lenses?
- How do optical phenomena such as total internal reflection and dispersion occur, and what are their applications?

Process

- How can you use ray diagrams to determine the location, size, and nature of an image formed by mirrors and lenses?
- What mathematical techniques can be used to calculate image distances, magnification, and focal lengths in optical systems?
- How can experimental methods be used to verify the laws of reflection and refraction?
- What steps are necessary to analyze and solve problems involving thin lenses and the mirror equation?
- How can you design and test an optical system, such as a telescope or microscope, using geometric optics principles?

Reflective

- How does an understanding of geometric optics contribute to the development of corrective lenses and vision improvement technologies?
- In what ways has the study of geometric optics influenced advancements in photography, telescopes, and microscopes?
- How do optical illusions and mirages occur, and what do they reveal about the nature of light and human perception?
- How has the use of fiber optics revolutionized communication and medical technology?
- What are the limitations of geometric optics, and how does wave optics extend our understanding of light behavior?

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.

- 13.1.A. Describe light as a ray.
    - 13.1.A.1. A light ray is a straight line that is perpendicular to the wavefront of a light wave and points in the direction of travel of the wave.
        - 13.1.A.1.i. Light rays can be used to determine the behavior of light in geometric optics, where the wave nature of light can be neglected.
        - 13.1.A.1.ii. Rays are not sufficient to understand the spreading of light. In interference and diffraction, the wave nature of the light is

important.

- 13.1.A.1.iii. A laser is a common source of a single coherent, monochromatic beam of light that can be modeled as a ray. The wave nature of lasers will be considered in Unit 14.
- 13.1.A.2. Ray diagrams depict the path of light before and after an interaction with matter.

- 13.1.B. Describe the reflection of light from a surface.
  - 13.1.B.1. Light that is incident on a surface can be reflected
  - 13.1.B.2. The law of reflection states that the angle between the incident ray and the normal (the line perpendicular to the surface) is equal to the angle between the reflected ray and the normal. Relevant equation: $\theta_i = \theta_r$
  - 13.1.B.3. Diffuse reflection is the reflection of light from a rough surface and results in light reflected in many different directions, because the line normal to the surface varies over the area over which the light is incident.
  - 13.1.B.4. Specular reflection is the reflection of light from a smooth surface and results in light uniformly reflected from the surface, because the line normal to the surface has an approximately constant direction over the area the light strikes.
- 13.2.A. Describe the image formed by a mirror.
  - 13.2.A.1. Incident light rays parallel to the principal axis of a concave (converging) mirror will be reflected toward a common location, called the focal point.
  - 13.2.A.2. Incident light rays parallel to the principal axis of a convex (diverging) mirror will be reflected such that they appear to have originated from a common location behind the mirror, called the focal point.
  - 13.2.A.3. The focal point of a plane mirror is an infinite distance from the mirror.
  - 13.2.A.4. The focal point of a spherical mirror may be approximated as a point located on the principal axis of the mirror halfway between the surface of the mirror and the center of the mirror’s radius of curvature.
  - 13.2.A.5. A real image is formed by a mirror when light rays emanating from a common point are reflected and then intersect at a common point.

- 13.2.A.6. A virtual image is formed by a mirror when reflected light rays diverge such that they appear to have originated from a common point.
- 13.2.A.7. The location of an image depends on the focal length of the mirror and the distance between the object and the surface of the mirror. Relevant equation: $1/s_o + 1/s_i = 1/f$
    - 13.2.A.7.i. The locations of a mirror's focal point, an object near the mirror, and the image of the object formed by the mirror follow sign conventions that are used to determine those locations relative to the mirror itself.
    - 13.2.A.7.ii. The distance between the image formed and a plane mirror is equal to the distance between the object and the plane mirror.
- 13.2.A.8. The magnification of an image formed by a mirror is the ratio of the size of the image produced to the size of the object itself and depends on the locations of the object and image relative to the mirror. Relevant equation: $M = h_i/h_o = s_i/s_o$
- 13.2.A.9. Ray diagrams can be used to determine the location, type, size, and orientation of images formed by mirrors.
    - 13.2.A.9.i. The three principal rays are typically used to find the images formed by mirrors. The principal rays are 1) the ray parallel to the principal axis, 2) the ray that reflects at the center of the mirror where the principal axis intersects the mirror, and 3) the ray that passes through the focal point of the mirror.
    - 13.2.A.9.ii. Images formed by a mirror can be upright or inverted, virtual or real, and reduced, enlarged, or the same size as the object.

- 13.3.A. Describe the refraction of light between two media.
    - 13.3.A.1. Refraction is the change in direction of a light ray as the ray passes from one medium into another.
    - 13.3.A.2. Refraction is a result of the speed of light changing when light enters a new medium.
    - 13.3.A.3. The index of refraction of a given medium is inversely proportional to the speed of light in the medium. Relevant equation: $n = c/v$
    - 13.3.A.4. Snell's law relates the angles of incidence and refraction of a

light ray passing from one medium into another to the indices of refraction of the two media. Relevant equation: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

- 13.3.A.4.i. When a light ray travels from a medium with a higher index of refraction into a medium with a lower index of refraction, the ray refracts away from the normal.
- 13.3.A.4.ii. When a light ray travels from a medium with a lower index of refraction into a medium with a higher index of refraction, the ray refracts toward the normal.
- 13.3.A.4.iii. When a light ray is incident along the normal to a surface, the transmitted ray is not refracted.

- 13.3.A.5. Total internal reflection may occur when light passes from one medium into another medium with a lower index of refraction.
    - 13.3.A.5.i. Total internal reflection of light occurs beyond a critical angle of incidence. Derived equation: $\theta_{critical} = \sin^{-1}(n_2/n_1)$
    - 13.3.A.5.ii. For incident rays at the critical angle, the ray refracts at 90 degrees and travels along the surface of the material.
    - 13.3.A.5.iii. For incident rays beyond the critical angle, all light is reflected (no light is transmitted into the other medium).

- 13.4.A. Describe the image formed by a lens.
    - 13.4.A.1. Incident light rays parallel to the principal axis of a thin convex (converging) lens will be refracted and converge toward a common location on the transmitted side of the lens, called the focal point.
    - 13.4.A.2. Incident light rays parallel to the principal axis of a thin concave (diverging) lens will be refracted and diverge as if they originated from a focal point on the incident side of the lens.
    - 13.4.A.3. A real image is formed by a lens when light rays originating from a common point are refracted such that they intersect at another common point.
    - 13.4.A.4. A virtual image is formed by a lens when refracted light rays diverge such that they appear to have originated from a common point.
    - 13.4.A.5. For a thin lens, the location of an image depends on the focal length of the lens and the distance between the object and the midline of the lens, as given by the thin-lens equation: $1/s_o + 1/s_i = 1/f$.
        - 13.4.A.5.i. The locations of a lens's focal point, an object, and the image of the object formed by the lens follow sign conventions

that are used to determine those locations relative to the lens itself.

        - 13.4.A.5.ii. Lenses have a focal point on both sides of the lens that depends on the shape of the respective side of the lens.
    - 13.4.A.6. For a thin lens, the magnification of an image is the ratio of the size of the image produced to the size of the object itself and depends on the locations of the object and image relative to the lens. Relevant equation: $M = h_i/h_o = s_i/s_o$
    - 13.4.A.7. Ray diagrams can be used to determine the location, type, size, and orientation of images formed by lenses.
        - 13.4.A.7.i. The three principal rays are typically used to find the images formed by lenses. The principal rays are 1) the ray parallel to the principal axis, 2) the ray that passes through the center of the lens where the principal axis intersects the lens, and 3) the ray that passes through the focal point of the lens.
        - 13.4.A.7.ii. Images formed by a lens can be upright or inverted, virtual or real, and reduced, enlarged, or the same size as the object.

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 14
Unit Title: Waves, Sound, and Physical Optics

Essential Question

- Why does an ambulance siren sound different when it is moving toward you than when it is moving from you?
- Why does it look like a rainbow when you see a puddle of water with oil in it at a gas station?
- Why do two notes an octave apart sound the same?
- Why can you hear a person around a corner, but you can't see them?
- What makes a sonic boom?

Unit Summary

In Unit 14, students will investigate the behavior of waves, including a focused look at sound waves. The study of waves includes ways to quantify a wave, such as amplitude, wavelength, period, frequency, and wave speed, and how light can be modeled as a wave. This unit will also address the concepts of diffraction and interference, polarization, the Doppler effect, and thin-film interference. The end of Unit 14 leaves an open question of whether light should be considered a wave or a particle, which will be further studied in Unit 15.

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 are the key properties of mechanical waves, and how do they differ from electromagnetic waves?
- How do the principles of superposition and interference apply to both sound waves and light waves?
- What factors affect the speed of sound in different media, and how does this relate to real-world applications?
- How do standing waves form in strings and air columns, and what role do they play in musical instruments?
- How does the Doppler effect describe changes in frequency due to relative motion, and where is it observed in nature and technology?

Process

- How can mathematical models be used to predict wave behavior, including frequency, wavelength, and speed?
- What experimental techniques can be used to measure wave properties such as frequency, amplitude, and phase?
- How can Young's double-slit experiment be used to demonstrate the wave nature of light and measure its wavelength?
- What methods can be used to analyze diffraction and interference patterns created by waves passing through slits or around obstacles?
- How can sound waves be visualized and analyzed using tools such as oscilloscopes and resonance tubes?

Reflective

- How does our understanding of wave behavior contribute to the development of medical technologies such as ultrasound imaging?
- How does knowledge of wave properties help in designing noise-canceling headphones and acoustically optimized spaces?
- What role does the study of wave optics play in technological advancements such as fiber optics and laser communication?
- How do real-world applications of the Doppler effect impact fields such as astronomy, meteorology, and law enforcement?
- In what ways has the dual nature of light as both a wave and a particle shaped modern physics and technological innovations?

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.

- 14.1.A. Describe the physical properties of waves and wave pulses.
    - 14.1.A.1. Waves transfer energy between two locations without transferring matter between those locations.

        14.1.A.1.i. A wave pulse is a single disturbance that transfers energy without transferring matter between two locations.

        14.1.A.1.ii. A wave is modeled as a continuous, periodic disturbance with well-defined wavelength and frequency.

- 14.1.A.2. Mechanical waves or wave pulses require a medium in which to propagate. Electromagnetic waves or wave pulses do not require a medium in which to propagate.
- 14.1.A.3. The speed at which a wave or wave pulse propagates through a medium depends on the type of wave and the properties of the medium.
  - 14.1.A.3.i. The speed of all electromagnetic waves in a vacuum is a universal physical constant, c = × 3.00 10^8 m/s .
  - 14.1.A.3.ii. The speed at which a wave pulse or wave propagates along a string is dependent upon the tension in the string, FT, and the mass per length of the string. Relevant equation: v_{string} =sqrt(F_T /(m/l))
  - 14.1.A.3.iii. In a given medium, the speed of sound waves increases with the temperature of the medium.
- 14.1.A.4. In a transverse wave, the direction of the disturbance is perpendicular to the direction of propagation of the wave.
- 14.1.A.5. In a longitudinal wave, the direction of the disturbance is parallel to the direction of propagation of the wave.
  - 14.1.A.5.i. Sound waves are modeled as mechanical longitudinal waves.
  - 14.1.A.5.ii. The regions of high and low pressure in a sound wave are called compressions and rarefactions, respectively.
- 14.1.A.6. Amplitude is the maximum displacement of a wave from its equilibrium position.
  - 14.1.A.6.i. The amplitude of a longitudinal pressure wave may be determined by the maximum increase or decrease in pressure from equilibrium pressure.
  - 14.1.A.6.ii. The loudness of a sound increases with increasing amplitude.
  - 14.1.A.6.iii. The energy carried by a wave increases with increasing amplitude.

- 14.2.A. Describe the physical properties of a periodic wave.
  - 14.2.A.1. Periodic waves have regular repetitions that can be described using period and frequency.
    - 14.2.A.1.i. The period is the time for one complete oscillation of the wave.

14.2.A.1.ii. The frequency is the rate at which the wave repeats. Relevant equation: $T = 1/f$

14.2.A.1.iii. The amplitude of a wave is independent of the period and the frequency of that wave.

14.2.A.1.iv. The energy of a wave increases with increasing frequency.

14.2.A.1.v. The frequency of a sound wave is related to its pitch.

14.2.A.1.vi. Wavelength is the distance between successive corresponding positions (such as peaks or troughs) on a wave.

- 14.2.A.2. A sinusoidal wave can be described by equations for the displacement from equilibrium at a specific location as a function of time. A wave can also be described by an equation for the displacement from equilibrium at a specific time as a function of position. Example equations: $x(t) = A\cos(\omega t) = A\cos(2\pi f t)$; $y(x) = A\cos(2\pi x/\lambda)$
- 14.2.A.3. For a periodic wave, the wavelength is proportional to the wave's speed and inversely proportional to the wave's frequency. Relevant equation: $\lambda = v/f$

- 14.3.A. Describe the interaction between a wave and a boundary
  - 14.3.A.1. A wave that travels from one medium to another can be transmitted or reflected, depending on the properties of the boundary separating the two media.

    14.3.A.1.i. A wave traveling from one medium to another (for example, a wave traveling between low-mass and high-mass strings), will result in reflected and transmitted waves.

    14.3.A.1.ii. A reflected wave is inverted if the transmitted wave travels into a medium in which the speed of the wave decreases.

    14.3.A.1.iii. A reflected wave is not inverted if the transmitted wave travels into a medium in which the speed of the wave increases.

    14.3.A.1.iv. The frequency of a wave does not change when it travels from one medium to another.
  - 14.3.A.2. Transverse waves that are reflected from a surface, refracted through a medium, or pass through specific openings may be polarized.

    14.3.A.2.i. Transverse waves can be polarized and oscillate in a single plane.

14.3.A.2.ii. Longitudinal waves cannot be polarized.

- 14.3.A.3. Polarization of a wave may result in a reduction of the wave's intensity.

  14.3.A.3.i. Intensity is a measure of the amount of power transferred per unit area.

  14.3.A.3.ii. The intensity of a wave is the average power per unit area over one period of the wave.

- 14.4.A. Describe the properties of an electromagnetic wave.
  - 14.4.A.1. Electromagnetic waves consist of oscillating electric and magnetic fields that are mutually perpendicular.

    14.4.A.1.i. Electromagnetic waves are transverse waves because the oscillations of the electric and magnetic fields are perpendicular to the direction of propagation.

    14.4.A.1.ii. Electromagnetic waves are commonly assumed to be plane waves, which are characterized by planar wave fronts.
  - 14.4.A.2. Electromagnetic waves do not need a medium through which to propagate.
  - 14.4.A.3. Categories of electromagnetic waves are characterized by their wavelengths.

    14.4.A.3.i. Categories of electromagnetic waves include (in order of decreasing wavelength, spanning a range from kilometers to picometers) radio waves, microwaves, infrared, visible, ultraviolet, X-rays, and gamma rays.

    14.4.A.3.ii. Visible electromagnetic waves are further broken into categories of color, including (in order of decreasing wavelength) red, orange, yellow, green, blue, and violet.

    14.4.A.3.iii. Visible electromagnetic waves are also called light. Sometimes, electromagnetic waves of all wavelengths are collectively referred to as light or electromagnetic radiation.
- 14.5.A. Describe the properties of a wave based on the relative motion between the source of the wave and the observer of the wave.
  - 14.5.A.1 The Doppler effect describes the relationship between the rest frequency of a wave source, the observed frequency of the source, and the relative velocity of the source and the observer.
  - 14.5.A.2. A greater relative velocity results in a greater measured difference between the observed and rest frequencies.

14.5.A.2.i. For a wave source moving at the same velocity as the observer, the observed frequency is equal to the rest frequency.
14.5.A.2.ii. For a wave source moving toward an observer, the observed frequency is greater than the rest frequency.
14.5.A.2.iii. For a wave source moving away from an observer, the observed frequency is less than the rest frequency.

- 14.6.A. Describe the net disturbance that occurs when two or more wave pulses or waves overlap.
  - 14.6.A.1. Wave interference is the interaction of two or more wave pulses or waves.
  - 14.6.A.2. When two or more wave pulses or waves interact with each other, they travel through each other and overlap rather than bouncing off each other.
  - 14.6.A.3. When two or more wave pulses or waves overlap, the resulting displacement can be determined by adding the individual displacements. This is called superposition.
  - 14.6.A.4. Wave interference may be constructive or destructive.

    14.6.A.4.i. When the displacements of the superposed wave pulses or waves are in the same direction, the interaction is called constructive interference.
    14.6.A.4.ii. When the displacements of the superposed wave pulses or waves are in opposite directions, the interaction is called destructive interference.
    14.6.A.4.iii. Two or more traveling wave pulses or waves can interact in such a way as to produce amplitude variations in the resultant wave pulse or wave.
  - 14.6.A.5. Visual representations of wave pulses or waves are useful in determining the result of two interacting wave pulses or waves.
  - 14.6.A.6. Beats arise from the addition of two waves of slightly different frequency.

    14.6.A.6.i. Waves with different frequencies are sometimes in phase and sometimes out of phase at locations along the waves, causing periodic amplitude changes in the resultant wave.
    14.6.A.6.ii. The beat frequency is the difference in the frequencies of the two waves. Relevant equation: $|f_{beat}| = |f_1 - f_2|$
    14.6.A.6.iii. Tuning forks are devices that are commonly used to

demonstrate beat frequencies.

- 14.6.B. Describe the properties of a standing wave.
  - 14.6.B.1. Standing waves can result from interference between two waves that are confined to a region and traveling in opposite directions.
    - 14.6.B.1.i. Standing waves have nodes and antinodes. A node is a point on the standing wave where the amplitude is always zero. An antinode is a point on the standing wave where the amplitude is always at maximum.
    - 14.6.B.1.ii. The possible wavelengths of a standing wave are determined by the size and boundary conditions of the region to which it is confined.
    - 14.6.B.1.iii. Common regions where standing waves can form include pipes with open or closed ends, as well as strings with fixed or loose ends.
  - 14.6.B.2. A standing wave with the longest possible wavelength is called the fundamental or first harmonic. The second-longest wavelength is typically called the second harmonic, the third longest wavelength is called the third harmonic, and so on. However, for a standing wave with a node at one end and an antinode at the other end, only odd harmonics can be established.
  - 14.6.B.3. Visual representations of standing waves are useful in determining the relationships between length of the region, wavelength, frequency, wave speed, and harmonic.
- 14.7.A. Describe the behavior of a wave and the diffraction pattern resulting from a wave passing through a single opening.
  - 14.7.A.1. Diffraction is the spreading of a wave around the edges of an obstacle or through an opening.
  - 14.7.A.2. Diffraction is most pronounced when the size of the opening is comparable to the wavelength of the wave.
  - 14.7.A.3. Diffraction of multiple wavefronts through a single opening leads to observable interference patterns.
  - 14.7.A.4. Diffraction is commonly demonstrated by monochromatic light of wavelength λ incident on a narrow opening of width a that is a distance L from a screen.
    - 14.7.A.4.i. Constructive and destructive interference of multiple wavefronts originating from the opening will result in bright and

dark bands on the screen.

14.7.A.4.ii. The amount of interference between two wavefronts depends on the path length difference ΔD of the wavefronts.

14.7.A.4.iii. The path length difference ΔD can be described in terms of the opening width a and the angle θ between the direction of propagation of the wavefront and the normal to the opening by the equation $\Delta D = a \sin\theta$.

14.7.A.4.iv. For small angles, where θ < ° 10 , the small angle approximation can be used to relate λ , a, and L to y_{min}, the distance from the middle of the central bright fringe to the mth order of minimum brightness on the screen. Relevant equation: $a(y_{min}/L) \approx m\lambda$

- 14.7.A.5. The diffraction pattern produced by a wave passing through an opening depends on the shape of the opening.
- 14.7.A.6. Visual representations of single-slit diffraction patterns are useful in determining the physical properties of the slit and the interacting waves.

- 14.8.A. Describe the behavior of a wave and the diffraction pattern resulting from the wave passing through multiple openings.
  - 14.8.A.1. The pattern resulting from monochromatic light of wavelength λ incident on two slits a distance d apart is caused by a combination of wave diffraction and wave interference.

14.8.A.1.i. When only considering wave interference, a double slit creates a pattern of uniformly spaced maxima.

14.8.A.1.ii. Constructive and destructive interference of the wavefronts originating from each slit will result in bright and dark bands on the screen.

14.8.A.1.iii. The amount of interference between two wavefronts depends on the path length difference ΔD of the wavefronts.

14.8.A.1.iv. The path length difference ΔD can be described in terms of the slit separation d and the angle θ between the direction of propagation of the wavefront and the normal to the opening by the equation $\Delta D = d \sin\theta$.

14.8.A.1.v. For small angles, where θ <10°, the small angle approximation can be used to relate λ, d, and L to y_{max} , the distance from the middle of the central bright fringe to the mth order of maximum brightness on the screen. Relevant equation: $d\,(y_{max}/L) \approx m\,\lambda$

14.8.A.1.vi. When considering wave interference and wave diffraction, a double slit creates an interference pattern of maxima and minima superimposed within the envelope created by single-slit diffraction.

- 14.8.A.2. Interference patterns produced by light interacting with a double slit indicate that light has wave properties. The source of this discovery was Young's double-slit experiment.
- 14.8.A.3. Visual representations of double-slit diffraction patterns are useful in determining the physical properties of the slits and the interacting waves.
- 14.8.A.4. A diffraction grating is a collection of evenly spaced parallel slits or openings that produce an interference pattern that is the combination of numerous diffraction patterns superimposed on each other.
- 14.8.A.5. When white light is incident on a diffraction grating, the center maximum is white and the higher-order maxima disperse white light into a rainbow of colors, with the longest-wavelength light (red) appearing farthest from the central maximum.

- 14.9.A. Describe the behavior of light that interacts with a thin film.
  - 14.9.A.1**.** When light travels from one medium to another, some of the light is transmitted, some is reflected, and some is absorbed.
  - 14.9.A.2. The phase change of a reflected ray depends on the relative indices of refraction of the materials with which the ray interacts.

    14.9.A.2.i. A phase change of 180 degrees occurs when a light ray is reflected from a medium with a greater index of refraction than the medium through which the ray is traveling.

    14.9.A.2.ii. No phase change occurs when a light ray is reflected from a medium with a lower index of refraction than the medium through which the ray is traveling.
  - 14.9.A.3. The phase of a wave does not change when it is refracted as it passes from one medium into another.
  - 14.9.A.4. Thin-film interference occurs when light interacts with a medium whose thickness is comparable to the light's wavelength.

    14.9.A.4.i. The interactions between the initial reflected light and

the light exiting the thin film after being reflected from the second interface exhibit wave interference behavior, resulting in a single wave that is the sum of the two interacting waves.
14.9.4.A.ii. The amount of constructive or destructive interference between the two reflected waves depends on the relationship between the thickness of the film, the wavelength of light, any phase shifts, and the angle at which the incident light strikes the film.

- 14.9.A.5. Practical examples of thin-film interference include the color variations seen in soap bubbles and oil films, as well as antireflection coatings.
  14.9.A.5.i. The spectrum of colors observed in oil films and soap bubbles arises from differences in the thickness of the film.
  14.9.A.5.ii. Antireflection coatings eliminate reflected light by applying the relationships between indices of refraction, phase shift, and wave interference to create destructive interference of the light reflected from the two surfaces of the coating.
  14.9.A.5.iii. The simplest antireflection coating has a thickness equal to one-quarter of the wavelength of the light in the coating, and the index of refraction of the coating is greater than that of air and less than that of the surface upon which the coating is applied. This assumes incident light is normal to the surface.

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 15
Unit Title: Modern Physics

Essential Question

1) What are the benefits and dangers of radioactivity?
2) How do we measure things we cannot see?
3) Why do infrared telescopes need to be cooled?
4) How does the infrared catastrophe link thermodynamics and modern physics?

Unit Summary

Unit 15 lays the groundwork for the study of modern physics by resolving the conflicts and unanswered questions from Units 13 and 14. While Unit 15 introduces new models and representations (such as energy level diagrams), students will make connections between this unit's content, the fundamental principles of physics, principles of conservation, and models and representations used earlier in the course. These connections will help students make predictions about a variety of phenomena—including radioactive decay rates or nuclear reaction types—and make and justify claims with evidence. Students will also revisit the wave- particle duality of light through their investigations of phenomena such as the photoelectric effect.

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

- How did the failure of classical physics lead to the development of quantum mechanics?
- What are the key postulates of special relativity, and how do they affect our understanding of time and space?
- How does the energy of a photon relate to its frequency and wavelength?
- What is the significance of the Heisenberg uncertainty principle in modern physics?
- How do nuclear fission and fusion processes release energy, and what are their real-world applications?

Process

- How can you use experimental evidence to support the existence of quantized energy levels in atoms?
- What problem-solving strategies help analyze the photoelectric effect using Einstein's equation?
- How can wave-particle duality be demonstrated through experiments like the double-slit experiment?
- What mathematical techniques can be used to determine the energy and momentum of photons?

Reflective

- How has quantum mechanics influenced modern technologies such as semiconductors, lasers, and medical imaging?
- In what ways does relativity challenge our everyday understanding of time and space?
- How do advancements in modern physics shape our understanding of the universe at both microscopic and cosmic scales?
- What ethical considerations arise from the development of nuclear energy and quantum computing?

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.

- 15.1.A. Describe the properties and behavior of an object that exhibits both particle-like and wave-like behavior.
    - 15.1.A.1. Quantum theory was developed to explain observations of matter and energy that could not be explained using classical mechanics. These phenomena include, but are not limited to, atomic spectra, blackbody radiation, and the photoelectric effect.
        - 15.1.A.1.i. Quantum theory is necessary to describe the properties of matter at atomic and subatomic scales.
        - 15.1.A.1.ii. In quantum theory, fundamental particles can exhibit both particle-like and wave-like behavior.
    - 15.1.A.2. Light can be modeled both as a wave and as discrete particles,

called photons.

    - 15.1.A.2.i. A photon is a massless, electrically neutral particle with energy proportional to the photon's frequency. Relevant equations: $E = hf$; $\lambda = c/f$
    - 15.1.A.2.ii. Photons travel in straight lines unless they interact with matter.
  - 15.1.A.3. The speed of a photon depends on the medium through which the photon travels.
    - 15.1.A.3.i. The speed of all photons in free space is equal to the speed of light, $c = \times\ 3.00\ 10^8$ m/s.
    - 15.1.A.3.ii. In general, the speed of photons through a given medium is inversely proportional to the index of refraction of that medium.
  - 15.1.A.4. Particles can demonstrate wave properties, as shown by variations of Young's double-slit experiment.
    - 15.1.A.4.i. A wave model of matter is quantified by the de Broglie wavelength, which increases as the momentum of a particle decreases. Relevant equation: $\lambda = h/p$
    - 15.1.A.4.ii. Quantum theory is necessary to describe systems where the de Broglie wavelength is comparable to the size of the system.
  - 15.1.A.5. Values of energy and momentum have discrete, or quantized, values for bound systems described by quantum theory.
- 15.2.A. Describe the properties of an atom.
  - 15.2.A.1. Atoms have internal structure.
    - 15.2.A.1.i. Atoms consist of a small, positively charged nucleus surrounded by one or more negatively-charged electrons.
    - 15.2.A.1.ii. The nucleus of an atom is made up of protons and neutrons.
    - 15.2.A.1.iii. The number of neutrons and protons in an atom can be represented using nuclear notation.
    - 15.2.A.1.iv. An ion is an atom with a nonzero net electric charge.
  - 15.2.A.2. Each atomic element has a unique number of protons.
    - 15.2.A.2.i. The number and arrangements of electrons affects how atoms interact.
    - 15.2.A.2.ii. The total number of neutrons and protons identifies the

isotope of an element.

    - 15.2.A.2.iii. The mass of an atom is dominated by the total mass of the protons and neutrons in its nucleus.
  - 15.2.A.3. The Bohr model of the atom is based on classical physics and was the historical representation of the atom that led to the description of the hydrogen atom in terms of discrete energy states.
    - 15.2.A.3.i. In the Bohr model of the atom, electrons are modeled as moving around the nucleus in circular orbits determined by the electron's charge and mass, as well as the electric force between the electron and the nucleus. Relevant equations: $F_e = k\,(q_1 q_2 / r^2)$; $F_{net} = (m\,v^2)/r$
    - 15.2.A.3.ii. The standing wave model of electrons accounts for the existence of specific allowed energy states of an electron in an atom, because the electron orbit's circumference must be an integer multiple of the electron's de Broglie wavelength.
- 15.3.A. Describe the emission or absorption of photons by atoms.
  - 15.3.A.1. Energy transfer occurs when photons are absorbed or emitted by an atom, which is modeled as a system consisting of a nucleus and an electron.
  - 15.3.A.2. Energy can only be absorbed or emitted by an atom if the amount of energy being absorbed or emitted corresponds to the energy difference between two atomic energy states.
    - 15.3.A.2.i. An atom in a given energy state may absorb a photon of the appropriate energy and transition to a higher energy state.
    - 15.3.A.2.ii. An atom in an excited energy state may emit a photon of the appropriate energy to spontaneously move to a lower energy state.
    - 15.3.A.2.iii. Because an atom is modeled as a system consisting of an electron and a nucleus, a change in the energy state of an atom corresponds to a change in the interaction energy between the electron and the nucleus.
  - 15.3.A.3. Transitions between two energy states of an atom correspond to the absorption or emission of a photon of a single frequency and, therefore, a single wavelength.
  - 15.3.A.4. Atoms of each element have a unique set of allowed energy levels and thereby a unique set of absorption and emission frequencies.

The unique set of frequencies determines the element’s spectrum.

- 15.3.A.4.i. An emission spectrum can be used to determine the elements in a source of light.
- 15.3.A.4.ii. An absorption spectrum can be used to determine the elements composing a substance by observing what light the substance has absorbed.
- 15.3.A.4.iii. Energy level diagrams are commonly used to visually represent the energy states of an atom.

- 15.3.A.5. Binding energy is the energy required to remove an electron from an atom, causing the atom to become ionized. An atom in the lowest energy level (ground state) will require the greatest amount of energy to remove the electron from the atom.

- 15.4.A. Describe the electromagnetic radiation emitted by an object due to its temperature.
  - 15.4.A.1. Matter will spontaneously convert some of its internal thermal energy into electromagnetic energy.
  - 15.4.A.2. A blackbody is an idealized model of matter that absorbs all radiation that falls on the body. If the body is in equilibrium at a constant temperature, then it must in turn emit energy.
  - 15.4.A.3. A blackbody will emit a continuous spectrum that only depends on the body’s temperature. The radiation emitted by a blackbody is often modeled by plotting intensity per unit wavelength as a function of wavelength.
    - 15.4.A.3.i. The distribution of the intensity of a blackbody’s spectrum as a function of temperature cannot be modeled using only classical physics concepts. A blackbody’s spectrum is described by Planck’s law, which assumes that the energy of light is quantized.
    - 15.4.A.3.ii. The peak wavelength emitted by a blackbody (the wavelength at which the blackbody emits the greatest amount of radiation per unit wavelength) decreases with increasing temperature, as described by Wien’s law. Relevant equation: $\lambda_{max} = b/T$
    - 15.4.A.3.iii. The rate at which energy is emitted (power) by a blackbody is proportional to the surface area of the body and to the temperature of the body raised to the fourth power, as

described by the StefanBoltzmann law. Relevant equation: $P = A\sigma T^4$

- 15.5.A. Describe an interaction between photons and matter using the photoelectric effect.
  - 15.5.A.1. The photoelectric effect is the emission of electrons when electromagnetic radiation is incident upon a photoactive material.
  - 15.5.A.2. The emission of electrons via the photoelectric effect requires a minimum frequency of incident light, called the threshold frequency.
    - 15.5.A.2.i. Light that is incident on a material and is at the threshold frequency or higher will induce electron emission, regardless of the number of photons that strike the material.
    - 15.5.A.2.ii. The energy of the emitted electrons is not dependent on the number of photons that are incident upon the material, which provides evidence that light is a collection of discrete, quantized energy packets called photons.
  - 15.5.A.3. The maximum kinetic energy of an emitted electron is related to the frequency of the incident light and the work function of the material, φ.
    - 15.5.A.3.i. The work function of a material is the minimum energy required to emit an electron from atoms in the material.
    - 15.5.A.3.ii. The maximum kinetic energy of an emitted electron is given by the equation $K_{max} = hf - \varphi$
    - 15.5.A.3.iii. In a typical experimental setup to demonstrate the photoelectric effect and determine the work function of a metal, two metal plates are placed in a vacuum chamber and connected to a variable source of potential difference. One of the plates is illuminated by monochromatic light that causes electrons to be ejected and the potential difference between the plates is adjusted until no current is measured in the circuit.
- 15.6.A. Describe the interaction between photons and matter using Compton scattering.
  - 15.6.A.1. In Compton scattering, a photon interacts with a free electron. The Compton effect is when a photon that emerges from the interaction has a lower energy and longer wavelength than the incoming photon. The magnitude of the change is related to the direction of the photon after the collision.

- 15.6.A.2. Compton scattering provides evidence that light is a collection of discrete, quantized energy packets called photons.
  - 15.6.A.2.i. Compton scattering can be explained by treating a photon as a particle and applying conservation of energy and conservation of momentum to the collision between the photon and electron.
  - 15.6.A.2.ii. The transfer of a photon's energy to an electron results in the energy, momentum, frequency, and wavelength of the photon changing. Relevant equations: $E = hf$; $\lambda = h/p$
- 15.6.A.3. The change in wavelength experienced by a photon after colliding with an electron is related to how much the photon's direction changes. Relevant equation: $\Delta\lambda = (h/m_e c)(1-\cos\theta)$

- 15.7.A. Describe the physical properties that constrain the behavior of interacting nuclei, subatomic particles, and nucleons.
  - 15.7.A.1. The strong force is exerted at nuclear scales and dominates the interactions of nucleons (protons or neutrons).
  - 15.7.A.2. Possible nuclear reactions are constrained by the law of conservation of nucleon number.
  - 15.7.A.3. The behavior of the constituent particles of a nuclear reaction is constrained by laws of conservation of energy, energy-mass equivalence, and conservation of momentum.
  - 15.7.A.4. For all nuclear reactions, mass and energy may be exchanged due to mass-energy equivalence. Relevant equation: $E = mc^2$
  - 15.7.A.5. Energy may be released in nuclear processes in the form of kinetic energy of the products or as photons.
  - 15.7.A.6. Nuclear fusion is the process by which two or more smaller nuclei combine to form a larger nucleus, as well as subatomic particles.
  - 15.7.A.7. Nuclear fission is the process by which the nucleus of an atom splits into two or more smaller nuclei, as well as subatomic particles.
  - 15.7.A.8. Nuclear fission may occur spontaneously or may require an energy input, depending on the binding energy of the nucleus.
- 15.7.B. Describe the radioactive decay of a given sample of material consisting of a finite number of nuclei.
  - 15.7.B.1. Radioactive decay is the spontaneous transformation of a nucleus into one or more different nuclei.

- 15.7.B.1.i. The time at which an individual nucleus undergoes radioactive decay is indeterminable, but decay rates can be described using probability
- 15.7.B.1.ii. The half-life, $t_{½}$, of a radioactive material is the time it takes for half of the initial number of radioactive nuclei to have spontaneously decayed.
- 15.7.B.1.iii. The decay constant λ can be related to the half-life of a radioactive material with the equation $\lambda = \ln 2/t_{½}$
- 15.7.B.2. A material's decay constant may be used to predict the number of nuclei remaining in a sample after a period of time, or the age of a material if the initial amount of material is known. Relevant equation: $N=N_0e^{-\lambda t}$; Derived equation: $\ln(N/N_0) = -\lambda t$
- 15.7.B.3. Different unstable elements and isotopes may have vastly different half-lives, ranging from fractions of a second to billions of years.
- 15.8.A. Describe the processes by which individual nuclei decay.
  - 15.8.A.1. Some processes by which nuclei decay emit subatomic particles with unique properties.
    - 15.8.A.1.i. An alpha particle, or helium nucleus, consists of two neutrons and two protons and is symbolized byα or He^{2+}. (In Physics 2, only He-4 nuclei will be considered.)
    - 15.8.A.1.ii. Neutrinos and antineutrinos are subatomic particles that have no electrical charge, have negligible mass, and are symbolized by ν and $\bar{\nu}$, respectively.
    - 15.8.A.1.iii. Neutrinos and antineutrinos only interact with matter via the weak force and the gravitational force, which results in very little interaction with normal matter.
    - 15.8.A.1.iv. Positrons, or antielectrons, are subatomic particles that have an electric charge opposite that of an electron, have the same mass as an electron, and are symbolized by e^+ or β^+ .
  - 15.8.A.2. Nuclei can undergo radioactive decay via alpha decay, beta-minus decay (β^-), beta-plus decay (β^+), and gamma decay (γ).
    - 15.8.A.2.i. In all nuclear decays, nucleon number (the number of neutrons and protons), lepton number (the number of electrons and neutrinos), and charge are conserved.
    - 15.8.A.2.ii. Alpha decay occurs when a nucleus ejects an alpha

particle.
    - 15.8.A.2.iii. Beta-minus decay occurs when a neutron changes to a proton by emitting an electron and antineutrino.
    - 15.8.A.2.iv. Beta-plus decay occurs when a proton changes to a neutron by emitting a positron and neutrino.
    - 15.8.A.2.v. Gamma decay occurs after a nucleus has undergone alpha or beta decay and the excited nucleus decays to a lower energy state by emitting a photon.
  - 15.8.A.3. The type of decay exhibited by a given nucleus is determined by the isotope of the element.

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.