



College Ready Physics Standards: A Look to the Future

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STANDARD 5

FORCES, ENERGY, AND FIELDS

Attractive and repulsive interactions at a distance (e.g., gravitational, magnetic, electrical and electromagnetic) can be described and explained using a field model.

Objective 5.1 Forces and Fields (Grades 5-8 and 9-12)

Students understand that the field model explains how objects exert attractive and repulsive forces on each other at a distance: their fields are the agents of the interaction.

Objective 5.2 Energy and Fields (Grades 5-8 and 9-12)

Students understand that the field model explains where the energy is stored in a system of two mutually attracting or repelling objects -- in the field of the system. Only systems (not single objects) can have field (potential) energies. Energy can be transferred to and from the field of the system.

Objective 5.3 Electromagnetic Interactions and Fields (Grades 5-8 and 9-12)

Students understand that an electromagnetic interaction occurs when a flow of charged particles creates a magnetic field around the moving particles, or when a changing magnetic field creates an electric field.

Students understand that one way scientists describe and explain how forces act over a distance without contact (without a mechanism) is by using a field model. In this model, spheres of influence, called “fields,” surround objects. When an object with the appropriate property is placed in the field of another object, the field exerts a force on it (e.g. the magnetic field of a magnet exerts a force on a compass needle).

An object with mass produces a gravitational field, and the gravitational field exerts a force on other objects with mass. An electrically charged object creates an electrical (electrostatic) field, and the electrical field exerts a force on other electrically charged and neutral objects. A magnetic field is produced by a magnet and by moving electrical charges (i.e., electric current), and the magnetic field exerts a force on other magnets, magnetic materials, and moving electrical charges. A changing magnetic field can produce an electric field (Faraday’s Law).

The field model also explains where energy is stored -- in the field around a system of two mutually attracting or repelling objects: gravitational field (potential) energy, electrical field (potential) energy, and magnetic field (potential) energy.

CLARIFICATION. The concept of a field is introduced in order to explain force at a distance (what is the mechanism) and where energy is stored in the system. The field concept also allows for the conservation of energy principle to be applied to numerous systems as discussed in other objectives in Standard 4.

Only basic, foundational ideas of the field model are introduced to ensure success in college introductory physics courses.

OBJECTIVE 5.1**FORCES AND FIELDS** (Grades 5-8 and Grades 9-12)

Students understand that the field model explains how objects exert attractive and repulsive forces on each other at a distance: their fields are the agents of the interaction.

Elementary Foundations

By the end of grade 4, students know that:

1. With a few exceptions (e.g., helium-filled balloons), objects fall to the ground no matter where the object is on located on Earth.
2. Without touching, the Earth pulls down on all objects with a force called *gravity* or *the gravitational force*.
3. Without touching them, a magnet pulls on all things made of iron and either pushes or pulls on other magnets. [BSL 4G/E2]
4. Without touching them, an object that has been electrically charged pulls on all other uncharged objects and may either push or pull other charged objects. [BSL4G/E3*]

Grades 5 - 8

Clarification. Students are introduced to the field concept in a very qualitative fashion starting with simple systems involving magnets and compasses. By analogy, the field idea is introduced for the gravitational interaction. Students begin to develop skills in drawing magnetic and gravitational field diagrams.❖

RELATED OBJECTIVES: Gravitational Interactions and Forces (3.4); Electrical and Magnetic Interactions and Forces (3.5)

BOUNDARY.[†] *Field diagrams students draw are limited to single objects only (i.e., no diagrams of interacting magnets, planet-sun systems, or interacting charges). Field line diagrams are excluded because of the conceptual difficulties students have understanding and interpreting field lines.*

ESSENTIAL KNOWLEDGE*

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

- M.5.1.1** Magnetic, electrical, gravitational, and electromagnetic interactions occur continually when objects are not touching, and they do not require a material (medium) between the two interacting objects. These types of interactions are referred to as action-at-a-distance interactions. [Same as in Objective 3.4]
- M.5.1.2** One reason for a field model is to explain how two mutually attracting and repelling objects can interact at a distance, without touching. In the field model, spheres of influence, called fields, surround attracting and repelling objects.
- M.5.1.3** When an object with the appropriate property is placed in the field of another object, the field exerts a force on it (e.g. a the magnetic field of a magnet influencing a steel nail or a compass needle). The stronger the field, the larger the magnitude of the force exerted by the field on objects placed in the field.
- a. The direction of the magnetic field at any location in space is the equilibrium direction of the north end of a compass placed at that point. The magnetic field strength decreases with increasing distance from the magnet.
 - b. The gravitational field strength at any point in space around a planet can be measured by hanging a unit mass on a stationary spring scale. The direction of the gravitational field is the direction of a plumb line,

❖ Underlined words and phrases are defined in the glossary.

[†] For further background and instructional guidance for each objective, including restrictions in the scope of the content for the learning outcomes, see Instructional Guidance for Standard 5 (starting on page 135).

* For further clarification of the learning outcomes and essential knowledge statements for each objective, see the objective *Table of Common Student Conceptual Difficulties* the Instructional Guidance for Standard 5.

ESSENTIAL KNOWLEDGE (5-8), continued

toward the center of the object causing the gravitational field. The gravitational field strength decreases with increasing distance from the planet.

- c. Magnetic and gravitational fields can be represented by field diagrams, obtained by plotting field-strength arrows at different locations around the object producing the field.

LEARNING OUTCOMES

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

- Investigate and explain how mutually attracting or repelling objects interact at a distance without touching. Justify the explanation based on knowledge of the field model.
- Draw a magnetic field diagram for a magnet, using a compass (or many small compasses).
- Analyze two magnetic field diagrams to determine which magnet has the strongest magnetic field; predict the differences that would be observed when compasses were placed at different locations around each magnet.
- Identify correct and incorrect gravitational field diagrams for a planet or moon. Draw a gravitational field diagram for a planet or moon.
- Analyze two gravitational field diagrams to determine which of two planets has the strongest gravitational field; predict the differences that would be observed when unit masses (1 kg) were hung from spring scales placed at different locations near the surface of the planet.

Grades 9 - 12

Clarification. Students relate the source of the field with the field itself, along with qualitative descriptions of the direction of the field. Students are also introduced to the mathematical representation of a gravitational field and an electric field.

RELATED OBJECTIVES: Gravitational Interaction and Forces (3.4); Magnetic and Electrical Interactions and Forces (3.5).

BOUNDARY.[†] *Field line diagrams are excluded.*

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes: {SSCS, page 168}

- H.5.1.1** The field of a particular source (such as Earth) depends only on the properties of the source and the position of an object relative to the source, not on any properties of objects placed in the field (such as a ball). The field of an object is always there, even if the object is not interacting with anything else.
- H.5.1.2** The strength of an object's gravitational field at a certain location is given by the gravitational force per unit of mass experienced by another object placed at that location: $g = F_g/m$. The field direction is toward the center of the source. If the gravitational field at a certain position is known, then the gravitational force exerted by the source of that field on any object at that position can be calculated by multiplying the gravitational field strength (g) and the mass of the object.
- H.5.1.3** The strength of the electrical field of a charged object at a certain location is given by the electric force per unit of charge experienced by another charged object placed at that location. The direction of the electric field at a certain location is parallel to the direction of the electrical force on a positively charged object at that location: $E = F_e/q$. The electric field caused by a collection of charges is equal to the vector sum of the electric fields caused by the individual charges (superposition of charge).

LEARNING OUTCOMES*

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

- Calculate the weights of an object on the surfaces of different planets or moons by using a table showing the gravitational field strength (gravitational force per unit of mass, g) at the surfaces of the planets and moons. [SSCS page 167]
- Calculate the electric forces on a point charge at different locations, given the magnitude of the electric field at these locations. [SSCS page 167]
- Analyze an electric field diagram for a collection of two or three point charges in a line (with the same charge magnitudes) to determine whether the diagram accurately represents the problem. Explain why the diagram is correct or incorrect. Justification is based on knowledge of field diagrams and electric fields. [SSCS page 168]
- Draw a sketch of the electric field diagram for two point charges, given each charge type, relative charge magnitudes and the distance between the two charges. [SSCS page 168]
- Recognize the electric field diagrams for a dipole, a large sheet of charges (uniform surface charge density) and two large capacitor plates. [SSCS page 168]
- Explain what happens to the magnetic or gravitational field of a source when an object is removed from its field. Justification is based on the field model.
- Explain why the gravitational or electrical force on an object does not depend on the specific properties of the object. Justification is based on the field model.

OBJECTIVE 5.2.**ENERGY AND FIELDS** (Grades 5-8 and Grades 9-12)

Students understand that the field model explains where the energy is stored in a system of two mutually attracting or repelling objects -- in the field of the system. Only systems (not single objects) can have field (potential) energies. Energy can be transferred to and from the field of the system.

Elementary Foundations. By the end of grade 4, students know that:

None expected.

Grades 5 - 8

Clarification. Students are introduced to the idea of energy stored in magnetic fields by analogy to the storage of energy in springs and rubber bands. The analogy is then extended to energy storage in gravitational fields.

RELATED OBJECTIVES: Gravitational Interactions and Forces (3.4); and Electrical and Magnetic Interactions and Forces (3.5)

BOUNDARY.[†] *Field line diagrams are excluded. The term "potential" energy is not used until grades 9 - 12 because of the conceptual difficulties students have understanding and using this term.*

ESSENTIAL KNOWLEDGE

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

ESSENTIAL KNOWLEDGE (5-8), continued

- M.5.2.1** When two mutually repelling or attracting objects interact, both objects' kinetic energies change, but since there are no other observable changes in the objects, neither is acting as the energy source or receiver. Instead, the energy is stored in or extracted from the field around the system. The individual objects do not store energy.
- M.5.2.2** During a magnetic interaction magnetic energy is stored in the magnetic field around the system (magnet–magnet or magnet–magnetic object). A change in the separation of magnets is evidence that the magnetic field energy around the system has changed.
- When two magnetically repelling objects are moved close to one another, energy is stored in the field (similar to compressing a spring). When these objects are moved apart, energy is extracted from the field (similar to releasing the spring).
 - When two objects attract one another magnetically, energy is stored in the field by moving the objects apart (similar to stretching a spring), and energy is extracted from the field by allowing them to move closer (similar to releasing the spring).
- M.5.2.3** In the field model, gravitational fields only produce attraction. Gravitational energy is stored in the gravitational field of an Earth–object system. A change in the separation between the objects is evidence that the gravitational field energy of the system has changed. When two attracting masses are moved farther apart, energy is stored in the field. When two attracting masses move closer together, the gravitational field energy decreases.

LEARNING OUTCOMES

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

- **Explain** why energy is stored in the fields of attracting or repelling objects and not in the objects themselves. Justification is based on the field model of stored energy.
- **Investigate** how the field of two repelling magnets changes: (a) when the magnets are moved closer together, and (b) when they are moved farther apart. Make a **claim** about how the stored field energy changed in each case.
- Investigate how the field of two attracting magnets changes: (a) when the magnets are moved farther apart, and (b) when they are moved closer together. For each case, record the observations and sketch the before and after field diagrams. Make a claim about how the stored field energy changed in each case.
- Predict how the gravitational field changes: (a) when an object is moved at a constant speed from the ground to a height h above the ground, and (b) when the object is released to fall to the ground. Justification is based on an analogy with attracting magnets and stretching a spring and releasing the spring.
- Compare by ranking the amount of gravitational potential energy stored in an Earth–object system for different positions of the object relative to Earth's surface.
- Compare and contrast the field models for energy stored in gravitational fields and the field model for energy stored in magnetic fields.
- Explain how we know that the gravitational, electric charge, and magnetic interactions are different. Justification is based on the defining characteristics of each interaction. [See also Objectives 3.4 and 3.5]

Grades 9 - 12

Clarification. In grades 9 - 12, the field model of potential energy is expanded to include mathematical representations of gravitational and electrical (electrostatic) potential energies. Students use these concepts as they continue to develop the skill of determining the terms in the conservation of energy equation that apply to easily observable systems.

RELATED OBJECTIVES: Conservation of Mass, Energy, and Charge (2.1); Gravitational Interactions and Forces (3.4); and Electrical and Magnetic Interactions and Forces (3.5); Contact Interactions and Energy (4.1)

BOUNDARY.[†] Field line diagrams are excluded.

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes: [SSCS, page 171]

H.5.2.1 The energy stored in the field around two mutually attracting or repelling objects is called potential energy (e.g., gravitational potential energy, electric potential energy). A single object does not have potential energy. Only the system consisting of two or more attracting or repelling objects can have potential energy.

H.5.2.2 For an object close to Earth's surface (where gravitational field strength, g , is constant), mechanical energy must be transferred into the Earth-object system (W_{in}) to lift an object at a constant velocity a distance (Δy) above a zero reference point. So for energy to be conserved, the gravitational potential energy stored in the field (ΔPE_{grav}) must increase. As the object is lifted it pushes on the air, so mechanical energy is transferred out of the Earth-object system (W_{out}):

$$\Delta E_{system} = E_{in} - E_{out}$$

$$\Delta PE_{grav} = W_{in} - W_{out}$$

$$\Delta PE_{grav} = mg\Delta y - W_{out}.$$

For objects that are not lifted too far or too fast through the atmosphere, the mechanical energy transfer (work) done to the air is very small and can be neglected.

H.5.2.3 For falling objects close to Earth's surface and a system defined as Earth and the object, the only mechanical energy transfer (work) is out of the system to the air that is pushed by the falling object. The kinetic energy of the object increases and the gravitational potential (field) energy of the Earth-object system decreases:

$$\Delta E_{system} = E_{in} - E_{out}$$

$$\Delta E_{kinetic} + \Delta PE_{grav} = -W_{out}$$

When the mechanical energy transfer (work) to the air is so small it can be neglected, then:

$$\Delta E_{kinetic} + \Delta PE_{grav} = 0$$

H.5.2.4 When charge is transferred from an object to another object (e.g., separating strips of tape, rubbing objects against each other, using batteries, or a van de Graff generator), a mechanical energy transfer (W_{in}) is required to separate the positive and negative charges, just like energy is required to stretch a spring:

$$\Delta E_{system} = E_{in} - E_{out}$$

$$\Delta PE_{electric} - \Delta E_{other} = W_{in}$$

where ΔE_{other} refers to other energy changes within the system (e.g., stored chemical energy of battery, thermal energy from friction).

H.5.2.5 Whenever mechanical energy is transferred to a system of charged objects and there is no change in kinetic energy and no energy is transferred out of the system, the electric potential energy stored in the system must increase for energy to be conserved. The change in electric potential energy per unit charge is called the *potential difference* (ΔV):

$$\Delta E_{system} = E_{in} - E_{out}$$

$$\Delta PE_{electric} = W_{in}$$

$$\Delta V = \Delta PE_{electric}/q$$

LEARNING OUTCOMES

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

- Calculate the change in gravitational potential energy of the Earth-object system for different objects at different locations above Earth's surface by using different reference points. [SSCS page 169]

LEARNING OUTCOMES (9-12), continued

- Identify, for different problems, when the correct system has been selected for describing gravitational or electric potential (field) energies. Justification is based on the field model of potential energy. [SSCS page169]
- Analyze problems involving separating and releasing attracting and repelling objects with the system defined as all the interacting objects (e.g., person separating attracting magnets, releasing repelling charges).
 - ◆ Determine and represent, with an energy diagram, the energy changes within the system and the transfers of energy within and across the boundaries of the system.
 - ◆ Make claims about which terms in the conservation of energy equation are applicable, not applicable or too small to be measurable. Justification is based on the conditions in the problem and knowledge of mechanical energy transfers (work) and magnetic potential energy.
 - ◆ Write the conservation of energy equation for the defined system.
 - ◆ Predict what would happen to a given energy term (increase, stay the same, decrease) in the conservation of energy equation under different conditions for the problem. Justification is based on the terms in the conservation of energy equation.
- Analyze problems involving lifting objects at a constant speed or falling objects near Earth's surface, with the system defined as the Earth and the object. [SSCS page169]
 - ◆ Determine and represent, with an energy diagram, the energy changes within the system and the transfers of energy within and across the boundaries of the system.
 - ◆ Make claims about which terms in the conservation of energy equation are applicable, not applicable or too small to be measurable. Justification is based on the conditions in the problem and knowledge of mechanical energy transfers (work) and gravitational potential energy.
 - ◆ Write the conservation of energy equation for the Earth-object system.
 - ◆ Predict what would happen to a given energy term (increase, stay the same, decrease) in the conservation of energy equation under different conditions for the problem. Justification is based on the terms in the conservation of energy equation.
 - ◆ Define the system as one of the interacting objects. Make and justify claims about which terms in the conservation of energy equation are applicable, not applicable or too small to be measurable.
 - ◆ Write the conservation of energy equation for the defined object.
- Analyze problems involving different methods of separating charges, with the system defined as the two interacting objects (e.g., a rubber rod rubbed with fur, then fur and rod separated). [SSCS page169 - 170]
 - ◆ Determine and represent, with an energy diagram, the energy changes within the system and the transfers of energy within and across the boundaries of the system.
 - ◆ Make claims about which terms in the conservation of energy equation are applicable, not applicable or too small to be measurable. Justification is based on the conditions in the problem and knowledge of mechanical energy transfers (work) and electric potential energy.
 - ◆ Write the conservation of energy equation for the defined system.
 - ◆ Predict what would happen to a given energy term (increase, stay the same, decrease) in the conservation of energy equation under different conditions for the problem. Justification is based on the terms in the conservation of energy equation.
 - ◆ Define the system as one of the interacting objects. Make and justify claims about which terms in the conservation of energy equation are applicable, not applicable or too small to be measurable.
 - ◆ Write the conservation of energy equation for the defined object.
- Translate between representations (e.g., verbal description, energy diagrams and the conservation of energy equation) of energy transfers and energy changes in a defined system for problems involving lifting or falling objects or changing the separation between the charged objects. [SSCS page169]

OBJECTIVE 5.3**ELECTROMAGNETIC INTERACTIONS AND FIELDS** (Grades 5-8 and Grades 9-12)

Students understand that an electromagnetic interaction occurs when a flow of charged particles creates a magnetic field around the moving particles, or when a changing magnetic field creates an electric field.

Elementary Foundations

By the end of grade 4, students know that:

1. Without touching them, a magnet pulls on all things made of iron and either pushes or pulls on other magnets. [BSL 4G/E2]
2. Without touching them, an object that has been electrically charged pulls on all other uncharged objects and may either push or pull other charged objects. [BSL4G/E3*]

Grades 5 - 8

Clarification. Grades 5 - 8 includes electromagnetic interactions as they relate to motors and generators because of the importance of these ideas in understanding the production of electricity and the application of the ideas in environmental science. Electromagnetism is approached in an empirical and qualitative fashion without specific reference to fields.

RELATED OBJECTIVES:
Electric Circuit Interactions and Energy (4.4); Electrical and Magnetic Interaction and Forces (3.5)

ESSENTIAL KNOWLEDGE

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

- M.5.3.1** An electromagnetic interaction occurs when a magnet and a nearby current-carrying wire exert forces on each other. The evidence of the interaction is a change in motion of the magnet, the wire, or both. This interaction is the basis for the design of a motor.
- M.5.3.2** Another type of electromagnetic interaction occurs when a magnet and a wire loop move relative to each other (e.g., magnet is moves, the coil moves, or both move). The evidence of the interaction is an electric current appears in the wire loop. This interaction is the basis of an electric generator.

LEARNING OUTCOMES

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

- Investigate and make a claim about the connection between electrical and magnetic interactions: Justification is based on the observed evidence and knowledge of electrical and magnetic interactions.
- Investigate the variables that influence the size of the magnetic force on the rotating coil of a motor (e.g., the amount of electric current in the wire coil, the number of loops of wire making up the coil; and the distance between the magnet and coil).
 - ◆ Ask and refine a scientific question about a variable that could affect the magnetic force on the rotating coil.
 - ◆ Follow a structured protocol for observing changes in the magnetic force for different values of the variable.
 - ◆ Analyze and represent the data on graphs.
 - ◆ Make a claim, based on the evidence, about the relationship between the variable and the magnetic force on the rotating coil of a motor.
 - ◆ Explain how the motor works, and suggest improvements to the design.
- Analyze a simple generator, explain how it works, and suggest improvements to the design.

LEARNING OUTCOMES (5-8), continued

- Predict and investigate, for different orientations of a magnet and a current-carrying wire, whether the magnet exerts a force on the current-carrying wire. Make a claim about which orientations of the magnet result in a force on the current-carrying wire.
- Distinguish between examples where there is relative motion between a magnet and a closed-loop wire or coil, and examples where the magnet and the wire or coil are both in motion, but not in motion relative to each other.

Grades 9 - 12

Clarification. Students extend their knowledge with qualitative ideas about changing electric and magnetic fields, including Faraday's law of induction.

RELATED OBJECTIVES: Forces and Changes of Motion (P.3.2); Electrical and Magnetic Interactions and Forces (3.5); Electric Current Interactions and Energy (4.2); and Radiant Energy Interactions (4.4).

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes: {SSCS page 172-173}

- H.5.3.1** Electric current and magnetic interactions are closely related, even though they appear to be distinct from each other. The interaction between electricity and magnetism is referred to as an electromagnetic interaction. A basic component of technology is the use of electromagnetic interactions to “convert” mechanical energy into electrical energy and vice versa.
- H.5.3.2** A flow of charged particles (including an electric current in a wire) creates a magnetic field around the moving particles or the current-carrying wire. The evidence of the interaction is a change in motion of a nearby magnet or a change of the flow of charged particles in the presence of a magnet.
- H.5.3.3** A moving charged particle interacts with a magnetic field. For this interaction:
- The magnetic force that acts on a moving charged particle is perpendicular to both the magnetic field and to the direction of motion of the charged particle.
 - The magnitude of the magnetic force depends on the speed of the moving particle, the magnitude of the charge of the particle, the strength of the magnetic field, and the angle between the velocity and the magnetic field.
 - There is no magnetic force on a particle moving parallel to the magnetic field.
 - Moving charged particles in magnetic fields typically follow spiral trajectories. Earth's magnetic field shields the Earth from high-energy charged particles (known as cosmic rays) by deflecting them away from Earth. Moving charged particles can also be trapped in the magnetic field of an object such as Earth. The Van Allen radiation belts are regions of high-energy particles trapped in Earth's magnetic field.
- H.5.3.4** A *changing* magnetic field creates an electric field (while the magnetic field is changing). For this interaction:
- If a closed conducting path such as a wire occupies the space where the magnetic field is changing, the electric field may cause the flow of a changing electric current (evidence of the interaction). This is known as Faraday's law of induction.
 - A changing magnetic field can be created through a closed-loop wire when a magnet and the loop move relative to each other. The magnitude of the induced electric current depends on the strength of the magnetic field, the speed and direction of the relative motion, and the configuration of the wire.
- H.5.3.5** A changing electric field creates a magnetic field, and a changing magnetic field creates an electric field. Thus, one model of radiant energy is an electromagnetic wave in which a pattern of changing electric and magnetic fields propagates at the speed of light.

LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective:
[SSCS page172]

- Investigate, and make a claim about, the variables that affect the magnitude of the induced electric current created by a changing magnetic field. Justification is based on the evidence and Faraday's law of induction.
- Explain why an electric current in a loop of wire, which is not connected to a battery, is detected when the wire is near a changing magnetic field. Justification is based on Faraday's law of induction.
- Explain the role of magnets and coils of wires in the functioning of microphones, speakers, generators and/or motors. Justification is based on the defining characteristics of electromagnetic interactions.
- Predict whether or not there will be an electromagnetic force on two current-carrying wires in different situations. Justification is based on the defining characteristics of electromagnetic interactions.
- Explain qualitatively why radiant energy creates electric currents in conductors. Justification is based on the defining characteristics of electromagnetic interactions.
- Predict whether there will be more cosmic rays trapped at the equator or at the poles of Earth. Justification is based on the defining characteristics of electromagnetic interactions.