Big Idea 2: Fields existing in space can be used to explain interactions.

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

Enduring Understanding 2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.

All fundamental forces, including gravitational force, electric force, and magnetic force, are exerted by one object on another object at a distance; this means that the two objects involved in the interaction do not physically touch each other. To understand and calculate such forces, it is often useful to model them in terms of fields. Forces are vectors, and the associated fields are also vectors, having a magnitude and direction assigned to each point in space. A field model is also useful for describing how scalar quantities, such as temperature and pressure, vary with position. In general, the field created by an array of sources, such as objects with electric charge, can be calculated by combining the fields created by the individual source objects. This is known as the principle of superposition.

Boundary Statement: Physics 1 treats gravitational fields; Physics 2 treats electric and magnetic fields.

PHYSICS 1 PHYSICS 2

Essential Knowledge 2.A.1: A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.

a. Vector fields are represented by field vectors indicating direction and magnitude.

b. When more than one source object with mass or electric charge is present, the field value can be determined by vector addition.

c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

PHYSICS 2

Essential Knowledge 2.A.2: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. In Physics 2, this should include electric potential.

a. Scalar fields are represented by field values.

b. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition.

c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources.

Content Connection:
This essential knowledge does not produce a specific learning objective but serves as a foundation for other learning objectives in the course.

Enduring Understanding 2.B: A gravitational field is caused by an object with mass.

The gravitational field is the field most accessible to students. The effect of a gravitational field $\vec{g}$ on an object with mass m positioned in the field is a force of magnitude mg that points in the direction of the field. The gravitational field can be represented mathematically. The gravitational field at a point in space due to a spherical object with mass M is a vector whose magnitude is equal to the gravitational force per unit of mass placed at that point. The direction of the field at the point is toward the center of mass of the source object. The magnitude of the field outside the object is equal to $G\frac{M}{r^2}$, where r is the distance between the center of mass of the object and the point of interest and G is a constant. As with any vector field, a gravitational field can be represented by a drawing that shows arrows at points that are uniformly distributed in space.

PHYSICS 1

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

a. On Earth, this gravitational force is called weight.

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

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

Learning Objective 2.B.1.1:
The student is able to apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass m in a gravitational field of strength g in the context of the effects of a net force on objects and systems.
[See **Science Practices 2.2 and 7.2**]

PHYSICS 1

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

a. The gravitational field caused by a spherically symmetric object is a vector whose magnitude outside the object is equal to $G\frac{M}{r^2}$.

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

Learning Objective 2.B.2.1:
The student is able to apply $g = G\frac{M}{r^2}$ to calculate the gravitational field due to an object with mass M, where the field is a vector directed toward the center of the object of mass M.
[See **Science Practice 2.2**]

Learning Objective 2.B.2.2:
The student is able to approximate a numerical value of the gravitational field (g) near the surface of an object from its radius and mass relative to those of the Earth or other reference objects.
[See **Science Practice 2.2**]

Enduring Understanding 2.C: An electric field is caused by an object with electric charge.

Coulomb's law of electric force describes the interaction at a distance between two electrically charged objects. By contrast, the electric field serves as the intermediary in the interaction of two objects or systems that have the property of electric charge. In the field view, charged source objects create an electric field. The magnitude and direction of the electric field at a given location are due to the vector sum of the fields created by each of the charged objects that are the source of the field. Another charged object placed at a given location in the field experiences an electric force. The force depends on the charge of the object and the magnitude and direction of the electric field at that location. The concept of the electric field greatly facilitates the description of electrical interactions between multiple-point charges or continuous distributions of charge. In this course, students should be familiar with graphical and mathematical representations of the electric field due to one or more point charges including the field of an electric dipole, the field outside a spherically symmetric charged object, and the uniform field between the plates when far from the edges of oppositely charged parallel plates. Students should be able to use these representations to calculate the direction and magnitude of

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the force on a small charged object due to such electric fields. Electric field representations are to be vectors and not lines.

Essential Knowledge 2.C.1: The magnitude of the electric force **F** exerted on an object with electric charge q by an electric field $\vec{E}$ is $\vec{F} = q\vec{E}$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

PHYSICS 2

Learning Objective 2.C.1.1:
The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $\vec{F} = q\vec{E}$; a vector relation.
[See **Science Practices 6.4 and 7.2**]

Learning Objective 2.C.1.2:
The student is able to calculate any one of the variables — electric force, electric charge, and electric field — at a point given the values and sign or direction of the other two quantities.
[See **Science Practice 2.2**]

Essential Knowledge 2.C.2: The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.

PHYSICS 2

Learning Objective 2.C.2.1:
The student is able to qualitatively and semiquantitatively apply the vector relationship between the electric field and the net electric charge creating that field.
[See **Science Practices 2.2 and 6.4**]

PHYSICS 2

Essential Knowledge 2.C.3: The electric field outside a spherically symmetric charged object is radial and its magnitude varies as the inverse square of the radial distance from the center of that object. Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.

a. The inverse square relation known as Coulomb's law gives the magnitude of the electric field at a distance r from the center of a source object of electric charge Q as $|E| = \frac{1}{4\pi\varepsilon_0}\frac{|Q|}{r^2}$.

b. This relation is based on a model of the space surrounding a charged source object by considering the radial dependence of the area of the surface of a sphere centered on the source object.

Learning Objective 2.C.3.1:
The student is able to explain the inverse square dependence of the electric field surrounding a spherically symmetric electrically charged object.
[See **Science Practice 6.2**]

Essential Knowledge 2.C.4: The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object. Electric dipoles are treated qualitatively in this course as a teaching analogy to facilitate student understanding of magnetic dipoles.

a. When an object is small compared to the distances involved in the problem, or when a larger object is being modeled as a large number of very small constituent particles, these can be modeled as charged objects of negligible size, or "point charges."

b. The expression for the electric field due to a point charge can be used to determine the electric field, either qualitatively or quantitatively, around a simple, highly symmetric distribution of point charges.

Learning Objective 2.C.4.1:
The student is able to distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semiquantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field.
[See **Science Practices 2.2**, **6.4**, **and 7.2**]

Learning Objective 2.C.4.2:
The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points.
[See **Science Practices 1.4 and 2.2**]

PHYSICS 2

Essential Knowledge 2.C.5: Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.

Learning Objective 2.C.5.1:
The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs and is able to recognize that the assumption of uniform field is not appropriate near edges of plates.
[See **Science Practices 1.1 and 2.2**]

Learning Objective 2.C.5.2:
The student is able to calculate the magnitude and determine the direction of the electric field between two electrically charged parallel plates, given the charge of each plate, or the electric potential difference and plate separation.
[See **Science Practice 2.2**]

Learning Objective 2.C.5.3:
The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field.
[See **Science Practices 1.1**, **2.2**, **and 7.1**]

Enduring Understanding 2.D: A magnetic field is caused by a magnet or a moving electrically charged object. Magnetic fields observed in nature always seem to be produced either by moving charged objects or by magnetic dipoles or combinations of dipoles and never by single poles.

Knowledge of the properties and sources of magnetic fields is necessary in other big ideas dealing with magnetism. This knowledge is critical to student understanding of areas such as geophysical processes and medical applications. Students also should know that magnetic fields observed in nature always seem to be caused by dipoles or combinations of dipoles and never by single poles. A magnetic dipole can be modeled as a current in a loop. A single magnetic pole (a magnetic monopole like an isolated north pole of a magnet) has never been observed in nature.

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Representations of these fields are important to the skills that students need to develop in the course. The pattern of magnetic field vectors tangent to concentric circles around a current-carrying wire and the dipole pattern of field vectors around a bar magnet are needed representations.

Magnetic materials contain magnetic domains that are themselves little magnets. Representations can be drawn of the atomic-scale structure of ferromagnetic materials, such as arrows or smaller bar magnets, which indicate the directional nature of magnets even at these small scales. These magnetic moments lead to discussions of important modern applications such as magnetic storage media.

PHYSICS 2

Essential Knowledge 2.D.1: The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity, and the magnitude of the magnetic field. It also depends on the angle between the velocity and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles.

Learning Objective 2.D.1.1:
The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field.
[See **Science Practice 2.2**]

PHYSICS 2

Essential Knowledge 2.D.2: The magnetic field vectors around a straight wire that carries electric current are tangent to concentric circles centered on that wire. The field has no component toward the current-carrying wire.

a. The magnitude of the magnetic field is proportional to the magnitude of the current in a long straight wire.

b. The magnitude of the field varies inversely with distance from the wire, and the direction of the field can be determined by a right-hand rule.

Learning Objective 2.D.2.1:
The student is able to create a verbal or visual representation of a magnetic field around a long straight wire or a pair of parallel wires.
[See **Science Practice 1.1**]

PHYSICS 2

Essential Knowledge 2.D.3: A magnetic dipole placed in a magnetic field, such as the ones created by a magnet or the Earth, will tend to align with the magnetic field vector.

a. A simple magnetic dipole can be modeled by a current in a loop. The dipole is represented by a vector pointing through the loop in the direction of the field produced by the current as given by the right-hand rule.

b. A compass needle is a permanent magnetic dipole. Iron filings in a magnetic field become induced magnetic dipoles.

c. All magnets produce a magnetic field. Examples should include magnetic field pattern of a bar magnet as detected by iron filings or small compasses.

d. Earth has a magnetic field.

Learning Objective 2.D.3.1:
The student is able to describe the orientation of a magnetic dipole placed in a magnetic field in general and the particular cases of a compass in the magnetic field of the Earth and iron filings surrounding a bar magnet.
[See **Science Practice 1.2**]

PHYSICS 2

Essential Knowledge 2.D.4: Ferromagnetic materials contain magnetic domains that are themselves magnets.

a. Magnetic domains can be aligned by external magnetic fields or can spontaneously align.

b. Each magnetic domain has its own internal magnetic field, so there is no beginning or end to the magnetic field — it is a continuous loop.

c. If a bar magnet is broken in half, both halves are magnetic dipoles in themselves; there is no magnetic north pole found isolated from a south pole.

Learning Objective 2.D.4.1:
The student is able to use the representation of magnetic domains to qualitatively analyze the magnetic behavior of a bar magnet composed of ferromagnetic material.
[See **Science Practice 1.4**]

Enduring Understanding 2.E: Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.

When visualizing a scalar field, it is useful to construct a set of contour lines connecting points at which the field has the same (constant) value. A good example is the set of contour lines (gravitational equipotentials) on which the gravitational potential energy per unit mass has a constant value. Such equipotential lines can be constructed using the electric potential and can also be associated with temperature and other scalar fields. When considering equipotential lines, the associated vector field (such as the electric field) is always perpendicular to the equipotential lines. When not provided with a diagram of field vectors, students will be expected to draw accurate equipotential lines ONLY for spherically symmetric sources and for sources that create approximately uniform fields.

Essential Knowledge 2.E.1: Isolines on a topographic (elevation) map describe lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential). As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational and electrical potential and potential differences.]

Learning Objective 2.E.1.1:
The student is able to construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential.
[See **Science Practices 1.4**, **6.4**, **and 7.2**]

PHYSICS 2

Essential Knowledge 2.E.2: Isolines in a region where an electric field exists represent lines of equal electric potential referred to as equipotential lines.

a. An isoline map of electric potential can be constructed from an electric field vector map, using the fact that the isolines are perpendicular to the electric field vectors.

b. Since the electric potential has the same value along an isoline, there can be no component of the electric field along the isoline.

Learning Objective 2.E.2.1:
The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field.
[See **Science Practices 6.4 and 7.2**]

Learning Objective 2.E.2.2:
The student is able to predict the structure of isolines of electric potential by constructing them in a given electric field and make connections between these isolines and those found in a gravitational field.
[See **Science Practices 6.4 and 7.2**]

Learning Objective 2.E.2.3:
The student is able to qualitatively use the concept of isolines to construct isolines of electric potential in an electric field and determine the effect of that field on electrically charged objects.
[See **Science Practice 1.4**]

PHYSICS 2

Essential Knowledge 2.E.3: The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

Learning Objective 2.E.3.1:
The student is able to apply mathematical routines to calculate the average value of the magnitude of the electric field in a region from a description of the electric potential in that region using the displacement along the line on which the difference in potential is evaluated.
[See **Science Practice 2.2**]

Learning Objective 2.E.3.2:
The student is able to apply the concept of the isoline representation of electric potential for a given electric charge distribution to predict the average value of the electric field in the region.
[See **Science Practices 1.4 and 6.4**]