TOPIC 2.3: ELECTRIC AND MAGNETIC FIELDS

S4P-2-13 Compare and contrast the inverse square nature of gravitational and electric fields.

S4P-2-14 State Coulomb's Law and solve problems for more than one electric force acting on a charge.

Include: one and two dimensions

S4P-2-15 Illustrate, using diagrams, how the charge distribution on two oppositely charged parallel plates results in a uniform field.

S4P-2-16 Derive an equation for the electric potential energy between two oppositely charged parallel plates ($E_e = qE\Delta d$).

S4P-2-17 Describe electric potential as the electric potential energy per unit charge.

S4P-2-18 Identify the unit of electric potential as the volt.

S4P-2-19 Define electric potential difference (voltage) and express the electric field between two oppositely charged parallel plates in terms of voltage and the separation between the plates $\left(\varepsilon = \frac{\Delta V}{d}\right)$.

S4P-2-20 Solve problems for charges moving between or through parallel plates.

S4P-2-21 Use hand rules to describe the directional relationships between electric and magnetic fields and moving charges.

S4P-2-22 Describe qualitatively various technologies that use electric and magnetic fields.

Examples: electromagnetic devices (such as a solenoid, motor, bell, or relay), cathode ray tube, mass spectrometer, antenna

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Describe and appreciate the similarity and diversity of forms, functions, and patterns within the natural and constructed world (GLO E1)

SPECIFIC LEARNING OUTCOME

S4P-2-13: Compare and contrast the inverse square nature of gravitational and electric fields.

SUGGESTIONS FOR INSTRUCTION

Entry Level Knowledge

The definition of gravitational fields around a point mass

$$\left(g = \frac{F_g}{m}\right)$$

and the diagram of the Earth's gravitational field have been introduced in Senior 3 Physics.

Also introduced were the corresponding definition of the electric field

$$\left(E = \frac{F_e}{q}\right)$$

and diagrams of electric fields around positive and negative charges.

The inverse square nature of the gravitational field for a mass

$$\left(g = \frac{Gm}{r^2}\right)$$

was examined in Topic 2.2.

Notes to the Teacher

When examining the gravitational field of a mass, it is useful to view the mass as a point mass, irrespective of its size. Similar treatment is given to electric charges. The electric and gravitational field diagrams are similar. Both fields exhibit an inverse square relationship with respect to the field strength versus the distance from the centre of the object. However, unlike gravitational fields, which are always attractive, electric fields can be repulsive as well. The formula for the electric field around a point charge

$$\left(E = \frac{kq}{r^2}\right)$$

can be expressed by analogy with gravitational fields. In this learning outcome, it is sufficient to compare and contrast the fields.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-2c: Formulate operational definitions of major variables or concepts.

S4P-0-2g: Develop mathematical models involving linear, power, and/or inverse relationships among variables.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Describe and appreciate the similarity and diversity of forms, functions, and patterns within the natural and constructed world (GLO E1)

SUGGESTIONS FOR INSTRUCTION

Teaching Notes

SUGGESTIONS FOR ASSESSMENT

Students use compare and contrast frames (SYSTH) for gravitational and electric fields.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the composition of the universe, the interactions within it, and the impacts of humankind's continued attempts to understand and explore it (GLO D6)

SPECIFIC LEARNING OUTCOME

S4P-2-14: State Coulomb's Law and solve problems for more than one electric force acting on a charge.

Include: one and two dimensions

SUGGESTIONS FOR INSTRUCTION

Entry Level Knowledge

The inverse square nature of the electric field of a point charge was introduced in the previous learning outcome, and the relationship between force on a charge in an electric field,

$$\left(E = \frac{F}{q}\right),$$

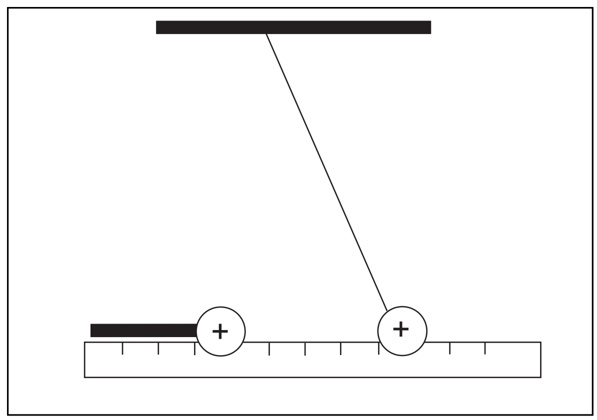
was introduced in Senior 3 Physics.

Notes to the Teacher

Coulomb believed that the force between electric charges would follow an inverse square relationship paralleling Newton's Law of Universal Gravitation, and he verified it experimentally. That is, it follows from the Law of Universal Gravitation that $F_e \alpha\, q_1 q_2$ and $F_e \alpha \frac{1}{R^2}$.

Laboratory Activity

Students use Coulomb's Law apparatus (a pith sphere that is repelled by a nearby, identical pith sphere) to demonstrate that $F_e \alpha \frac{1}{R^2}$.



Coulomb's Experiment

Mathematical Connection

Another approach is to reason that one can imagine a concentric sphere enclosing the charge at a specified radius. Noting that the number of field lines is constant and equally spread out over the sphere, it follows that the field lines will spread out as one enlarges the sphere to a new radius. Given that the surface area of a sphere is

$$\text{Surface Area} = 4\pi r^2,$$

it can be reasoned that the field strength will fall off as an inverse square relationship. Incorporating this reasoning and combining it with $\left(E = \frac{F}{q}\right)$, one can obtain $F = \frac{kq_1q_2}{r^2}$.

SKILLS AND ATTITUDES OUTCOME

S4P-0-2h: Analyze problems using vectors.

Include: Adding and subtracting vectors in straight lines, at right angles, and at non-orthogonal angles

GENERAL LEARNING OUTCOME CONNECTION

Students will…

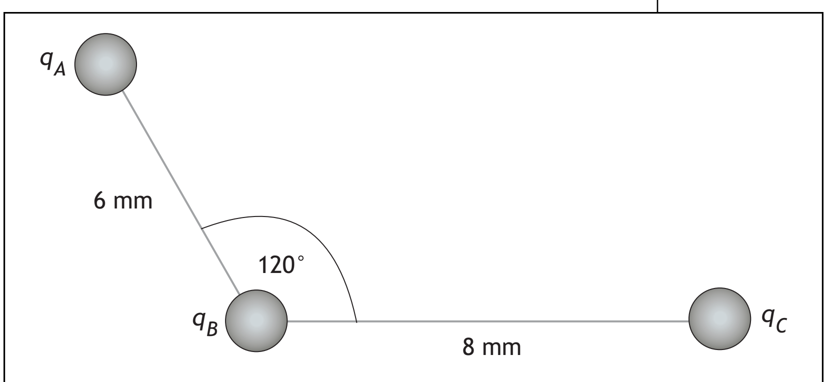
Recognize that characteristics of materials and systems can remain constant or change over time, and describe the conditions and processes involved (GLO E3)

SUGGESTIONS FOR INSTRUCTION

Class Activity

When solving problems using Coulomb's Law, vector solutions should include force vectors acting at any angle in a plane.

Illustrative example: Place charges as illustrated below with q_A = –4.0 nC, q_B = –10 nC, and q_C = 6.0 nC. Find the net force exerted on charge B.



First, we need to recognize that the force qA exerts on q_C does not affect the force exerted on q_B. Likewise, we don't need to consider the force q_C exerts on q_A. Next, the students must make a diagram to illustrate the direction of the forces on charge B. The force between q_A and q_B is repulsive (see $\vec{F}_{AB}$) and the force between q_C and q_B is attractive (see $\vec{F}_{CB}$). $\vec{F}_{AB}$ should be resolved into components as shown.

SUGGESTIONS FOR ASSESSMENT

Pencil-and-Paper Tasks

Students solve problems using various configurations of charge.

General Learning Outcome Connection

Students will…

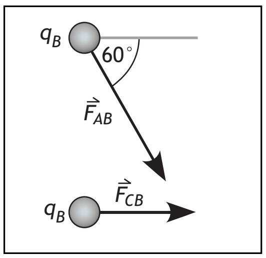
Understand the composition of the universe, the interactions within it, and the impacts of humankind's continued attempts to understand and explore it (GLO D6)

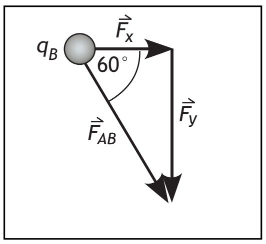
Specific Learning Outcome

S4P-2-14: State Coulomb's Law and solve problems for more than one electric force acting on a charge.

Include: one and two dimensions

Suggestions for Instruction





Now, find the forces.

$$F_{AB} = \frac{\left(9.0\times10^{9}\ \frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)\left(4.0\times10^{-9}\ \mathrm{C}\right)\left(10\times10^{-9}\ \mathrm{C}\right)}{\left(6.0\times10^{-3}\ \mathrm{m}\right)^2}$$

$$F_{AB} = 1.00\times10^{-2}\ N 60^\circ \text{ below the horizontal}$$

The two components for F_{AB} are:

x-comp: $+(1.00 \times 10^{-2}$ N) cos 60 = $+5.0 \times 10^{-3}$ N

y-comp: $+(1.00 \times 10^{-2}$ N) sin 60 = -8.7×10^{-3} N

$$F_{CB} = \frac{\left(9.0\times10^{9}\ \frac{\mathrm{N\cdot m^2}}{\mathrm{C^2}}\right)\left(6.0\times10^{-9}\ \mathrm{C}\right)\left(10\times10^{-9}\ \mathrm{C}\right)}{\left(8.0\times10^{-3}\ \mathrm{m}\right)^2}$$

$$= 8.4\times10^{-3}\ \mathrm{N}$$

F_{CB} = only has an x:comp: $+8.4 \times 10^{-3}$ N

The vector sum of these three components is 1.6×10^{-2} N 33° below the horizontal.

SKILLS AND ATTITUDES OUTCOME

S4P-0-2h: Analyze problems using vectors.

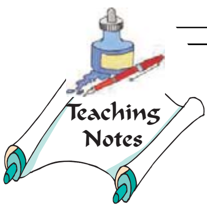
Include: Adding and subtracting vectors in straight lines, at right angles, and at non-orthogonal angles

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Recognize that characteristics of materials and systems can remain constant or change over time, and describe the conditions and processes involved (GLO E3)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

General Learning Outcome Connection

Students will…

Employ effective communication skills and utilize information technology to gather and share scientific and technological ideas and data (GLO C6)

Specific Learning Outcome

S4P-2-15: Illustrate, using diagrams, how the charge distribution on two oppositely charged parallel plates results in a uniform field.

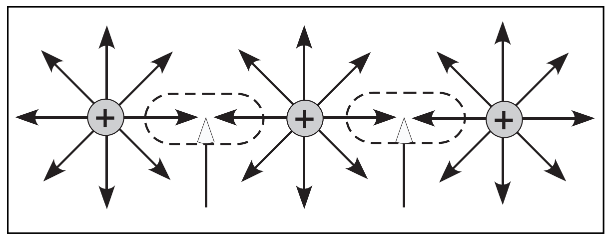
Suggestions for Instruction

Entry Level Knowledge

Students have seen the field between oppositely charged plates in Senior 3 Physics. In this learning outcome, students quantitatively determine why the field is uniform. The vector nature of the electric force was covered in the previous learning outcome.

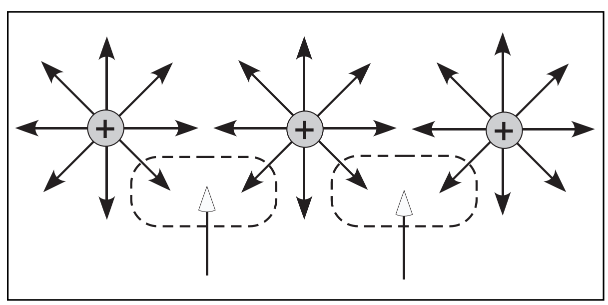
Notes to the Teacher

For a parallel plate, picture a plane of positive charges on the top plate. Each charge creates an equal electric field around itself. For an even distribution of charges on a 2-D plate, there would always be an equal magnitude and opposite direction field from neighbouring charges that would cancel. In regions below and above the plane, any components of the fields parallel to the plane will cancel. Any components of the field perpendicular to the plane will increase the electric field perpendicular to the plane. For a positively charged plate, the field will point away from the plates. For a negatively charged plate, the field will point toward the plate. By placing a negative plate in parallel with a positive plate, the field between the plates will be strengthened and the fields outside the plates will experience some amount of cancellation. Note that we are disregarding the fringing effects that occur at the edges of the pair of parallel plates.



Horizontal Fields Cancel

Using Coulomb's Law and vector addition, it can be shown quantitatively that the resultant force is a constant. A productive approach is to have students complete examples as part of the previous outcome. In this way, the uniform field will be obvious.



Horizontal Fields Cancel / Vertical Components Add

SKILLS AND ATTITUDES OUTCOME

S4P-0-2f: Record, organize, and display data using an appropriate format.

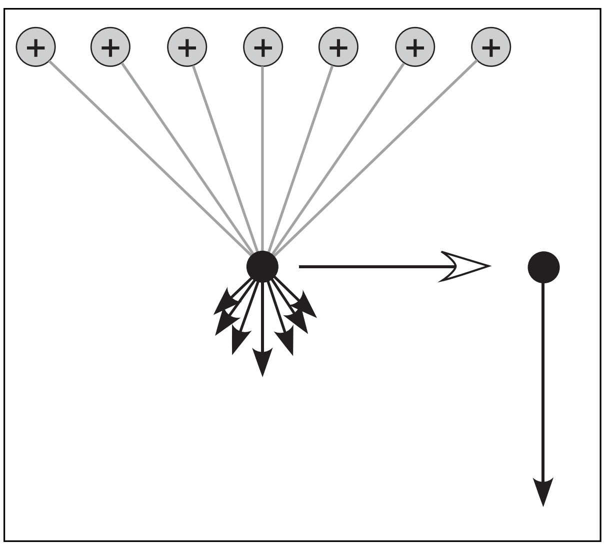
Include: labelled diagrams, tables, graphs

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Employ effective communication skills and utilize information technology to gather and share scientific and technological ideas and data (GLO C6)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

Visual Displays

Students sketch and correct field diagrams through a peer-review and commentary format.

General Learning Outcome Connection

Students will…

Recognize that scientific knowledge is based on evidence, models, and explanations, and evolves as new evidence appears and new conceptualizations develop (GLO A2)

Specific Learning Outcomes

S4P-2-16: Derive an equation for the electric potential energy between two oppositely charged parallel plates ($E_e = qE\Delta d$).

S4P-2-17: Describe electric potential as the electric potential energy per unit charge.

S4P-2-18: Identify the unit of electric potential as the volt.

S4P-2-19: Define electric potential difference (voltage) and express the electric field between two oppositely charged parallel plates in terms of voltage and the separation between the plates $\left(\varepsilon = \frac{\Delta V}{d}\right)$.

Suggestions for Instruction

Entry Level Knowledge

Students know that work done on an object is equal to the change in potential energy.

Notes to the Teacher

The field between parallel plates is examined quantitatively to introduce the idea of electric potential difference (voltage) to students. The voltage concept is later used in the analysis of circuits in Topic 3.

Class Discussion

If we placed a positive charge between two oppositely charged parallel plates, it would rest comfortably at the negative plate. In order to move the charge to the positive plate, we must do work (apply a force through a distance). The work done moving the charge closer to the positive plate is given by $W = \vec{F}\Delta\vec{d}$. Since the force on an electric charge is $\vec{F} = q\vec{\varepsilon}$, we get $W = (q\vec{\varepsilon})\Delta d$ where $\vec{\varepsilon}$ is the electric field vector. The work done on an object always equals the change in energy of the object (W = ΔE). In this case, the work done on the charge is equal to the electric potential energy gained by the charge. This is analogous to raising a mass in a gravitational field. Using E_e to represent electric potential energy, if we move the charge from a point where the initial energy is zero, the electric potential energy between the plates is $E_e = q\vec{\varepsilon}\Delta\vec{d}$. Note that E_e is a scalar quantity. If an outside force moves the charge against the electric force, then work will be positive and potential energy will increase. If electric force moves the charge, work will be negative and electric potential energy will decrease.

The concept of electric potential makes work and energy calculations in electric fields easier. Electric potential (V) is the electrical potential energy per unit charge

$$\left(V = \frac{E_e}{q}\right).$$

Electric potential is a unit concept, similar to the gravitational and the electric field constants. Electric potentials are similar to elevations in gravitational fields; it is really only the change in elevation (and not the measurement from the point of zero potential) that interests us. Consequently, we usually use the electric potential difference (voltage) in our calculations.

The language of energy is very tricky and can be summarized as follows:

- Electric potential energy (E_e)—the energy between two charges
- Electric potential (V)—the electric potential energy per unit charge
- Electric potential difference (ΔV)—the difference in electric potential between two points (as in an electric circuit)

Skills and Attitudes Outcomes

S4P-0-2c: Formulate operational definitions of major variables or concepts.

S4P-0-2d: Estimate and measure accurately using SI units.

S4P-0-2g: Develop mathematical models involving linear, power, and/or inverse relationships among variables.

General Learning Outcome Connection

Students will…

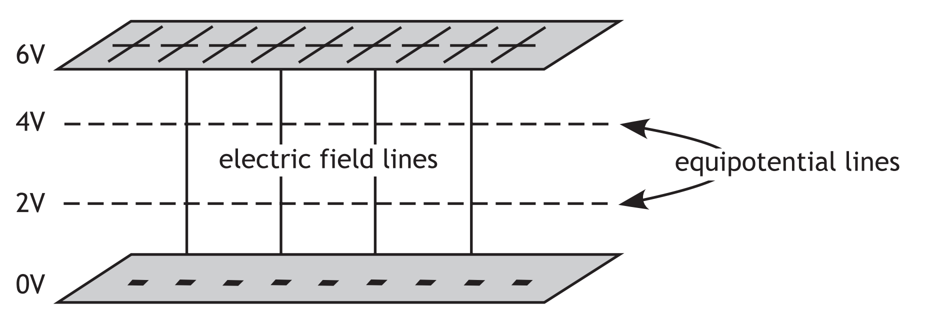
Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

Suggestions for Instruction

Physicists are sometimes imprecise with this language, commonly using only the term *potential*. Textbooks also often omit the Greek Δ sign (delta = "change in"), creating even more confusion.

Since electric potential is defined as the electric potential energy per unit charge, the units would measured in joules/coulomb. One joule per coulomb is defined as the **volt**.

The diagram illustrates the electric potential at various points between parallel plates in a manner similar to gravitational potential fields.



Suggestions for Assessment

Observation

Carefully monitor the correct usage of the energy terms.

Pencil-and-Paper Tasks

Students solve various problems to calculate the energy between parallel plates.

Students compare and contrast electric and gravitational potential energy.

Students solve various problems to calculate field between parallel plates.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Recognize that scientific knowledge is based on evidence, models, and explanations, and evolves as new evidence appears and new conceptualizations develop (GLO A2)

SPECIFIC LEARNING OUTCOMES

S4P-2-16: Derive an equation for the electric potential energy between two oppositely charged parallel plates ($E_e = qE\Delta d$).

S4P-2-17: Describe electric potential as the electric potential energy per unit charge.

S4P-2-18: Identify the unit of electric potential as the volt.

S4P-2-19: Define electric potential difference (voltage) and express the electric field between two oppositely charged parallel plates in terms of voltage and the separation between the plates $\left(\varepsilon = \frac{\Delta V}{d}\right)$.

SUGGESTIONS FOR INSTRUCTION

To derive the expression for the field between parallel plates, we combine $E_e = q\vec{\varepsilon}\Delta\vec{d}$ and $V = \frac{E_e}{q}$.

$$E_e = q\vec{\varepsilon}\Delta\vec{d}$$

$$\frac{E_e}{q} = \vec{\varepsilon}\Delta\vec{d}$$

$$V = \vec{\varepsilon}\Delta\vec{d}$$

$$\vec{\varepsilon} = \frac{V}{\Delta\vec{d}}$$

Student Activity

Students complete Three-Point Analysis frames (SYSTH) for the concepts of electric potential energy, electric potential, electric potential difference, and voltage.

Skills and Attitudes Outcomes

S4P-0-2c: Formulate operational definitions of major variables or concepts.

S4P-0-2d: Estimate and measure accurately using SI units.

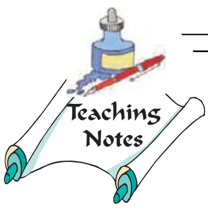
S4P-0-2g: Develop mathematical models involving linear, power, and/or inverse relationships among variables.

General Learning Outcome Connection

Students will…

Understand the properties and structures of matter as well as various common manifestations and applications of the actions and interactions of matter (GLO D3)

Suggestions for Instruction



Suggestions for Assessment

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Recognize that scientific and technological endeavours have been and continue to be influenced by human needs and the societal context of the time (GLO B2)

SPECIFIC LEARNING OUTCOME

S4P-2-20: Solve problems for charges moving between or through parallel plates.

SUGGESTIONS FOR INSTRUCTION

Entry Level Knowledge

Students know that $\Delta V = q\varepsilon\Delta d$ for a charge between parallel plates. Also, the force on a charge in an electric field is $\vec{F} = q\vec{\varepsilon}$. The Millikan experiment was also described in Senior 3 Physics.

Notes to the Teacher

Parallel plates have a uniform electric field between them and a charged particle in that field will experience a constant force, resulting in a constant acceleration. These conditions allow us to apply the kinematics equations from Topic 1 to analyze the motion.

A charged particle projected horizontally into the field between parallel plates will behave like a projectile in a gravitational field. Consequently, the particle is deflected up or down. Instead of g, we use the electric field constant for the plates to make our calculations.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-2e: Evaluate the relevance, reliability, and adequacy of data and data-collection methods.
Include: discrepancies in data and sources of error

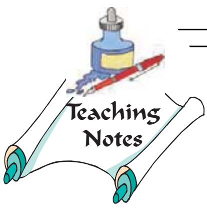
S4P-0-2g: Develop mathematical models involving linear, power, and/or inverse relationships among variables.

GENERAL LEARNING OUTCOME CONNECTION

Students will…

Understand the composition of the universe, the interactions within it, and the impacts of humankind's continued attempts to understand and explore it (GLO D6)

SUGGESTIONS FOR INSTRUCTION



SUGGESTIONS FOR ASSESSMENT

Pencil-and-Paper Tasks

Students solve problems for the motion of a charged particle in a constant field.

General Learning Outcome Connection

Students will…

Describe scientific and technological developments, past and present, and appreciate their impact on individuals, societies, and the environment, both locally and globally (GLO B1)

Specific Learning Outcomes

S4P-2-21: Use hand rules to describe the directional relationships between electric and magnetic fields and moving charges.

Examples: electromagnetic devices (such as solenoid, motor, bell, or relay), cathode ray tube, mass spectrometer, antenna

S4P-2-22: Describe qualitatively various technologies that use electric and magnetic fields.

Skills and Attitudes Outcomes

S4P-0-2a: Select and use appropriate visual, numeric, graphical, and symbolic modes of representation to identify and represent relationships.

Suggestions for Instruction

Entry Level Knowledge

At this time, students have studied electrostatics, electric fields, and magnetic fields. Specifically, understanding the magnetic field around a current carrying wire and the magnetic field of a solenoid were outcomes in Senior 3 Physics.

Notes to the Teacher

The right-hand rules are also related to learning outcomes in Topic 3. The right-hand rules are summarized here, but you may introduce the rules as they are needed.

Class Discussion

Static electric charges exert forces of repulsion and attraction on each other. In the early 1800s, Hans Christian Öersted observed the deflection of a compass needle when an electric current flowed in a nearby wire to establish a connection between electricity and magnetism. Magnetic fields act on moving charges. However, there is a significant difference: the magnetic force (F_B) is perpendicular to the direction of the motion of the charge. Consequently, no work is done on the charge and there is no change in the magnitude of velocity—only a change in direction occurs. If the force and velocity are constant and at right angles to each other, the particle will go in a circle of radius R, and the magnetic force F_B will act as a centripetal force F_C. To determine the direction of the force, field, or motion, physicists use a set of right-hand rules (in some texts these are described as left-hand rules). The right-hand rules use a conventional current flow (positive to negative) and the left-hand rules use the electron flow (negative to positive).

Right-Hand Rules

To determine the direction of the magnetic field around a current-carrying wire:

Point the thumb of the right hand in the direction of the current (positive to negative) and the fingers will curl in the direction of the magnetic field around the wire.

To determine the direction of the magnetic field of a solenoid:

Curl the fingers in the direction of the current (positive to negative) and the thumb points in the direction of the magnetic field (inside a solenoid the field points S to N).

To determine the direction of magnetic force on a moving charge:

The thumb points in the direction of the positive velocity of the charge, the fingers point in the direction of the field, and the force points in the direction the palm would push. **Note:** The positive velocity of a positive charge moving to the right is right, the positive velocity of a negative charge moving right is left.

SKILLS AND ATTITUDES OUTCOMES

S4P-0-2f: Record, organize, and display data using an appropriate format.

Include: labelled diagrams, tables, graphs

S4P-0-3b: Describe examples of how technology has evolved in response to scientific advances, and how scientific knowledge has evolved as the result of new innovations in technology.

S4P-0-3c: Identify social issues related to science and technology, taking into account human and environmental needs and ethical considerations.

S4P-0-4e: Demonstrate a continuing and more informed interest in science and science-related issues.

GENERAL LEARNING OUTCOMES CONNECTION

Students will…

Recognize that scientific and technological endeavours have been and continue to be influenced by human needs and the societal context of the time (GLO B2)

Demonstrate appropriate scientific inquiry skills when seeking answers to questions (GLO C2)

SUGGESTIONS FOR INSTRUCTION

Student Research/Report

Students research and report or display the applications of electric and magnetic fields. In their report, students should provide an explanatory model of how the device works.

Several technologies use electric and magnetic fields to manipulate charges. Many of these technologies, such as the cathode ray tube, are very common and should be of interest to students.

Math Connection

Students research the historical development of the particle model of electricity and derive the charge to mass (*e/m*) ratio of Thomson's experiment.

SUGGESTIONS FOR ASSESSMENT

Visual/Multimedia Display

Students prepare a visual (poster) or multimedia (PowerPoint or web page) display describing a technology that uses electric and/or magnetic fields.

Notes