14.2 Describing Fields

In Figure 14.5 (A), a woodcutter exerts a splitting force on a log by direct contact between the axe and the log. In contrast, in Figure 14.5 (B), a charged comb is exerting a force on charged pith balls without coming into contact with the balls. This electrostatic force between the comb and pith balls is an example of an action-at-a-distance force. You have just been studying the characteristics of the three common action-at-a-distance forces: gravitational, electric, and magnetic forces. The phrase **action at a distance** describes some of the characteristics of these forces, but does not really explain how these results are achieved. The critical question now is: How is each mass or charge or magnet “aware” of the other?

Figure 14.5 **(A)** A woodcutter chopping a log is an example of a contact force. **(B)** When a charged comb exerts a force on charged pith balls, the force is acting at a distance and is a non-contact force.

The question of how an object can exert a force on another object without making contact with the object was addressed by Michael Faraday (1792–1867), who proposed the concept of a field. This field concept became quite popular and was extended to explain the gravitational forces between masses.

The fundamental concept is that a **field** is a property of space. An object influences the space around it, setting up either an electric, gravitational, or magnetic field. The object producing the field is called the “source” of the field. This field in turn exerts a force on other objects located within it. This concept is consistent with the inverse square law, which implies that an object influences the space around it.

SECTION OUTCOMES

- Define and describe the concepts related to electric, gravitational, and magnetic fields.
- Compare the properties of electric, gravitational, and magnetic fields.
- Analyze the electric field and the electric forces produced by point charges.
- Sketch simple field patterns using field lines.

KEY TERMS

- action at a distance
- field
- test charge
- electric field intensity
- electric field
- gravitational field intensity
- magnetic field intensity
- electric field line
- gravitational field line
- magnetic field line

In 1600, William Gilbert (1540–1603) hypothesized that the rubbing of certain materials, such as amber, removes a fluid or "humour" from the material and releases an "effluvium" into the surroundings. He proposed that the effluvium made contact with other materials and caused the force now known as the "electrostatic force." As you continue to study this section, decide whether Gilbert was on the right track.

Defining Field Intensity

Figure 14.6 illustrates the generation of an electric field by a charge, q_1. The density of the shading designates the strength of the field. If a second charge, q_2, is introduced into the field at point P, for example, it is the *field* that interacts with q_2. Because the interaction is between the field and charge q_2, it is not necessary to describe forces between objects separated by any distance.

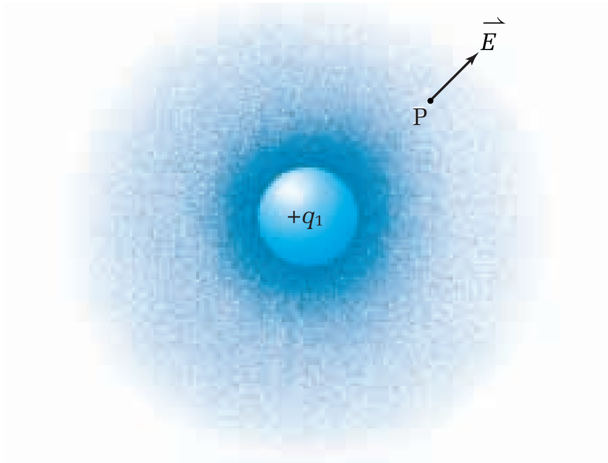


Figure 14.6 Charge q_1 influences the space around it by generating an electric field. The density of the shading indicates the strength of the field.

To describe the field around a charge, q, it is convenient to use the concept of a test charge. By definition, a **test charge** is a point charge with a magnitude so much smaller than the source charge that any field generated by the test charge itself is negligible in relation to the field generated by the source charge. You can place the test charge, q_t, at any point P within the field generated by q, and then take the following steps.

- Write Coulomb's law to describe the force between the source charge, q, and the test charge, q_t. $$F = k\frac{qq_t}{r^2}$$
- Divide both sides of the equation by q_t. $$\frac{F}{q_t} = k\frac{q}{r^2}$$

The term on the right-hand side of the equation contains only the source charge and the distance that q_t is from the source charge. Since it is independent of anything that might be located at q_t, it provides a convenient way to describe the condition of space at point P. Now the term on the left-hand side of this equation is defined as the magnitude of the **electric field intensity**, $\vec{E}$, which is commonly called the **electric field**.

DEFINITION OF ELECTRIC FIELD INTENSITY

The electric field intensity at a point is the quotient of the electric force on a charge and the magnitude of the charge located at the point.

$$\vec{E} = \frac{\vec{F}_Q}{q}$$

Quantity	Symbol	SI unit
electric field intensity	$\vec{E}$	$\frac{N}{C}$ (newtons per coulomb)
electric force	$\vec{F}_Q$	N (newtons)
electric charge	q	C (coulombs)

Unit Analysis

$$\frac{\text{newtons}}{\text{coulomb}} = \frac{N}{C}$$

Note: Electric field intensity has not been given a unique unit.

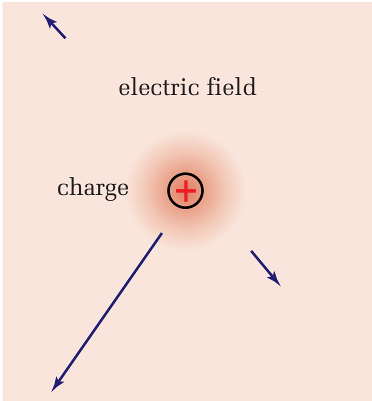


Figure 14.7 Vector arrows can be used to represent the magnitude and direction of the electric field around a charge at various locations.

Since force is a vector quantity, so also is an electric field. An electric force can be attractive or repulsive, so physicists have accepted the convention that the direction of the electric field vector at any point is given by the direction of the force that would be exerted on a *positive* charge located at that point. Using this concept, you can illustrate an electric field by drawing force vectors at a variety of points in the field. As shown in Figure 14.7, the length of the vector represents the magnitude of the field at the tail of the vector, and the direction of the vector represents the direction of the field at that point.

MODEL PROBLEM

Calculating Electric Field Intensity

A positive test charge, $q_t = +2.0 \times 10^{-9}$ C, is placed in an electric field and experiences a force of $\vec{F} = 4.0 \times 10^{-9}$ N[W].

(a) What is the electric field intensity at the location of the test charge?

(b) Predict the force that would be experienced by a charge of $q = +9.0 \times 10^{-6}$ C if it replaced the test charge, q_t.

Frame the Problem

- The *electric field intensity* is related to the *force* and the test *charge*.
- If you know the *electric field intensity* at a point in space, you can determine the *force* on any *charge* that is placed at that point without knowing anything about the source of the field.

continued

continued from previous page

Identify the Goal

The electric field, $\vec{E}$, at a given point in space
The force, $\vec{F}$, on the new charge located at the same point

Variables and Constants

Known	**Unknown**
$\vec{F}_{q_t} = 4.0 \times 10^{-9}$ N[W]	$\vec{E}$
$q_t = 2.0 \times 10^{-9}$ C	$\vec{F}$
$q = 9.0 \times 10^{-6}$ C	

Strategy

Find the electric field intensity by using the equation that defines electric field.

Calculations

$$\vec{E} = \frac{\vec{F}}{q_t}$$

$$\vec{E} = \frac{4.0 \times 10^{-9}\ \text{N[W]}}{2.0 \times 10^{-9}\ \text{C}}$$

$$\vec{E} = 2.0\ \frac{\text{N}}{\text{C}}\text{[W]}$$

(a) The electric field intensity is $\vec{E} = 2.0\ \frac{\text{N}}{\text{C}}\text{[W]}$.

Rearrange the equation for electric field to solve for the new force.

$$\vec{E} = \frac{\vec{F}}{q}$$

$$\vec{F} = q\vec{E}$$

Substitute the numerical values and solve.

$$\vec{F} = (9.0 \times 10^{-6}\ \cancel{\text{C}})\left(2.0\ \frac{\text{N}}{\cancel{\text{C}}}\text{[W]}\right)$$

$$\vec{F} = 18 \times 10^{-6}\ \text{N[W]}$$

$$\vec{F} = 1.8 \times 10^{-5}\ \text{N[W]}$$

(b) The force on the 9.0×10^{-6} C charge is $\vec{F} = 1.8 \times 10^{-5}$ N[W].

Validate

You would expect the electric field to have units N/C and be pointing west which it does.

Since the second charge is larger than the first, you would expect the second force to be larger than the first. Charges in the microcoulomb range are considered to be average charges that occur in electrostatic experiments.

PRACTICE PROBLEMS

11. A positive charge of 3.2×10^{-5} C experiences a force of 4.8 N to the right when placed in an electric field. What is the magnitude and direction of the electric field at the location of the charge?

12. An electric field points due east with a magnitude of 3.80×10^{3} N/C at a particular location. If a charge of –5.0 μC is placed at this location, what will be the magnitude and the direction of the electric force that it experiences?

13. A negative charge of 2.8×10^{-6} C experiences an electrostatic force of 0.070 N to the right. What is the magnitude and direction of the electric field at the location of the charge?

14. A small charged sphere is placed at a point in an electric field that points due west and has a magnitude of 1.60×10^4 N/C. If the sphere experiences an electrostatic force of 6.4 N east, what is the magnitude and sign of its charge?

A discussion similar to that for the electric field intensity can be made for gravitational field intensity. A mass, such as Earth, can exert a gravitational force on a test mass placed in its vicinity. The ratio of the gravitational force to the test mass depends only on the source and the location in the field. This ratio is called the **gravitational field intensity**, for which the symbol is $\vec{g}$.

DEFINITION OF GRAVITATIONAL FIELD INTENSITY

The gravitational field intensity at a point is the quotient of the gravitational force and the magnitude of the test mass.

$$\vec{g} = \frac{\vec{F}_g}{m}$$

Quantity	Symbol	SI unit
gravitational field intensity	$\vec{g}$	$\frac{N}{kg}$ (newtons per kilogram)
gravitational force	$\vec{F}_g$	N (newtons)
mass	m	kg (kilograms)

Unit Analysis

$$\frac{\text{newtons}}{\text{kilogram}} = \frac{N}{kg}$$

In the past, you have used the symbol g to represent the acceleration due to gravity at Earth's surface. If you analyze the equation that described gravitational field intensity in the box above, you will see that it can be rearranged to give $\vec{F} = m\vec{g}$, which is the same as the equation for the weight of an object at Earth's surface. So, in fact, the g that you have been using is the same as the gravitational field intensity at Earth's surface.

Conceptual Problem

- Show that the units for g, m/s^2, are equivalent to the units for gravitational field intensity, or N/kg.

MODEL PROBLEM

Calculating Gravitational Field Intensity

A mass of 4.60 kg is placed 6.37×10^6 m from the centre of a planet and experiences a gravitational force of attraction of 45.1 N.

(a) Calculate the gravitational field intensity at this location.

(b) Discuss the significance of your answer.

Frame the Problem

- The definition of *gravitational field intensity* is the gravitational *force* per unit *mass*.

Identify the Goal

The gravitational field intensity, $\vec{g}$, at this location

Variables and Constants

Known	Unknown
$\lvert\vec{F}\rvert = 45.1$ N	$\vec{g}$
$m = 4.60$ kg	
$r = 6.37 \times 10^6$ m	

Strategy

Find the gravitational field intensity by using the equation for field intensity and the given variables.

Calculations

$$\vec{g} = \frac{\vec{F}}{m}$$

$$\lvert\vec{g}\rvert = \frac{45.1 \text{ N}}{4.60 \text{ kg}}$$

$$\vec{g} = 9.80 \frac{\text{N}}{\text{kg}} \text{[in the direction of the force]}$$

(a) The gravitational field intensity at this location is 9.80 N/kg.

Look for recognizable characteristics, then investigate other data.

The value of the field intensity is identical to that of Earth's near its surface.

The distance given is actually the average radius of Earth.

(b) The location seems to be at the surface of Earth, although another alternative is that it could be *above* the surface of a planet with gravitational field intensity at its surface that is greater than that of Earth.

Validate

The units are correct for gravitational field. The values for both distance and field intensity provide more validation, because they are identical to the values for the surface of Earth. However, this does not preclude the possibility of the object being above another planet.

PRACTICE PROBLEMS

15. What is the gravitational field intensity at the surface of Mars if a 2.0 kg object experiences a gravitational force of 7.5 N?

16. The gravitational field intensity on the surface of Jupiter is 26 N/kg. What gravitational force would a 2.0 kg object experience on Jupiter?

17. The planet Saturn has a gravitational field intensity at its surface of 10.4 N/kg. What is the mass of an object that weighs 36.0 N on the surface of Saturn?

18. What would be the gravitational field intensity at a location exactly one Saturn radius above the surface of Saturn?

19. What is the centripetal acceleration of a satellite orbiting Saturn at the location described in the previous problem?

The gravitational field can also be mapped in the region of a source mass by drawing the gravitational field vectors at corresponding points in the field. Similar to the electric field, the vector length represents the magnitude of the gravitational field and the direction of the vector represents the direction in which a gravitational force would be exerted on a test mass placed in the field.

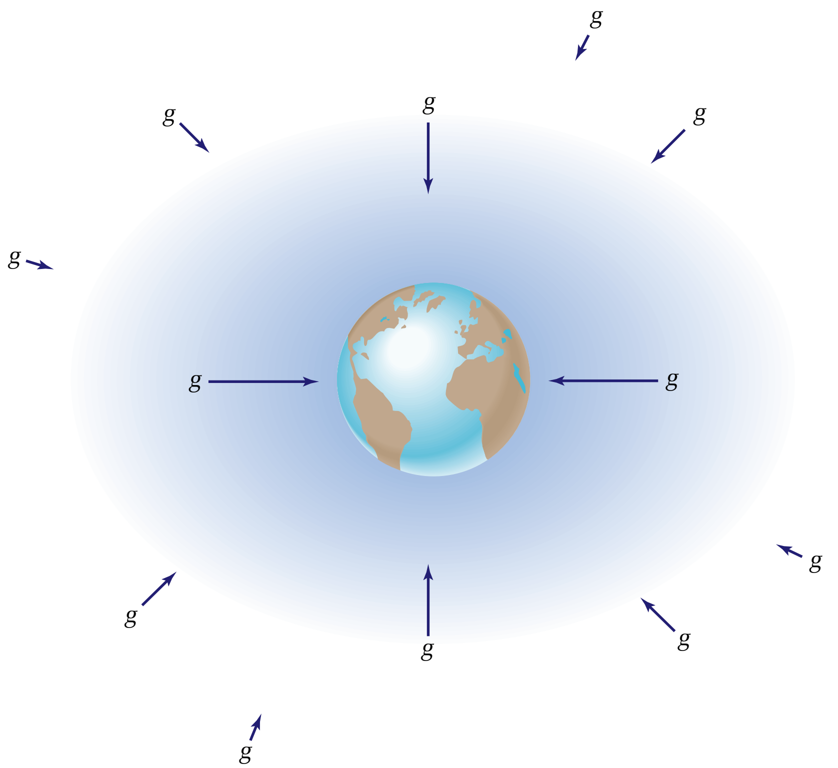
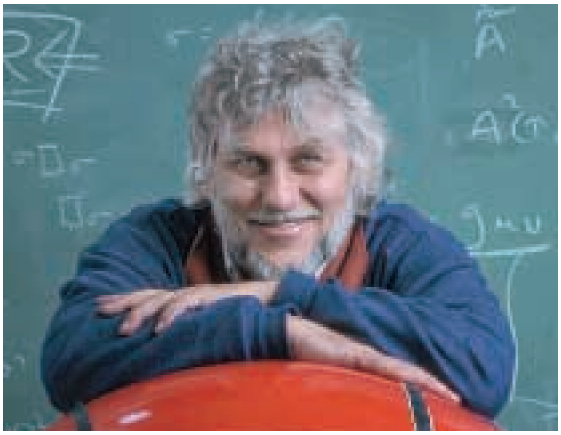


Figure 14.8 Earth's gravitational field can be represented by vectors, with the length of each being proportional to the field intensity at that point.

CANADIANS IN PHYSICS

Gravity: A Matter of Time

William George Unruh was born in Winnipeg, the son of a high school physics teacher. "As a boy I loved looking at the pictures in my father's physics textbooks," he recalls. "They aroused my curiosity about how the world works." He attended the University of Manitoba and then Princeton University, where he received his Ph.D. Today, he is a professor of physics and astronomy at the University of British Columbia and a Fellow of the Canadian Institute for Advanced Research.



Dr. Unruh with the beach ball that he sometimes uses to help explain the concept of gravity.

Dr. Unruh explains that, according to Albert Einstein, "The rate at which time flows can change from place to place, and it is this change in the flow of time that causes the phenomenon we usually refer to as gravity." Dr. Unruh's work focusses on understanding aspects of Einstein's theories. "For example," he says, "Since matter can influence time and matter influences gravity, which is just the variable flow of time, the very measuring instruments we use to measure time can change time. While this is not important in most situations, it becomes very important in trying to decide how the universe operates; for example, in understanding black holes." Dr. Unruh explains that, in black holes, the structures of space and time collaborate, creating regions through which even light cannot travel.

"All of physics is now described in terms of field theories," Dr. Unruh points out. "However, we also experience the world in terms of particles. Since fields exist everywhere at all times, part of my work has been trying to understand the particulate nature of fields. Probably my best known work is showing that the particle nature of fields depends on the observer's state of motion. If an observer is accelerated through a region that seems to be empty of particles to an observer at rest, that region will, to the accelerated observer, appear to be filled with a hot bath of particles. Thus, the existence or non-existence of particles in a field can depend on how the observer moves as he or she observes that field. The effect is extremely small, but it is there."

Another area in which Dr. Unruh works is gravity wave detection. A gravity wave might be called a "vibration of space and time." It is caused by the acceleration of masses; for example, of black holes around each other. The techniques that Dr. Unruh and others have developed will be important to the future refinement of gravity wave detectors now being built in the states of Louisiana and Washington, as well as elsewhere in the world.

Since magnetic monopoles are not known to exist, it is not practical to try to define magnetic field intensities in a way that is analogous to the definitions of electric and gravitational fields. The most practical way to describe magnetic field intensity at this point is to relate it to the effect of a magnetic field on a current-carrying wire, which you studied in previous science courses. The following steps show you how to relate the magnitude of **magnetic field intensity**, B, to the magnitude of the force, F_B, exerted by the magnetic field on a length, l, of wire carrying a current, I.

- Write the equation describing the magnitude of the force on a current-carrying conductor in a magnetic field when the direction of the current is perpendicular to the magnetic field.

$$F_B = I\,l\,B$$

- Rearrange the equation to solve for the magnetic field intensity.

$$B = \frac{F}{Il}$$

- The SI unit of magnetic field intensity is the tesla, T. Substitute SI units for the symbols in the equation above.

$$\mathrm{T} = \frac{\mathrm{N}}{\mathrm{A \cdot m}} \text{ or}$$

$$\text{tesla} = \frac{\text{newton}}{\text{ampere} \cdot \text{metre}}$$

The above relationship states that if each metre of a conductor that is carrying a current of one ampere experiences a force of one newton due to the presence of a magnetic field that is perpendicular to the direction of the current, the magnitude of the magnetic field is one tesla.

Fields near Point Sources

The definition and accompanying equation that you learned for electric field strength, $\vec{E} = \vec{F}_Q/q$, is a general definition. If you know the force on a charge due to an electric field, you can determine the electric field intensity without knowing anything about the source of the field. It is convenient, however, to develop equations that describe the electric field intensity for a few common, special cases, such as point charges.

- Write the equation describing the magnitude of the force on a test charge, q_t, that is a distance, r, from a point charge, q.

$$|\vec{F}_Q| = k\frac{qq_t}{r^2}$$

- Write the general definition for the electric field intensity.

$$\vec{E} = \frac{\vec{F}_Q}{q_t}$$

- Substitute the expression for force into the above equation and simplify.

$$|\vec{E}| = \frac{k\frac{q\cancel{q_t}}{r^2}}{\cancel{q_t}}$$

$$|\vec{E}| = k\frac{q}{r^2}$$

ELECTRIC FIELD INTENSITY NEAR A POINT CHARGE

The magnitude of the electric field intensity a distance away from a point charge is the product of Coulomb's constant and the charge, divided by the square of the distance from the charge. The direction of the field is radially outward from a positive point charge and radially inward toward a negative point charge.

$$|\vec{E}| = k\frac{q}{r^2}$$

Quantity	Symbol	SI unit
electric field intensity	$\vec{E}$	$\frac{\mathrm{N}}{\mathrm{C}}$ (newtons per coulomb)
Coulomb's constant	k	$\frac{\mathrm{N}\cdot\mathrm{m}^2}{\mathrm{C}^2}$ (newton · metres squared per coulomb squared)
source charge	q	C (coulombs)
distance	r	m (metres)

Unit Analysis

$$\frac{\text{newton}\cdot\text{metre}^2}{\text{coulomb}^2}\cdot\frac{\text{coulomb}}{\text{metre}^2} = \frac{\text{newton}}{\text{coulomb}}$$

$$\frac{\mathrm{N}\cdot\cancel{\mathrm{m}^2}}{\mathrm{C}^{\cancel{2}}}\cdot\frac{\cancel{\mathrm{C}}}{\cancel{\mathrm{m}^2}} = \frac{\mathrm{N}}{\mathrm{C}}$$

Note: This equation applies only to the field surrounding an isolated point charge.

MODEL PROBLEMS

Field Intensity near a Charged Sphere

1. **What is the electric field intensity at a point 30.0 cm from the centre of a small sphere that has a positive charge of 2.0×10^{-6} C?**

Frame the Problem

- At any point outside of a *charged sphere*, the *electric field* is the same as it would be if the charge was *concentrated at a point* at the *centre* of the sphere.
- The *electric field* is related to the source *charge* and *distance*.
- The *direction* of the field is the direction in which a *positive charge would move* if it was placed at that point in the field.

Identify the Goal

The electric field intensity, $\vec{E}$

Variables and Constants

Known	Implied	Unknown
$q = +2.0 \times 10^{-6}$ C	$k = 9.0 \times 10^{9} \frac{\text{N} \cdot \text{m}^2}{\text{C}^2}$	$\vec{E}$
$r = 0.30$ m		

Strategy / Calculations

Find the magnitude of the field intensity by using the equation for the special case of the field near a point charge.

$$|\vec{E}| = k\frac{q}{r^2}$$

Substitute the numerical values for charge and distance and solve.

$$|\vec{E}| = \left(9.0 \times 10^{9} \frac{\text{N} \cdot \text{m}^2}{\text{C}^2}\right)\left(\frac{2.0 \times 10^{-6}\ \text{C}}{(0.30\ \text{m})^2}\right)$$

The direction is radially outward from the positive charge.

$$|\vec{E}| = 2.0 \times 10^{5}\ \frac{\text{N}}{\text{C}}$$

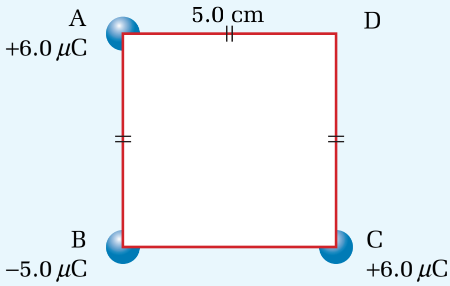
The electric field intensity is 2.0×10^5 N/C in a direction pointing directly away from the source charge.

Validate

Close to a charge of "average" magnitude, the field is expected to be quite strong. Check that the units cancel to give N/C.

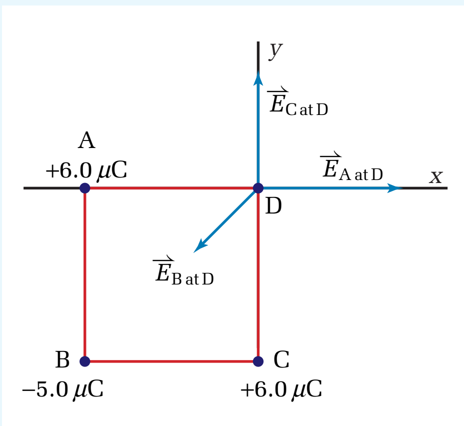
$$\frac{\text{N} \cdot \cancel{\text{m}^2}}{\cancel{\text{C}^2}} \cdot \frac{\cancel{\text{C}}}{\cancel{\text{m}^2}} = \frac{\text{N}}{\text{C}}$$

2. Three charges, A (+6.0 μC), B (–5.0 μC), and C (+6.0 μC), C (+6.0 μC), are located at the corners of a square with sides that are 5.0 cm long. What is the electric field intensity at point D?



Frame the Problem

- Since field intensities are vectors they must also be *added vectorially*.
- The magnitude of the field vectors can be determined individually.
- Draw a *vector diagram* showing the *field intensity* vectors at point D and then superimpose an *x-y coordinate* system on the drawing, with the *origin* at point D.



Identify the Goal

The resultant electric field intensity, $\vec{E}$, at point D

Variables and Constants

Known	Implied	Unknown
$d_{AB} = d_{BC} = 5.0$ cm	$k = 9.0 \times 10^{9} \frac{\text{N} \cdot \text{m}^2}{\text{C}^2}$	$\vec{E}_D$
$q_A = +6.0\ \mu$C		d_{BD}
$q_B = -5.0\ \mu$C		
$q_c = +6.0\ \mu$C		

continued ►

continued from previous page

Strategy | **Calculations**

Calculate the diagonal of the square by using the Pythagorean theorem.

Since the result is a distance, the negative root has no meaning. Use the positive root.

$$d_{BC}^2 = (5.0\ \text{cm})^2 + (5.0\ \text{cm})^2$$
$$d_{BC}^2 = 50.0\ \text{cm}^2$$
$$d_{BC} = \pm\sqrt{50.0\ \text{cm}^2}$$
$$d_{BC} = \pm 7.07\ \text{cm}$$
$$d_{BC} = 7.07\ \text{cm}$$

Calculate the magnitude of the electric field intensity of each of the given charges at point D, using the equation for the special case of the field intensity near a point charge.

$$|\vec{E}| = k\frac{q}{r^2}$$
$$|\vec{E}_{\text{A at D}}| = \left(9.0 \times 10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\left(\frac{6.0 \times 10^{-6}\ \text{C}}{(0.050\ \text{m})^2}\right)$$
$$|\vec{E}_{\text{A at D}}| = 2.16 \times 10^7\ \frac{\text{N}}{\text{C}}$$
$$|\vec{E}_{\text{B at D}}| = \left(9.0 \times 10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\left(\frac{5.0 \times 10^{-6}\ \text{C}}{(0.0707\ \text{m})^2}\right)$$
$$|\vec{E}_{\text{B at D}}| = 9.00 \times 10^6\ \frac{\text{N}}{\text{C}}$$
$$|\vec{E}_{\text{C at D}}| = \left(9.0 \times 10^9\ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}\right)\left(\frac{6.0 \times 10^{-6}\ \text{C}}{(0.050\ \text{m})^2}\right)$$
$$|\vec{E}_{\text{C at D}}| = 2.16 \times 10^7\ \frac{\text{N}}{\text{C}}$$

Use the method of components to find the resultant electric field vector.

The angle between the x-axis and the vector for the field at point D due to charge B is 45°, because it points along the diagonal of a square.

***x*-components**

$$E_{(\text{A at D})\text{x}} = 2.16 \times 10^7\ \frac{\text{N}}{\text{C}}$$
$$E_{(\text{B at D})\text{x}} = -\left(9.00 \times 10^6\ \frac{\text{N}}{\text{C}}\right)\cos 45^\circ$$
$$E_{(\text{B at D})\text{x}} = -6.36 \times 10^6\ \frac{\text{N}}{\text{C}}$$
$$E_{(\text{C at D})\text{x}} = 0$$
$$E_{(\text{net})\text{x}} = 1.524 \times 10^7\ \frac{\text{N}}{\text{C}}$$

***y*-components**

$$E_{(\text{A at D})\text{y}} = 0$$
$$E_{(\text{B at D})\text{y}} = -\left(9.00 \times 10^6\ \frac{\text{N}}{\text{C}}\right)\sin 45^\circ$$
$$E_{(\text{B at D})\text{y}} = -6.36 \times 10^6\ \frac{\text{N}}{\text{C}}$$
$$E_{(\text{C at D})\text{y}} = 2.16 \times 10^7\ \frac{\text{N}}{\text{C}}$$
$$E_{(\text{net})\text{y}} = 1.524 \times 10^7\ \frac{\text{N}}{\text{C}}$$

Use the Pythagorean theorem to find the magnitude of the resultant vector.

$$|\vec{E}_{(\text{net})}|^2 = \left(E_{(\text{net})\text{x}}\right)^2 + \left(E_{(\text{net})\text{y}}\right)^2$$
$$|\vec{E}_{(\text{net})}|^2 = \left(1.524 \times 10^7\ \frac{\text{N}}{\text{C}}\right)^2 + \left(1.524 \times 10^7\ \frac{\text{N}}{\text{C}}\right)^2$$
$$|\vec{E}_{(\text{net})}|^2 = 4.6452 \times 10^{14}\left(\frac{\text{N}}{\text{C}}\right)^2$$
$$|\vec{E}_{(\text{net})}| = 2.1553 \times 10^7\ \frac{\text{N}}{\text{C}}$$
$$|\vec{E}_{(\text{net})}| \cong 2.2 \times 10^7\ \frac{\text{N}}{\text{C}}$$

Use the definition of the tangent function to find the direction of the electric field vector at point D.

$$\tan\theta = \frac{1.524 \times 10^7\ \frac{\text{N}}{\text{C}}}{1.524 \times 10^7\ \frac{\text{N}}{\text{C}}}$$
$$\tan\theta = 1.00$$
$$\tan\theta = \tan^{-1} 1.00$$
$$\tan\theta = 45^\circ$$

The electric field intensity at point D is 2.2×10^7 N/C at an angle of 45˚ counterclockwise from the positive x-axis.

Validate

Since two positive charges and one negative charge of similar magnitudes are creating the field, you would expect that the net field would be similar in magnitude to those created by the individual charges. The angle is 45˚ as predicted.

PRACTICE PROBLEMS

20. Calculate the electric field intensity at a point 18.0 cm from the centre of a small conducting sphere that has a charge of $-2.8\ \mu$C.

21. The electric field intensity at a point 0.20 m away from a point charge is 2.8×10^6 N/C, directed toward the charge. What is the magnitude and sign of the charge?

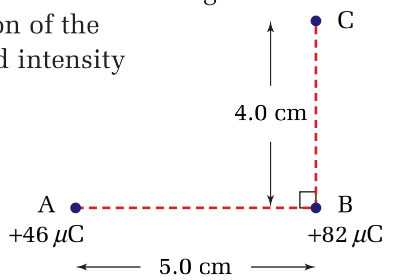
22. The electric field intensity at a point, P, near a spherical charge of 4.6×10^{-5} C, is 4.0×10^6 N/C. How far is point P from the centre of the charge?

23. How many electrons must be removed from a spherical conductor with a radius of 4.60 cm in order to make the electric field intensity just outside its surface 3.95×10^3 N/C?

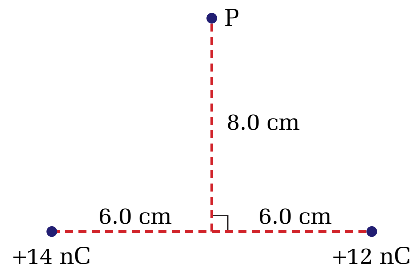
24. What is the electric field intensity at a point 15.2 cm from the centre of a sphere charged uniformly at $-3.8\ \mu$C?

25. A charge of $+7.4\ \mu$C establishes an electric field intensity at point M of 1.04×10^7 N/C. How far is point M from the centre of the charge?

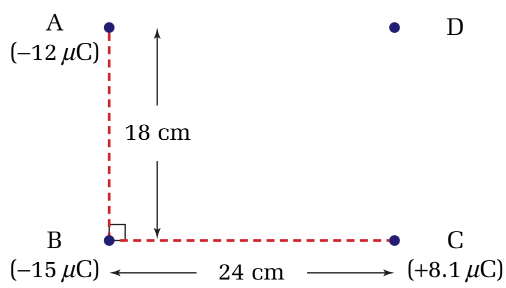
26. In the diagram, A and B represent small spherical charges of $+46\ \mu$C and $+82\ \mu$C, respectively. What is the magnitude and direction of the electric field intensity at point C ?



27. Determine the magnitude and direction of the electric field intensity at point P in the diagram.



28. The diagram shows three small charges at three corners of a rectangle. Calculate the magnitude and direction of the electric field intensity at the fourth corner, D.



29. Two point charges of $-40.0\ \mu$C and $+50.0\ \mu$C are placed 12.0 cm apart in air. What is the electric field intensity at a point midway between them?

30. Points A and B are 13.0 cm apart. A charge of $+8.0\ \mu$C is placed at A and another charge of $+5.0\ \mu$C is placed at B. Point P is located 5.0 cm from A and 12.0 cm from B. What is the magnitude and direction of the electric field intensity at P?

The approach taken above for electric fields can also be applied to gravitational fields. The following steps develop an expression for the gravitational field intensity near a point source. As stated previously, the field at any point outside of a spherical mass is the same as it would be if the mass was concentrated at a point at the centre of the sphere.

- Write the equation for the general definition of gravitational field intensity.

$$\vec{g} = \frac{\vec{F}_g}{m}$$

- Write the general equation for the gravitational force between two masses. Let m_1 be the source of a gravitational field and m_2 be any mass, m, in that field.

$$|\vec{F}_g| = G\frac{m_s m}{r^2}$$

- Substitute the expression for the force of gravity into the general expression for gravitational field intensity.

$$|\vec{g}| = \frac{G\frac{m_s \cancel{m}}{r^2}}{\cancel{m}}$$

$$|\vec{g}| = G\frac{m_s}{r^2}$$

GRAVITATIONAL FIELD INTENSITY NEAR A POINT MASS

The gravitational field intensity at a point a distance r from the centre of an object is the product of the universal gravitation constant and mass, divided by the square of the distance from the centre of the object. The direction of the gravitational field intensity is toward the centre of the object creating the field.

$$|\vec{g}| = G\frac{m_s}{r^2}$$

Quantity	Symbol	SI unit
gravitational field intensity	$\vec{g}$	$\frac{\mathrm{N}}{\mathrm{kg}}$ (newtons per kilogram)
universal gravitation constant	G	$\frac{\mathrm{N \cdot m^2}}{\mathrm{kg^2}}$ (newton · metres squared per kilogram squared)
mass of source of field	m_s	kg (kilograms)
distance from centre of source	r	m (metres)

Unit Analysis

$$\left(\frac{\text{newton} \cdot \text{metre}^2}{\text{kilogram}^2}\right)\left(\frac{\text{kilogram}}{\text{metre}^2}\right) = \left(\frac{\text{newton}}{\text{kilogram}}\right)$$

$$\frac{\mathrm{N} \cdot \cancel{\mathrm{m}^2}}{\mathrm{kg}^{\cancel{2}}} \cdot \frac{\cancel{\mathrm{kg}}}{\cancel{\mathrm{m}^2}} = \frac{\mathrm{N}}{\mathrm{kg}}$$

MODEL PROBLEM

Field Intensity near Earth

Calculate the gravitational field intensity at a height of 300.0 km from Earth's surface.

Frame the Problem

- Since the point in question is *outside* of the *sphere* of Earth, the gravitational field there is the same as it would be if Earth's mass was concentrated at *a point at Earth's centre*. Therefore, the equation for the *gravitational field intensity* near a *point mass* applies.

Identify the Goal

The gravitational field intensity, $\vec{g}$

Variables and Constants

Known	Implied	Unknown
$h = 300.0\ \text{km}$	$G = 6.67 \times 10^{-11}\ \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$	$\vec{g}$
	$r_\text{E} = 6.38 \times 10^6\ \text{m}$	
	$m_\text{E} = 5.98 \times 10^{24}\ \text{kg}$	

Strategy

Convert the height above Earth's surface into SI units and calculate the distance, r, from the centre of Earth.

Use the equation for the gravitational field intensity near a point source.

Substitute numerical values and solve.

Calculations

$h = 300.0\ \text{km} = 3.000 \times 10^5\ \text{m}$

$r = 3.000 \times 10^5\ \text{m} + 6.38 \times 10^6\ \text{m}$

$r = 6.68 \times 10^6\ \text{m}$

$$|\vec{g}| = G\frac{m_\text{s}}{r^2}$$

$$|\vec{g}| = \frac{\left(6.67 \times 10^{-11}\ \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}\right)(5.98 \times 10^{24}\ \text{kg})}{(6.68 \times 10^6\ \text{m})^2}$$

$$|\vec{g}| = 8.9387\ \frac{\text{N}}{\text{kg}}$$

$$|\vec{g}| \cong 8.94\ \frac{\text{N}}{\text{kg}}$$

The gravitational field intensity 300.0 km from the surface of Earth is 8.94 N/kg.

Validate

You would expect the gravitational field intensity to be less than 9.81 N/kg at a great distance from Earth's surface.

continued ▶

continued from previous page

PRACTICE PROBLEMS

31. What is the gravitational field intensity at a distance of 8.4×10^7 m from the centre of Earth?

32. If the gravitational field intensity at the surface of Saturn is 26.0 N/kg and its mass is 5.67×10^{26} kg, what is its radius?

33. What is the acceleration due to gravity on the surface of Venus? ($m_{\text{Venus}} = 4.83 \times 10^{24}$ kg; $r_{\text{Venus}} = 6.31 \times 10^6$ m)

34. An astronaut drops a 3.60 kg object onto the surface of a planet. It takes 2.60 s to fall 1.86 m to the ground. If the planet is known to have a radius of 8.40×10^6 m, what is its mass?

35. What is the gravitational field intensity at a distance of 2.0 m from the centre of a spherical metal ball of mass 3.0 kg? (Calculate only the field due to the ball, not to Earth.)

36. Calculate the gravitational field intensity at a height of 560.0 m above the surface of the planet Venus. (See problem 33 for data.)

37. The planet Neptune has a gravitational field intensity of 10.3 N/kg at a height of 1.00×10^6 m above its surface. If the radius of Neptune is 2.48×10^7 m, what is its mass?

Field Lines

Electric Field Lines

You have learned that an electric field at a particular point can be represented by a vector arrow with a length that corresponds to the magnitude of the field intensity at a given point. The direction of the vector arrow indicates the direction of the electric field at that point.

If you wanted to visualize the entire field around an electric charge, however, you would need to draw a set of these vector arrows at many points in the space around the charge. This process would be very tedious and complicated, so an idea originally used by Michael Faraday has been adapted. Using this method, the vectors are replaced by a series of lines that follow the path that a tiny point charge would take if it was free to move in the electric field. These lines are called **electric field lines**. In the vicinity of a positive charge, such field lines would radiate straight out, just as a positive test charge would be pushed straight out.

The field lines are constructed so that, at every point on the line, the direction of the field is tangent to the line. The strength of the field is represented by the density of the lines. The farther apart these lines are, the weaker the field is. Figure 14.9 shows the electric field lines that represent the electric field in various charge arrangements.

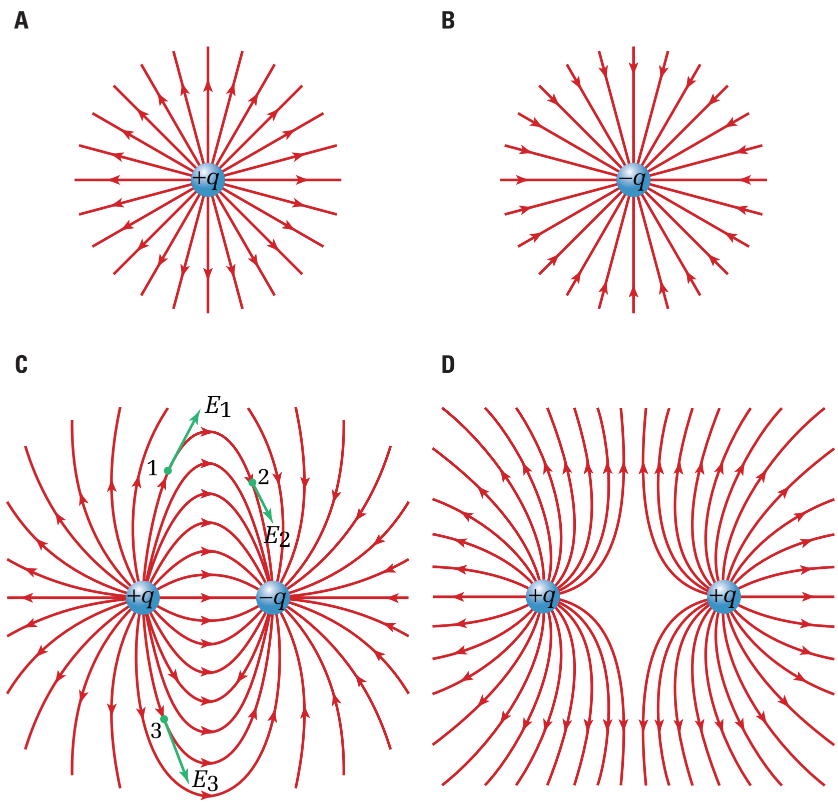


Figure 14.9 **(A)** The electric field lines from positive charge $+q$ are directed radially outward. **(B)** The electric field lines are directed radially inward toward negative point charge $-q$. **(C)** The electric field lines of an electric dipole are curved, and extend from the positive to the negative charge. At any point, such as 1, 2, or 3, the field created by the dipole is tangent to the line through the point. **(D)** The electric field lines for two identical positive point charges are shown. If both of the charges were negative, the directions of the lines would be reversed.

Note that when more than one electric source charge is present, the electric field vector at a point is the vector sum of the electric field attributable to each source charge separately. Since the field lines are often curved, this vector will be tangent to the field line at that point.

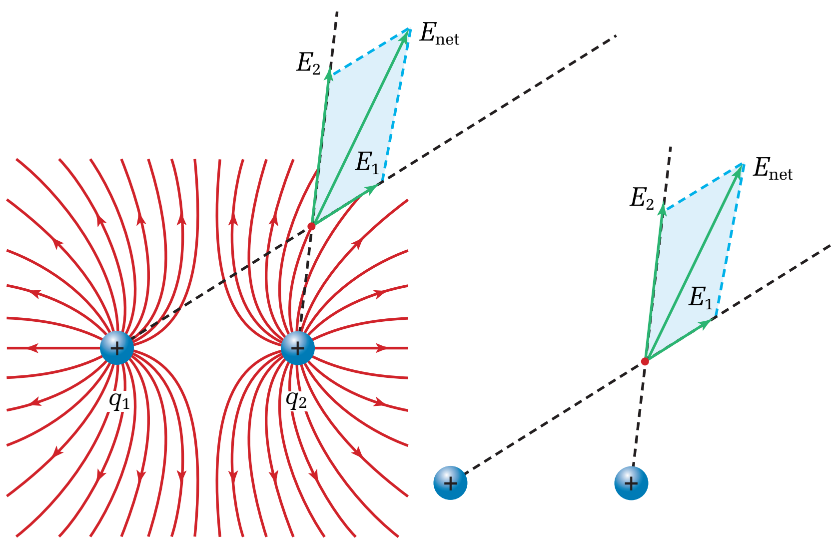


Figure 14.10 The electric field at a point near two positive charges

Gravitational Field Lines

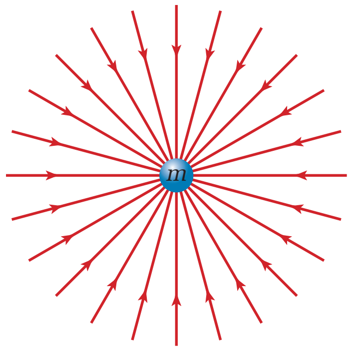


Figure 14.11 The gravitational field lines are directed radially inward toward a mass, *m*.

Since the force of gravity is always attractive, the shape of **gravitational field lines** will resemble the electric field lines associated with a negative charge. Gravitational field lines will always point toward the centre of a spherical mass and arrive perpendicular to the surface.

Conceptual Problems

- Can there be a gravitational field diagram similar to the electric field in Figure 14.9 (D)? Explain.
- Sketch the gravitational field lines due to the two identical masses shown in the diagram here.

Magnetic Field Lines

Since no isolated magnetic poles are known to exist (magnetic monopoles), the **magnetic field lines** have to be drawn so that they are associated with both poles of the magnet (magnetic dipole). The direction of the magnetic field at a particular location is defined as the direction in which the N-pole of a compass would point when placed at that location. The magnetic field lines leave the N-pole of a magnet, enter the S-pole, and continue to form a closed loop inside the magnet. The number of magnetic field lines, called the "magnetic flux," passing through a particular unit area is directly proportional to the magnetic field intensity. Consequently, flux lines outside of the magnet are more concentrated at the poles of a magnet, where the magnetic field is greatest.

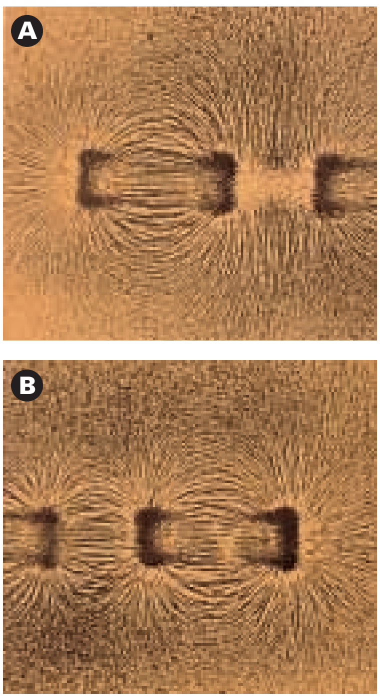


Figure 14.13 The field lines for **(A)** like poles and **(B)** unlike poles

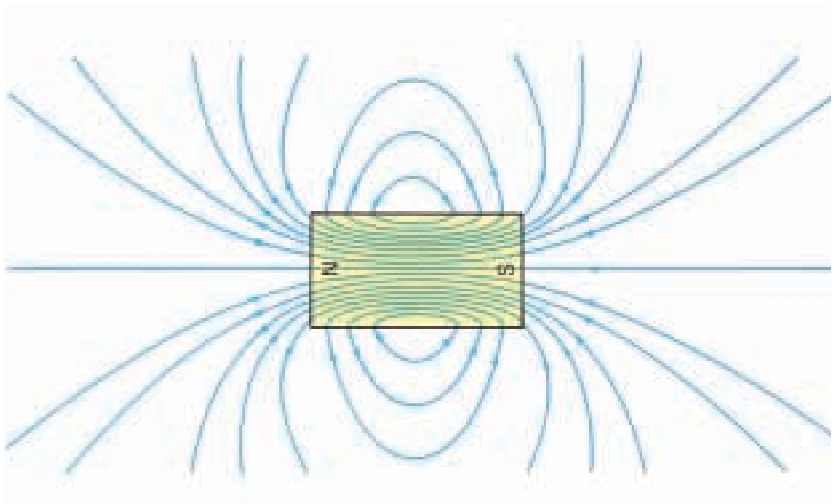


Figure 14.12 The magnetic field lines are closed loops leaving the N-pole of the magnet and entering the S-pole.

Conceptual Problems

- How does the magnetic dipole pattern compare with the electric field pattern of two opposite charges (an electric dipole)?
- What electrostatic evidence suggests that a water molecule is an electric dipole?
- What happens if you place a small bar magnet in a uniform magnetic field?
- What happens if you place a water molecule in a uniform electric field?

14.2 Section Review

1. I Place a strong bar magnet flat on a semi-rough surface, with the N-pole to the right. Place another bar magnet to the right of the first, but with its like N-pole to the left, so that it is suspended directly over the other N-pole. Adjust the top magnet until it balances. Now slide a piece of paper over the first magnet to hide it. Gently tap the suspended N-pole to start it vibrating vertically in space. What do your observations suggest about magnetic fields?
2. K/U What is the general definition for the electric field intensity at a distance r from a point charge q?
3. I Why is it not considered useful to define magnetic field intensity in the same way in which you defined the electric field intensity in question 2?
4. C Explain how you might calculate the gravitational field intensity at the various points along the path of a communication satellite orbiting Earth.
5. K/U In the vicinity of several point charges, how is the direction of the electric field intensity vector calculated?
6. C List four characteristics of electric field lines.