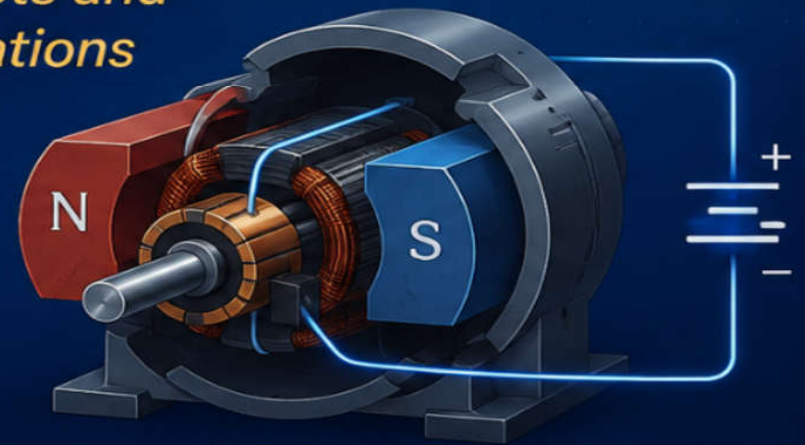
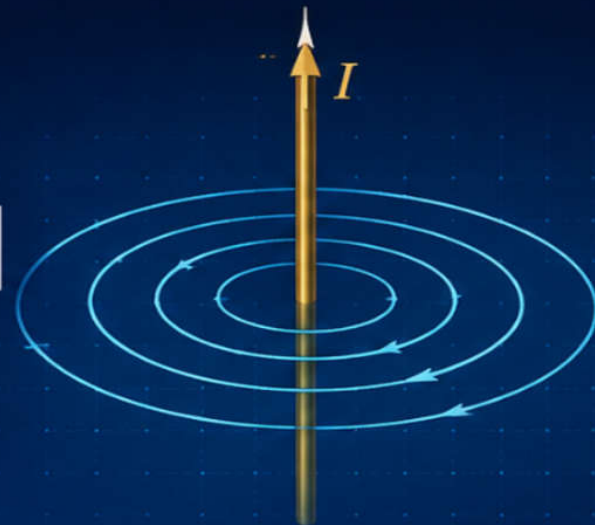
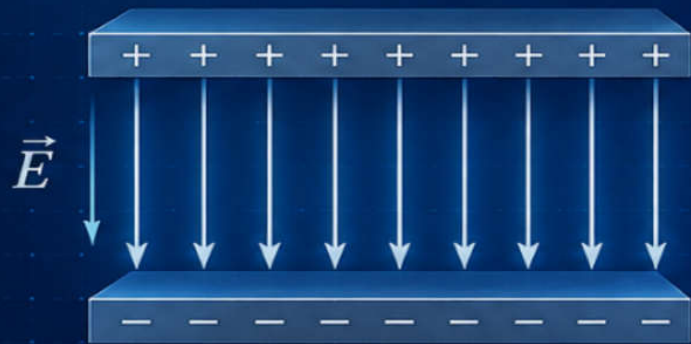
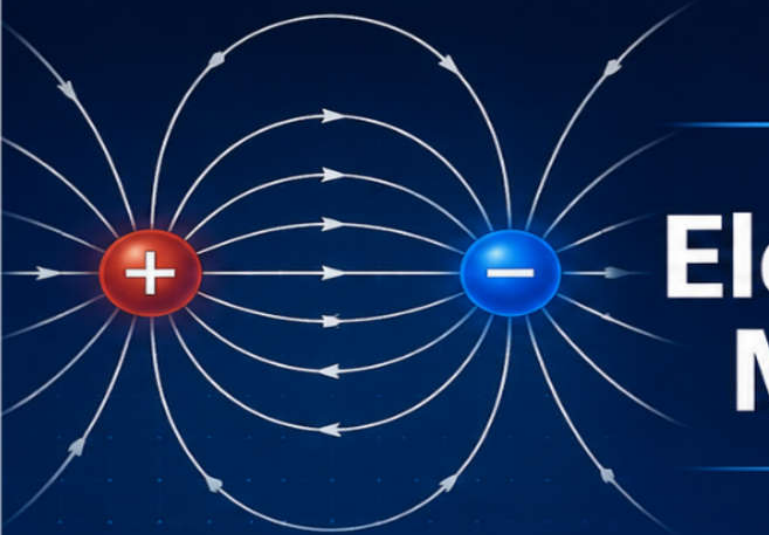


Lecture 8

Electric Fields and Magnetic Fields

Fundamental Concepts and Engineering Applications



Physics for Engineering Students

Department of Optics and Quantum Electronics

University of Szeged

Based on

*A Handbook of Mathematical Methods
and Problem-Solving Tools for
Introductory Physics (2nd Edition)*

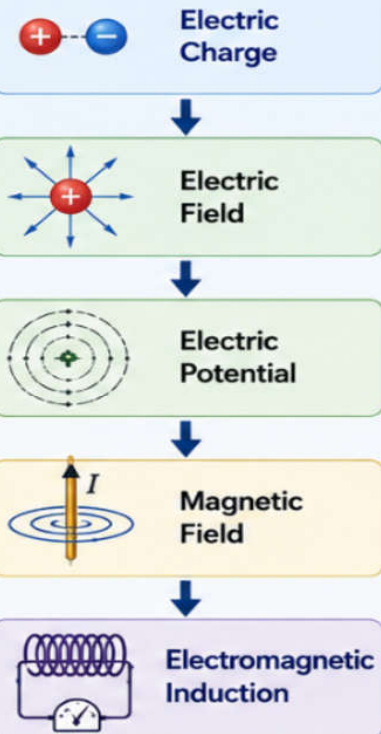
Joshua F. Whitney & Heather M. Whitney

Chapters 8–9

Learning Objectives

By the end of this lecture, you will be able to:

Concepts We Will Cover



- 1 Explain electric charge and Coulomb's law**
 - Identify positive and negative electric charges.
 - Describe electrostatic forces between charged objects.
 - Apply Coulomb's law to simple charge configurations.
- 2 Describe electric fields and electric potential**
 - Define the electric field as force per unit charge.
 - Interpret electric field lines.
 - Explain the relationship between electric field and electric potential.
- 3 Understand magnetic fields**
 - Explain how moving charges produce magnetic fields.
 - Apply the right-hand rule.
 - Distinguish between electric and magnetic forces.
- 4 Explain electromagnetic induction**
 - Describe Faraday's law.
 - Explain Lenz's law.
 - Recognize how electrical energy is generated.
- 5 Recognize engineering applications**
 - Connect fundamental principles to real-world engineering systems and technologies.

Engineering Applications



Electric Motors



Electric Generators



Transformers



Electric Vehicles



Wireless Charging



Sensors



Medical Imaging (MRI)



Industrial Robotics



Power Systems



These technologies rely on electric and magnetic fields to convert energy, transmit information, and control motion.



Today's goal is not only to learn the equations but also to understand the physics behind modern electrical engineering.



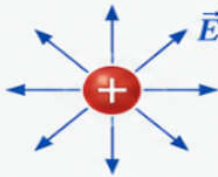
Electromagnetism: A Unifying Framework

Electricity and magnetism are two sides of the same physical reality.

Two Fundamental Phenomena

Electricity

Electric charges produce electric fields and electric forces.



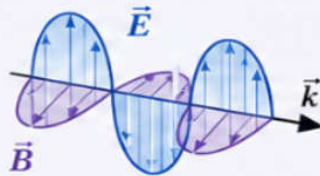
Magnetism

Moving charges and currents produce magnetic fields and magnetic forces.



Electromagnetic Interaction

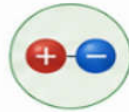
Electric fields and magnetic fields are inseparably linked and influence each other.



Key Idea:

A changing electric field creates a magnetic field, and a changing magnetic field creates an electric field.

Unifying Principles



1. Charges are the Source

Electric charges are the source of electric fields.



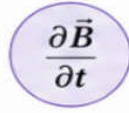
2. Currents Create Magnetism

Moving charges (currents) create magnetic fields.



3. Dynamic Connection

A changing electric field induces a magnetic field.



4. Dynamic Connection

A changing magnetic field induces an electric field.



These principles explain a wide range of natural phenomena and enable modern technologies.

The Complete Description: Maxwell's Equations

Gauss's Law (Electricity)

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

Electric charges are the source of $\vec{E}$.

Gauss's Law (Magnetism)

$$\nabla \cdot \vec{B} = 0$$

No magnetic monopoles exist.

Faraday's Law

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Changing $\vec{B}$ induces $\vec{E}$.

Ampère–Maxwell Law

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Currents and changing $\vec{E}$ produce $\vec{B}$.

What This Means for Engineers



Electromagnetism is the foundation of electrical, electronic, and communication systems.



It enables the generation, transmission, and control of energy and information.



It connects theory with real-world devices and technologies.



Electromagnetism unifies electricity, magnetism, optics, and modern technology into a single, coherent physical theory.

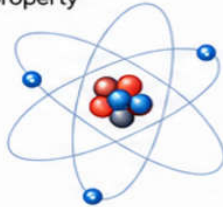


Electric Charge and Coulomb's Law

Electric charges exert forces on each other. Coulomb's law quantifies these forces.

Electric Charge

- Electric charge is a fundamental property of matter.
- Two types of charge:
 - Positive charge (+)
 - Negative charge (-)
- Like charges repel.
- Unlike charges attract.



Properties of Charge

- Charge is conserved.
- Charge is quantized: $q = ne$, where $n = 0, \pm 1, \pm 2, \dots$
- Elementary charge: $e = 1.602 \times 10^{-19} \text{ C}$
- The SI unit of charge is the coulomb (C).

Examples



Rubbed balloon



Plastic comb (rubbed)



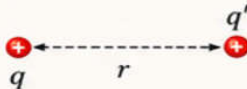
Thundercloud (charges)



Ion

Point Charge Model

If the size of a charged object is much smaller than the distance between objects, it can be treated as a point charge.



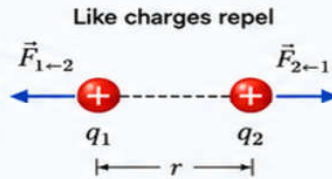
Coulomb's Law

The electrostatic force between two point charges q_1 and q_2 separated by a distance r is

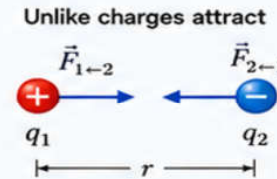
$$\vec{F}_{2 \leftarrow 1} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2} \hat{r}_{12}$$

where $\hat{r}_{12}$ is a unit vector pointing from q_1 to q_2 , and $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2)$ (permittivity of free space).

Direction of the Force

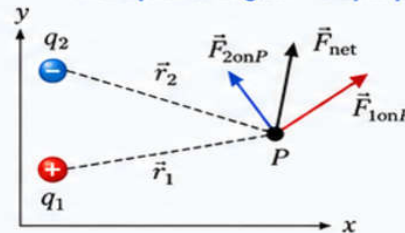


Like charges repel



Unlike charges attract

Multiple Charges – Superposition Principle



The net force on charge q_0 at point P is the vector sum of the forces due to all other charges:

$$\vec{F}_{\text{net}} = \sum_i \vec{F}_{i \text{ on } P}$$



Coulomb's law is the foundation for electric fields, electric potential, and all of electromagnetism.

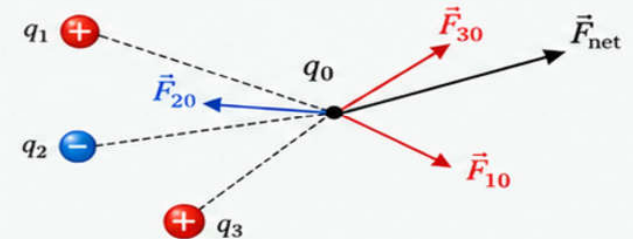
SI Units

- Charge: coulomb (C)
- Force: newton (N)
- Distance: meter (m)
- $1 \text{ C} = 1 \text{ A} \cdot \text{s}$

C	N
m	s

Superposition Principle

The total electrostatic force on a charge is the vector sum of the forces exerted by all other charges independently.



Key Takeaways

- Electric charges can be positive or negative.
- Charges exert forces on each other.
- Like charges repel; unlike charges attract.
- Coulomb's law quantifies the force between point charges.
- The superposition principle allows us to handle systems with many charges.

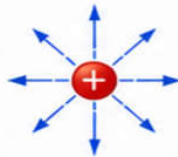


Electric Fields

Electric charges create electric fields that exert forces on other charges.

What is an Electric Field?

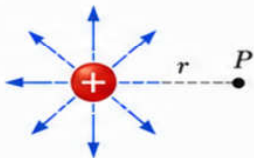
- An electric field is a vector field that describes the electric force per unit positive charge at a point in space.
- It is a property of space, independent of the presence of a test charge.



$$\vec{E} = \frac{\vec{F}}{q_0}$$

$\vec{E}$: electric field (N/C)
 $\vec{F}$: force on a positive test charge q_0
 q_0 : positive test charge

Electric Field of a Point Charge

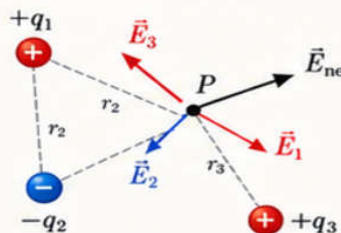


The electric field at a distance r from a point charge q is

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \hat{r}$$

$\hat{r}$ is a unit vector pointing radially away from a positive charge and toward a negative charge.

Electric Field of Multiple Charges

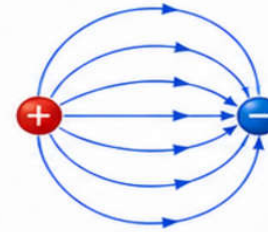


The net electric field is the vector sum of the fields to all charges:

$$\vec{E}_{\text{net}} = \sum_i \vec{E}_i$$

Electric Field Lines

- Field lines represent the direction of $\vec{E}$ at every point.
- They start on positive charges and end on negative charges.
- The density of lines indicates the field strength.
- Field lines never cross.



Examples of Field Line Patterns

Positive point charge



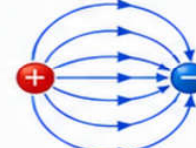
Lines radiate outward.

Negative point charge



Lines converge inward.

Electric dipole



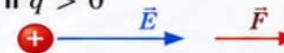
Lines go from + to -.

Force on a Charge in an Electric Field

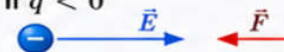
A charge q placed in an electric field $\vec{E}$ experiences a force

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

If $q > 0$



If $q < 0$



Electric fields allow charges to interact across space without direct contact.

SI Units

- Electric field: newton per coulomb (N/C) (also volt per meter, V/m)
- 1 N/C = 1 V/m
- Dimensions: $[E] = \text{MLT}^{-3}\text{I}^{-1}$

$$\frac{\text{N}}{\text{C}} = \frac{\text{V}}{\text{m}}$$

Applications



Capacitors

Store energy in electric fields between conductors.



Particle Accelerators

Use electric fields to accelerate charged particles.



Electrostatic Printers

Use electric fields to attract and transfer toner particles.



Lightning

Large electric fields in clouds lead to breakdown of air.

Key Takeaways

- ✓ Electric fields are created by electric charges.
- ✓ They exert forces on other charges.
- ✓ Field lines visualize the direction and strength of $\vec{E}$.
- ✓ The electric field principle superposes for multiple charges.
- ✓ Electric fields are essential in many engineering systems and technologies.





Distance Matters!

How does the force change with distance?

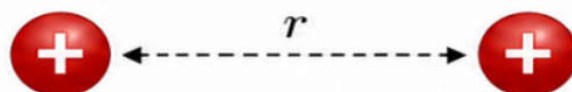


If we **change the distance** between two charges, how does the **electric force** change?

Scenario

Two identical positive charges.

What happens to the force if we change their separation?



Let's Think Qualitatively (No Calculations Yet!)

Case	Distance	What happens to the force?	Why?
1		Baseline	Our reference case.
2		Stronger (Larger)	Closer charges interact more strongly.
3		Weaker (Smaller)	Farther charges interact more weakly.



Think & Discuss

Why does the force increase so quickly when the distance becomes smaller?
Think about everyday experiences (magnets, pushing two objects together, etc.).

Key Idea

The electric force between two point charges is **inversely proportional to the square** of the distance between them.

$$F \propto \frac{1}{r^2}$$

Therefore:

- ✓ If r increases $\rightarrow F$ decreases rapidly.
- ✓ If r decreases $\rightarrow F$ increases rapidly.

What if...

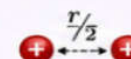
- If we **double the distance** ($r \rightarrow 2r$):

The force becomes **1/4** of the original.



- If we **halve the distance** ($r \rightarrow r/2$):

The force becomes **4** times larger.



Small change in distance $\rightarrow$ big change in force!

Takeaway Message



The **distance** between charges is one of the most powerful factors that controls the **electric force**.
Always check the distance carefully in problems!



Electric Potential

Electric potential describes the potential energy per unit charge.

What is Electric Potential?

- The electric potential V at a point is the potential energy U per unit positive charge.
- It is a scalar quantity.

$$V = \frac{U}{q}$$

V : electric potential (V)
 U : potential energy (J)
 q : positive test charge (C)

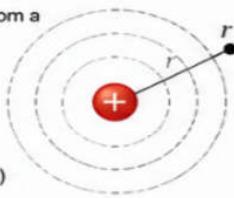
Electric Potential of a Point Charge

The electric potential at a distance r from a point charge q is

$$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$$

where $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2)$

- If $q > 0$, then $V > 0$ (positive potential)
- If $q < 0$, then $V < 0$ (negative potential)
- As $r \rightarrow \infty$, $V \rightarrow 0$ (reference: $V = 0$ at infinity)

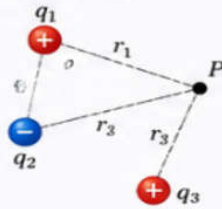


Potential Due to Multiple Point Charges

The electric potential at a point due to multiple charges is the algebraic sum of the potentials:

$$V = \frac{1}{4\pi\epsilon_0} \sum_i \frac{q_i}{r_i}$$

where r_i is the distance from charge q_i to the point P .



Relationship to Electric Field

The electric field is the negative gradient of the potential:

$$\vec{E} = -\nabla V$$

In one dimension (along s):

$$E_s = -\frac{dV}{ds}$$

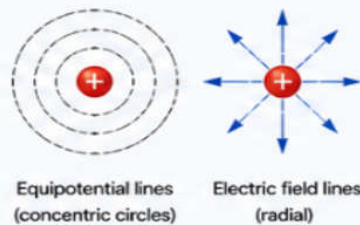
Implications

- $\vec{E}$ points in the direction of the greatest decrease of V .
- Field lines are perpendicular to equipotential surfaces.

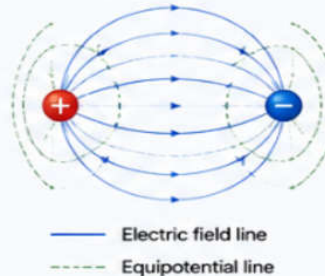
Equipotential Surfaces and Lines

Equipotential surfaces are surfaces on which the electric potential is the same everywhere.

Point Charge ($q > 0$)



Electric Dipole



Equipotential lines (concentric circles)

Electric field lines (radial)

— Electric field line
 --- Equipotential line



Moving a positive charge from a region of higher potential to lower potential releases energy; moving it to higher potential requires energy.

SI Unit

- Electric potential: **volt (V)**
- 1 volt = 1 joule per coulomb (1 V = 1 J/C)



Properties of Electric Potential

- ✓ Potential is a scalar quantity.
- ✓ Reference: $V = 0$ at infinity (common choice).
- ✓ Potential can be positive, negative, or zero.
- ✓ Potential difference between two points a and b :

$$V_b - V_a = -\int_a^b \vec{E} \cdot d\vec{l}$$

Engineering Applications

Capacitors



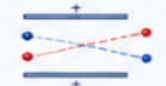
Store energy in electric fields.

Circuit Analysis



Voltage differences drive currents.

Particle Control



Fields guide and accelerate particles.

Electrostatics



Printers, filters, and coating.

Key Takeaways

- ✓ Electric potential is potential energy per unit charge.
- ✓ $\vec{E} = -\nabla V$: fields point from high to low potential.
- ✓ Equipotential surfaces help visualize potential.
- ✓ Potential differences cause charges to move.

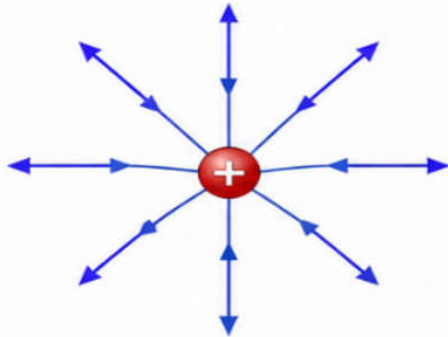


Uniform and Non-Uniform Electric Fields

Not all electric fields look the same

A. Non-Uniform Electric Field

Around a Point Charge

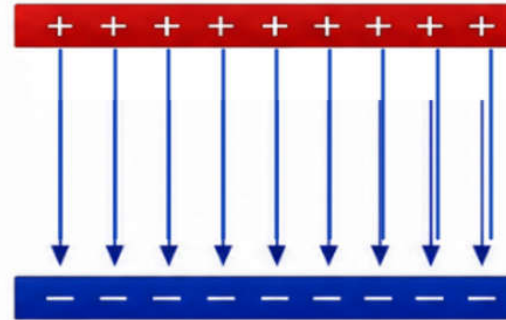


Characteristics

- ✓ Field strength changes with distance.
- ✓ Field lines spread farther apart as the distance increases.
- ✓ The electric field is strongest close to the charge.

B. Uniform Electric Field

Between Two Parallel Plates



Characteristics

- ✓ Same direction everywhere.
- ✓ Nearly constant magnitude.
- ✓ Parallel field lines.

Comparison

Point Charge		Parallel Plates
Field changes with distance	📍	Field is nearly constant
Radial field lines	☰	Parallel field lines
Non-uniform	≈	Uniform

Engineering Examples

Non-uniform field

-  Electrostatic spraying
-  Charged particles
-  Sensors

Uniform field

-  Capacitors
-  Deflection plates
-  Laboratory experiments



Think About It

If you move a positive test charge inside a uniform electric field...

Will the electric force:

- ☐ A Increase?
 ☐ B Decrease?
 ☐ C Stay approximately constant?

Answer: C

In a uniform field, the force is approximately constant throughout the region.

Key Message



The shape of the field depends on the **geometry** of the source.



★ Worked Example 1

Electric Field Produced by Two Point Charges

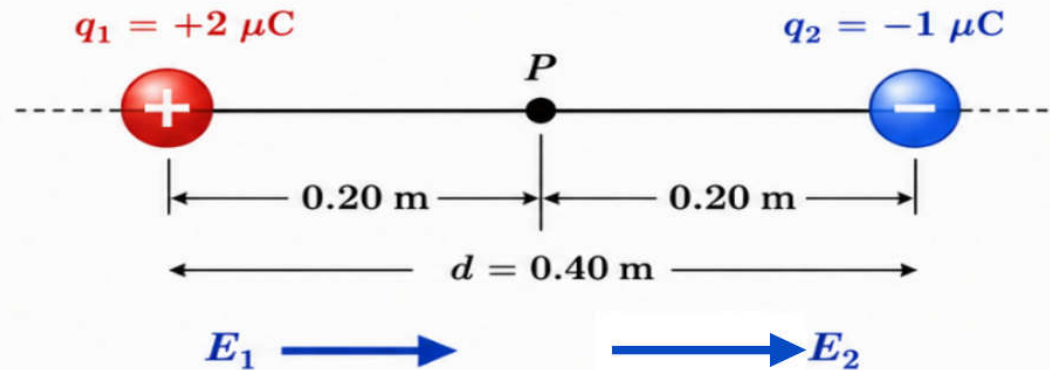
Problem Statement

Two point charges are fixed in space:

- $q_1 = +2.0 \mu\text{C}$
- $q_2 = -1.0 \mu\text{C}$

The charges are separated by
 $d = 0.40 \text{ m}$

Determine the electric field at
point P located midway
between the two charges.



At point P , the electric field due to the positive charge points away from q_1 (to the right), and the field due to the negative charge points toward q_2 (also to the right). Both fields point in the **same direction**.

★ Key Idea Before Calculating

Always determine the direction of each field first!

- ➕ → Electric field points **away** from a positive charge.
- ➖ → Electric field points **toward** a negative charge.

- ✓ Both E_1 and E_2 point to the right. Therefore, the fields add. The net field will point **to the right**.



Given

Quantity	Value
q_1	$+2.0 \mu\text{C}$
q_2	$-1.0 \mu\text{C}$
Distance between charges	0.40 m
Distance to point P	0.20 m

Question



Find the magnitude and direction of the electric field at point P .

Constants

$$k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$$

$$1 \mu\text{C} = 10^{-6} \text{ C}$$



Next: We will calculate the electric field due to each charge separately, then combine the results using the superposition principle.

1
Find E_1

+

2
Find E_2

=

3
Net E at P



★ Worked Example 1 – Analytical Solution

Electric Field Produced by Two Point Charges

Problem Summary

- $q_1 = +2.0 \mu\text{C}$ (left)
- $q_2 = -1.0 \mu\text{C}$ (right)
- Distance between charges:
 $d = 0.40 \text{ m}$
- Point P is midway
- Find: net electric field at P

Approach

- 1 Find the contribution E_1 at P due to q_1 .
- 2 Find the contribution E_2 at P due to q_2 .
- 3 Determine directions of $\vec{E}_1$ and $\vec{E}_2$.
- 4 Add the vectors using superposition:

$$\vec{E}_{\text{net}} = \vec{E}_1 + \vec{E}_2$$

Formula Used

Electric field of a point charge:

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

Direction: **away** from $+$ charge,
toward $-$ charge.

Step 1: Field at P due to $q_1 (+2.0 \mu\text{C})$

Distance from q_1 to P : $r_1 = 0.20 \text{ m}$

$$E_1 = \frac{k|q_1|}{r_1^2} = \frac{(8.99 \times 10^9) (2.0 \times 10^{-6})}{(0.20)^2}$$

$$E_1 = 4.50 \times 10^5 \text{ N/C}$$

Direction: to the right
(away from $+$ charge)

Step 2: Field at P due to $q_2 (-1.0 \mu\text{C})$

Distance from q_2 to P : $r_2 = 0.20 \text{ m}$

$$E_2 = \frac{k|q_2|}{r_2^2} = \frac{(8.99 \times 10^9) (1.0 \times 10^{-6})}{(0.20)^2}$$

$$E_2 = 2.25 \times 10^5 \text{ N/C}$$

Direction: to the right
(toward $-$ charge)

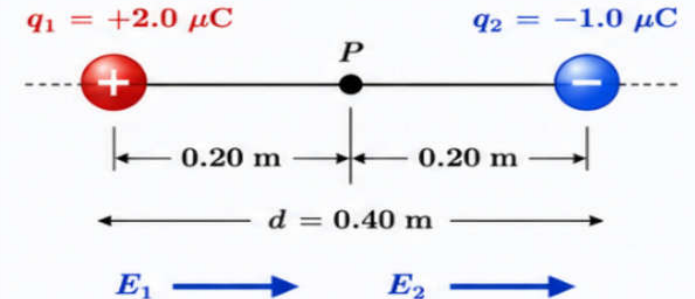
Step 3: Net Electric Field at P

- Both fields point to the right, so they add.

$$E_{\text{net}} = E_1 + E_2 = (4.50 + 2.25) \times 10^5 \text{ N/C}$$

$$E_{\text{net}} = 6.75 \times 10^5 \text{ N/C} \quad \text{to the right}$$

Geometry and Directions



Result

The electric field at point P is

$$E_{\text{net}} = 6.75 \times 10^5 \text{ N/C}$$

Direction: **to the right** (from q_1 toward q_2).

Check (Reasonableness)

- ✓ Both contributions are positive (same direction).
- ✓ The positive charge has larger magnitude ($|q_1| > |q_2|$), so the net field is greater than E_2 , but less than $E_1 + E_2$.
- ✓ Units are N/C , as expected.



Key Takeaway: Use Coulomb's law to find each contribution, determine directions, and then apply the superposition principle to obtain the net electric field.

Find E_1

+

Find E_2

=

Net E at P



★ Worked Example 1 – Discussion

Electric Field Produced by Two Point Charges

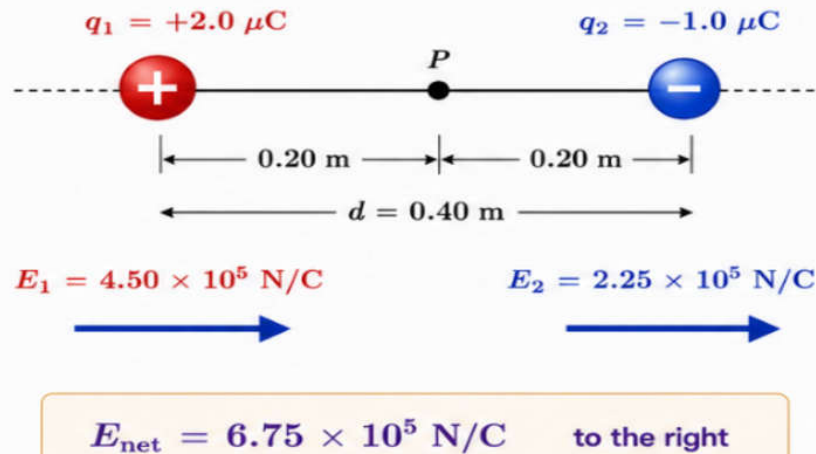
Physical Interpretation

- ✓ The positive charge ($+2.0 \mu\text{C}$) creates a stronger field at P because its magnitude is larger.
- ✓ The negative charge ($-1.0 \mu\text{C}$) also produces a field at P , but it is weaker.
- ✓ Both fields point to the right at P , so they reinforce each other. Therefore, the net field is **to the right**.

Key Takeaways

- ✓ Always draw the geometry and determine directions before calculating.
- ✓ Use Coulomb's law for each charge separately.
- ✓ Apply the superposition principle (vector sum).
- ✓ If fields point in the same direction, add. If opposite, subtract.

Recap of the Situation



What If?

- If q_2 were $+1.0 \mu\text{C}$ (same sign as q_1):
The fields would point in opposite directions. Since $|q_1| > |q_2|$, the net field points right.
- If q_2 were $-3.0 \mu\text{C}$ (larger magnitude):
Both fields would point to the right. The stronger q_2 contribution makes the net field point to the right.

General Strategy (Summary)

- 1 Sketch the configuration and identify the point of interest.
- 2 Determine the direction of each field contribution.
- 3 Use Coulomb's law: $E = \frac{k|q|}{r^2}$ for each charge.
- 4 Use the superposition principle to find the net field.
- 5 State the magnitude and direction of the result.

Superposition Principle:

The total electric field at a point is the vector sum of the fields due to all charges:

$$\vec{E}_{\text{net}} = \sum_i \vec{E}_i$$

Units Check

- ✓ Each field is in N/C .
- ✓ Adding vectors with the same direction keeps the unit N/C .
- ✓ Final answer:

$$6.75 \times 10^5 \text{ N/C}$$

(correct unit)

Common Pitfalls

- ✗ Forgetting to determine directions first.
- ✗ Using $r = 0.40 \text{ m}$ instead of 0.20 m .
- ✗ Ignoring the sign of the charges.
- ✗ Adding magnitudes when directions are opposite (should subtract).



Summary: By understanding the physics, applying Coulomb's law, and using superposition, we found that the electric field at the midpoint is $6.75 \times 10^5 \text{ N/C}$ **to the right**.

$$E_1 \text{ (from } q_1) + E_2 \text{ (from } q_2) = E_{\text{net}} \text{ (result)}$$



★ Worked Example 2

Electric Potential at a Point Due to Two Point Charges

Problem Statement

Two point charges are fixed in space:

- $q_1 = +3.0 \mu\text{C}$
- $q_2 = -2.0 \mu\text{C}$

as shown in the figure.

Determine the electric potential V at point P .

Given

q_1	$+3.0 \mu\text{C}$
q_2	$-2.0 \mu\text{C}$
r_1 (distance q_1 to P)	0.30 m
r_2 (distance q_2 to P)	0.40 m

Formula

Electric potential due to a point charge:

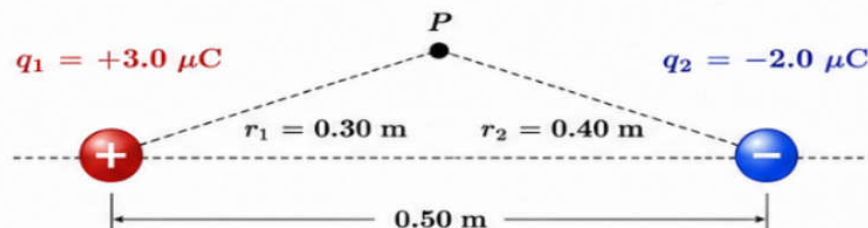
$$V = k \frac{q}{r}$$

Total potential (superposition):

$$V = V_1 + V_2$$

where $k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$

Geometry



Electric potential is a scalar. Contributions from each charge algebraically add. Positive charge → **positive potential**; negative charge → **negative potential**.

Solution

Step 1: Potential at P due to q_1

$$V_1 = k \frac{q_1}{r_1} = (8.99 \times 10^9) \frac{3.0 \times 10^{-6}}{0.30} = \boxed{8.99 \times 10^4 \text{ V}}$$

Step 2: Potential at P due to q_2

$$V_2 = k \frac{q_2}{r_2} = (8.99 \times 10^9) \frac{-2.0 \times 10^{-6}}{0.40} = \boxed{-4.50 \times 10^4 \text{ V}}$$

Step 3: Total potential at P

$$V = V_1 + V_2 = (8.99 - 4.50) \times 10^4 = \boxed{4.49 \times 10^4 \text{ V}}$$

$$\boxed{V = 4.49 \times 10^4 \text{ V (positive)}}$$

Interpretation

- The positive charge q_1 produces a positive potential of $+8.99 \times 10^4 \text{ V}$ at P .
- The negative charge q_2 produces a negative potential of $-4.50 \times 10^4 \text{ V}$ at P .
- The positive contribution is larger in magnitude, so the net potential is positive.



A positive test charge would have higher potential energy at P than at infinity.

Check (Reasonableness)

- ✓ $|V_1| > |V_2|$, and both distances are of the same order of magnitude $\Rightarrow$ net V should be positive.
- ✓ Unit of potential is volt (V).
- ✓ If both charges had been positive, the result would be even larger and positive.

Common Pitfalls

- ✗ Forgetting the sign of the charge in $V = kq/r$.
- ✗ Adding magnitudes instead of algebraic values.
- ✗ Using the wrong distance for each charge.
- ✗ Thinking the negative charge makes no contribution (it does — with a negative sign).



Key Takeaway: Electric potential from multiple point charges is the algebraic sum of the potentials from each charge: $V = \sum_i k \frac{q_i}{r_i}$. **Sign matters!**

$$\boxed{V_1 \text{ (from } q_1)} + \boxed{V_2 \text{ (from } q_2)} = \boxed{V \text{ (Net)}}$$



★ Worked Example 2 – Discussion

Electric Potential at a Point Due to Two Point Charges

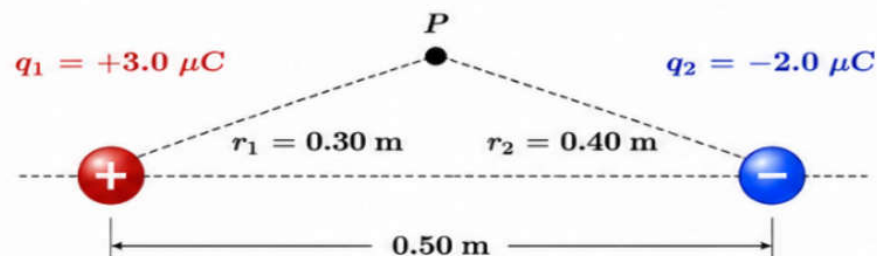
Physical Interpretation

- ✓ A positive charge creates a positive potential.
- ✓ A negative charge creates a negative potential.
- ✓ At point P , the positive charge q_1 produces a larger (positive) potential than the negative contribution in magnitude.
- ✓ Therefore, the net potential at P is **positive**.

Key Takeaways

- ✓ Electric potential is a scalar.
- ✓ Contributions add **algebraically**.
- ✓ Always keep track of signs!
- ✓ Distance matters: potential decreases with larger r .
- ✓ A negative charge can decrease the potential but may not be enough to make it negative.

Recap of the Situation



$$V_1 = +8.99 \times 10^4 \text{ V (due to } q_1, \text{ positive)}$$

$$V_2 = -4.50 \times 10^4 \text{ V (due to } q_2, \text{ negative)}$$

$$V_{\text{net}} = +4.49 \times 10^4 \text{ V (positive)}$$

General Strategy (Summary)

- 1 Identify the charges and the point of interest.
- 2 Determine distances $r_1, r_2, \dots$ to the point.
- 3 Compute each potential $V_i = k \frac{q_i}{r_i}$ with sign.
- 4 Add algebraically: $V_{\text{net}} = \sum_i V_i$.
- 5 State the magnitude and sign of the result.

Units Check

- ✓ Potential has unit volt (V).
- ✓ $[kq/r] = \frac{\text{N}\cdot\text{m}^2/\text{C}^2 \cdot \text{C}}{\text{m}} = \text{N}\cdot\text{m}/\text{C} = \text{V}$
- ✓ Our final answer is in volts. ✓

$$V_{\text{net}} = 4.49 \times 10^4 \text{ V}$$

(correct unit)

What If?

- If q_2 were $-5.0 \mu\text{C}$ (same distances):
The negative contribution would be larger in magnitude.

$$V_2' = -(8.99 \times 10^9) \frac{5.0 \times 10^{-6}}{0.40}$$

$$= -1.12 \times 10^5 \text{ V}$$

➔ Net potential would be **negative**.

- If both charges were positive:
Both contributions would be positive.
The net potential would be even larger and **positive**.

Common Pitfalls

- ✗ Forgetting the sign of the charge in $V = kq/r$.
- ✗ Adding magnitudes instead of algebraic values.
- ✗ Using the wrong distance for a charge.
- ✗ Confusing potential (scalar) with electric field (vector).
- ✗ Thinking a negative charge gives zero contribution (it gives a negative one).



Summary: Electric potential at a point due to multiple point charges is the algebraic sum of the potentials from each charge:

$$V = \sum_i \frac{k q_i}{r_i}$$

Signs determine whether contributions increase or decrease the total potential.

$$V_1 \text{ (from } q_1)$$

+

$$V_2 \text{ (from } q_2)$$

=

$$V_{\text{net}} \text{ (Net)}$$



★ Summary – Key Equations and Engineering Takeaways

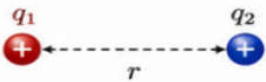
Electrostatics in Engineering



Electrostatics describes how stationary electric charges create electric fields and potentials. These concepts are fundamental to many engineering systems and technologies.

1. Key Equations

1 Coulomb's Law



$$F = \frac{k|q_1 q_2|}{r^2}$$

$$k = \frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9 \text{ N m}^2/\text{C}^2$$

2 Electric Field



$$\vec{E} = \frac{kq}{r^2} \hat{r} \quad (\text{point charge})$$

Unit: N/C or V/m

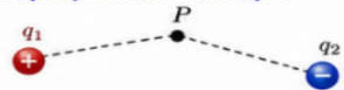
3 Electric Potential



$$V = \frac{kq}{r}$$

Unit: volt (V)

4 Superposition Principle



Electric field: $\vec{E}_{\text{net}} = \sum_i \vec{E}_i$

Electric potential: $V_{\text{net}} = \sum_i V_i$

2. Key Concepts

- ✓ Electric charges create electric fields that exert forces on other charges.
- ✓ Electric fields are vectors; electric potentials are scalars.
- ✓ The electric field points from positive charges and toward negative charges.
- ✓ Electric potential is the potential energy per unit charge.
- ✓ Use superposition to combine contributions from multiple charges.

3. Field and Potential Relationship

The electric field is related to the electric potential by:

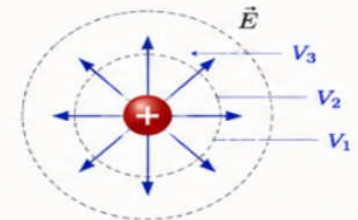
$$\vec{E} = -\nabla V$$

In one dimension:

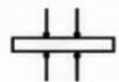
$$E_x = -\frac{dV}{dx}$$

4. Common Situations

- Field of a point charge
- Potential of a point charge
- Field of multiple point charges
- Potential of multiple point charges
- Two charges: superposition
- Equipotential surfaces are perpendicular to $\vec{E}$.



5. Engineering Applications



Capacitors and energy storage



Electrostatic discharge (ESD)



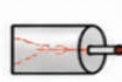
Photocopiers and printers



Electrostatic spray painting



Sensors and field probes



Charged particle devices

6. Units

- Charge: C (coulomb)
- Electric field: N/C or V/m
- Electric potential: V (volt)
- Force: N (newton)
- Potential energy: J (joule)

7. Key Takeaways

- ★ Understand the physics first, then apply the equations.
- ★ Always determine **directions** before calculations.
- ★ Use **vector** addition for fields and **algebraic** addition for potentials.
- ★ Check units, signs, and limiting cases.
- ★ Visualize the problem whenever possible.



Remember:

Electrostatics is the foundation for many areas of electrical and electronics engineering. Mastering these fundamentals enables you to design, analyze, and innovate with confidence.





What Creates a Magnetic Field?

Block V – Magnetic Fields



Electric currents and magnetic moments create magnetic fields.

Where can we find magnetic fields in the real world?

1. Permanent Magnets



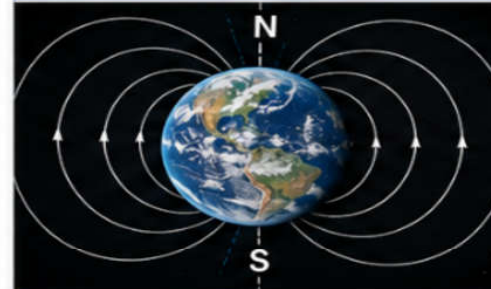
A permanent magnet produces a magnetic field around it, even without electricity.

2. Electric Current



Any electric current creates a magnetic field around the conductor.

3. Earth



The Earth has its own magnetic field that protects us from solar radiation.

4. Electric Motors



Electric motors use magnetic fields and currents to produce motion and do work.



Why is this important for engineers?

- Magnetic fields are the **foundation** of many technologies.
- They allow us to convert **electrical energy** into **motion**.
- They enable **energy transfer**, **sensing**, **data storage**, and more.

Remember this first!

Magnetic fields arise from:

- electric currents
- aligned atomic magnetic moments





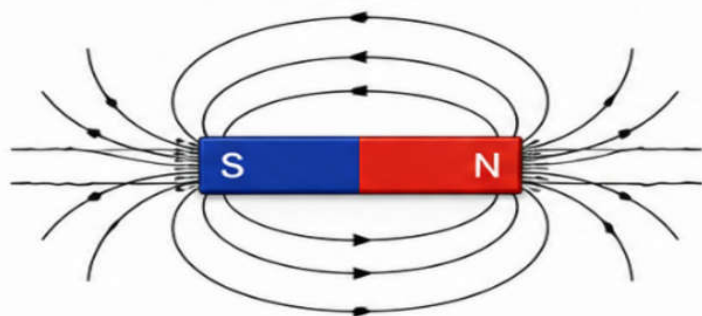
Visualizing Magnetic Fields

Block V – Magnetic Fields

Magnetic fields are invisible, but we can represent them using field lines.

1. Bar Magnet

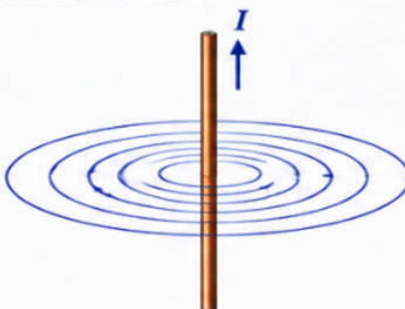
Field lines outside the magnet go from North (N) to South (S).



Field lines are denser near the poles. That means the magnetic field is stronger there.

2. Straight Current-Carrying Wire

A steady current in a straight wire creates **circular magnetic field lines** around the wire.



Field lines form closed loops. There are no beginning or end points for magnetic field lines.

Right-Hand Rule

Point your right thumb in the direction of the current (I). Your fingers curl in the direction of the magnetic field.

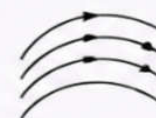


Understanding Field Lines



Direction

The arrow shows the direction of the magnetic field at that point.



Density

Closer lines mean a stronger magnetic field.



Closed Loops

Magnetic field lines always form continuous loops.



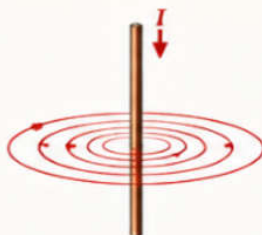
Not Real Lines

Field lines are a model to help us visualize the magnetic field.

? Think About It

If we reverse the current direction in the wire, what happens to the magnetic field?

- (A) The field disappears.
- (B) The field becomes stronger.
- (C) The field direction reverses.
- (D) Nothing changes.



Key Takeaway

- ✓ Magnets and currents create magnetic fields.
- ✓ Field lines help us understand the magnitude and direction of the field.
- ✓ Field lines go from North to South outside a magnet.
- ✓ Around a current-carrying wire, the field forms concentric circles.



Real-World Connection



Compasses align with Earth's magnetic field.



Solenoids and electromagnets use current to create strong magnetic fields.



Magnetic fields are the basis for motors, transformers, and wireless charging.





Right-Hand Rule

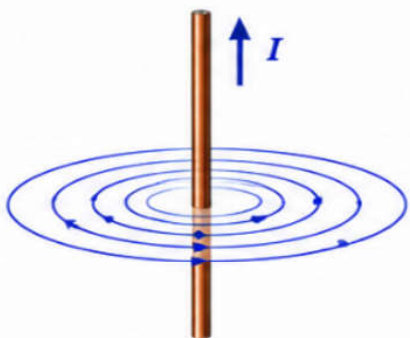
Block V – Magnetic Fields



The **right-hand rule** helps us find the **direction** of the magnetic field around a current.

1. Setup

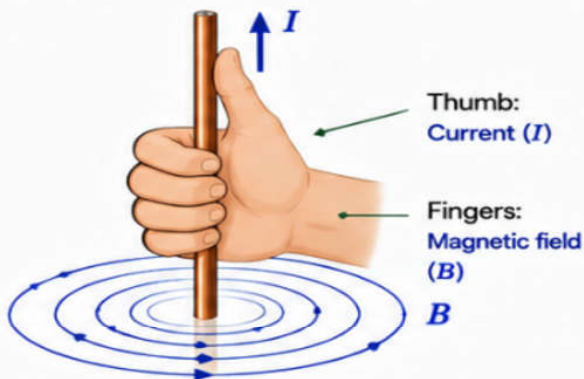
Consider a straight wire carrying **current I** upward.



What is the direction of the magnetic field **B** ?

2. Right-Hand Rule

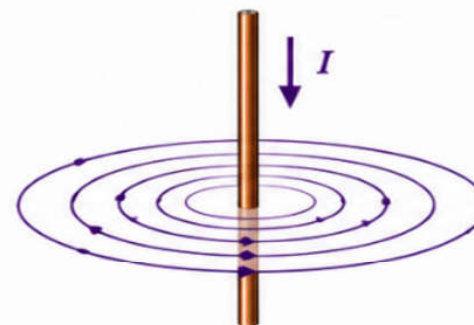
- 1 Point your right thumb in the direction of the **current (I)**.
- 2 Curl your fingers around the wire.
- 3 Your fingers show the direction of the **magnetic field (B)**.



If the current flows upward, the magnetic field circles **counterclockwise** when viewed from above.

3. Change the Current Direction

If we reverse the current direction, the magnetic field direction also **reverses**.

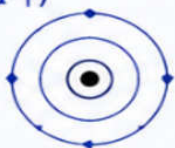


If the current flows downward, the magnetic field circles **clockwise** when viewed from above.

Top View Summary

Current upward ($I \uparrow$)

Field is **counterclockwise**



Current downward ($I \downarrow$)

Field is **clockwise**

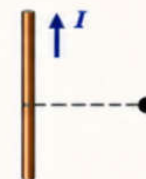


Think Before Calculating

A wire carries current upward.

At the point directly to the **right** of the wire, what is the direction of the magnetic field?

- (A) Upward
- (B) Downward
- (C) Into the page ($\otimes$)
- (D) Out of the page ($\odot$)



Concept Check

Block V – Magnetic Fields



Test your understanding! No calculations needed—just your physical intuition.

Question

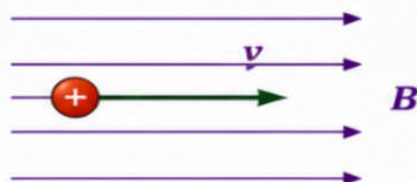
Which particle experiences the **largest** magnetic force?

All three particles have the same:

- charge q
- speed v
- magnetic field magnitude B

Only the **angle θ** between $\mathbf{v}$ and $\mathbf{B}$ is different.

A Parallel ($\theta = 0^\circ$)

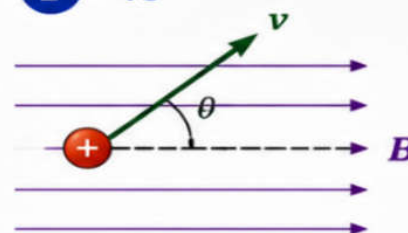


$\mathbf{v}$ is parallel to $\mathbf{B}$.

$$\sin 0^\circ = 0$$

$$F = qvB \sin \theta = 0$$

B 45°

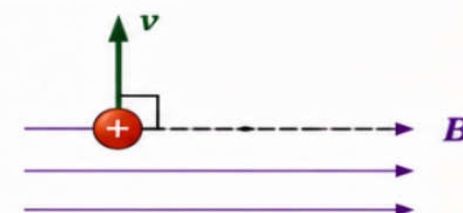


$$\theta = 45^\circ$$

$$\sin 45^\circ = \frac{\sqrt{2}}{2} \approx 0.707$$

$$F = qvB \sin \theta$$

C Perpendicular ($\theta = 90^\circ$)



$\mathbf{v}$ is perpendicular to $\mathbf{B}$.

$$\sin 90^\circ = 1$$

$$F = qvB$$



Hint: Use the formula for magnetic force: $F = qvB \sin \theta$ → The force depends on $\sin \theta$.



Key Idea

The magnetic force depends on the angle θ between the velocity $\mathbf{v}$ and the magnetic field $\mathbf{B}$.

- $\sin \theta$ is smallest at 0° (or 180°).
- $\sin \theta$ is largest at 90° .
- Therefore, the force is largest when $\mathbf{v} \perp \mathbf{B}$.

Answer

C Perpendicular ($\theta = 90^\circ$)

This gives the largest magnetic force because $\sin 90^\circ = 1$ (the maximum).

A gives zero force.
B gives a smaller force than C.



Why This Matters

This idea is used in many real-world applications:



Mass spectrometers separate charged particles using magnetic fields.



Cathode-ray tubes control electron beams with magnetic fields.



Particle accelerators use magnetic fields to steer and bend charged particles.



Magnetic Force on a Moving Charge

Block V – Magnetic Fields

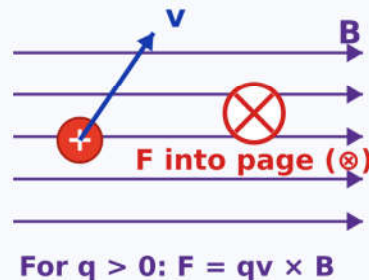


A **moving** electric charge in a **magnetic field** experiences a **force**.

The Key Equation

$$\mathbf{F} = q \mathbf{v} \mathbf{B} \sin \theta$$

- $\mathbf{F}$ = magnetic force (Newtons, N)
- q = charge (Coulombs, C)
- $\mathbf{v}$ = speed of the charge (m/s)
- $\mathbf{B}$ = magnetic field strength (Tesla, T)
- θ = angle between the velocity $\mathbf{v}$ and the magnetic field $\mathbf{B}$

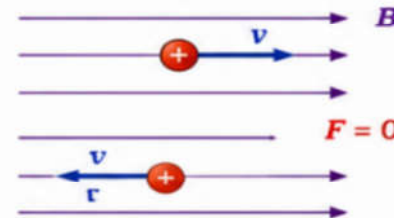


When is the Magnetic Force ... ?

Zero

$$\theta = 0^\circ \text{ or } 180^\circ$$

($\mathbf{v}$ is parallel or anti-parallel to $\mathbf{B}$)

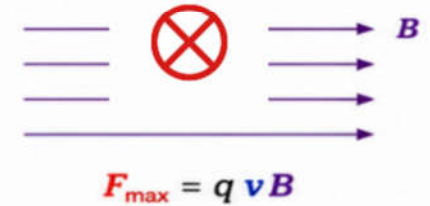


Maximum

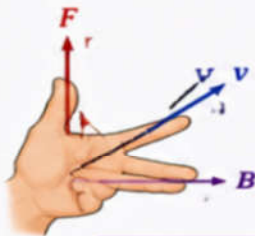
$$\theta = 90^\circ$$

($\mathbf{v}$ is perpendicular to $\mathbf{B}$)

F into page



Direction of the Force



Use the right-hand rule:

- Index finger → velocity $\mathbf{v}$
- Middle finger → magnetic field $\mathbf{B}$
- Thumb → magnetic force $\mathbf{F}$



$\mathbf{F}$ is always **perpendicular** to both $\mathbf{v}$ and $\mathbf{B}$.

Key Characteristics



The force is perpendicular to both $\mathbf{v}$ and $\mathbf{B}$.



The magnetic force does no work. It changes the direction of motion, not the speed.



The force depends on the angle θ . Only the perpendicular component of $\mathbf{v}$ contributes to the force.

Think About It

A positive charge moves in a magnetic field as shown. What is the direction of the magnetic force?



- (A) To the right
- (B) To the left
- (C) Out of the page ($\odot$)
- (D) Into the page ($\otimes$)
- (E) Zero



Magnetic Force on a Current-Carrying Wire

Block V – Magnetic Fields

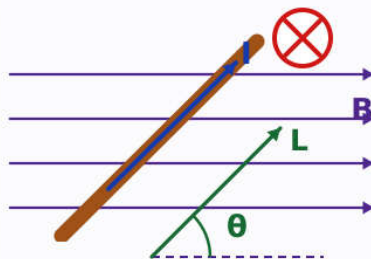
💡 A **current**-carrying wire placed in a **magnetic field** experiences a **force**.

The Key Equation

$$F = B I L \sin \theta$$

- F = magnetic force (Newtons, N)
- B = magnetic field strength (Tesla, T)
- I = current in the wire (Amperes, A)
- L = length of the wire in the field (meters, m)
- θ = angle between the wire (or current direction) and the magnetic field B

F into page

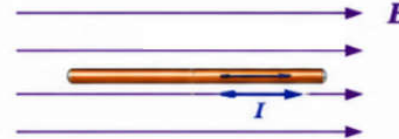


The force is perpendicular to both the current direction (along the wire) and the magnetic field B .

When is the Magnetic Force ... ?

Zero Force

$\theta = 0^\circ$ or 180°
(wire **parallel** to B)



$$F = 0$$

No pushing or pulling when the wire is parallel to the magnetic field.

Maximum Force

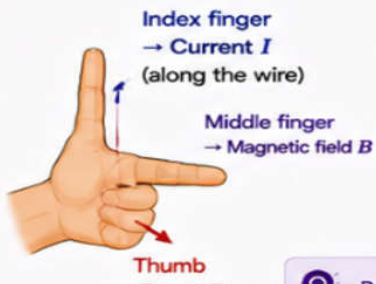
$\theta = 90^\circ$
(wire **perpendicular** to B)



$$F_{\max} = B I L$$

The force is largest when the wire is perpendicular to B .

Direction of the Force



Use the right-hand rule:
Point your fingers in the direction of I and B .
Your thumb shows the direction of the **force** F .



Reverse I or $B \rightarrow$ the force reverses.

Key Characteristics



The force is perpendicular to both the **current** direction and the magnetic field.



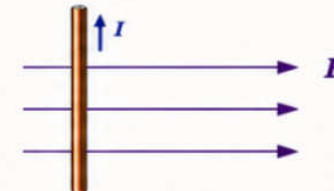
The force increases with larger B , I , and L .



The force depends on $\sin \theta$.
Only the perpendicular component of the current produces force.

Think About It

A straight wire carries current upward in a uniform magnetic field to the right, as shown.
What is the direction of the magnetic force on the wire?



- (A) To the right
- (B) To the left
- (C) Out of the page ($\odot$)
- (D) Into the page ($\otimes$)
- (E) Zero



Faraday's Law

Block V – Magnetic Fields



A **changing magnetic flux** through a loop induces an **emf (voltage)** in the loop.

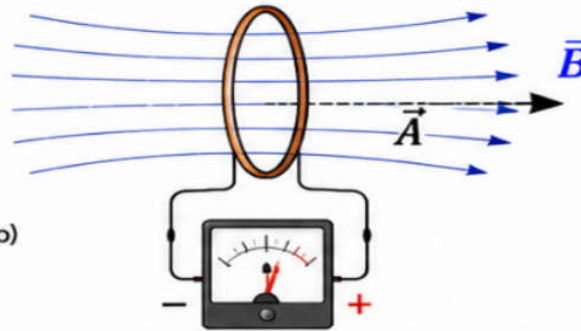
The Law

$$\mathcal{E} = - \frac{d\Phi_B}{dt}$$

$\mathcal{E}$ = induced emf (volts, V)

Φ_B = magnetic flux through the loop (weber, Wb)

t = time (seconds, s)



What Does It Mean?



The magnetic flux Φ_B through the loop **changes** with time.



This change induces an **emf (voltage)** around the loop.



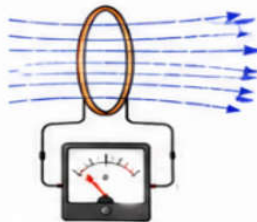
The minus sign tells us the induced emf **opposes** the change in flux.
This is **Lenz's Law**.

Examples: Changing Magnetic Flux

Flux increasing

$$d\Phi_B/dt > 0$$

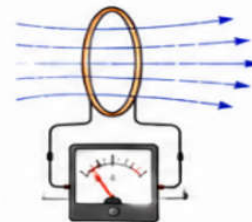
Induced emf acts to **oppose** the increase.



Flux decreasing

$$d\Phi_B/dt < 0$$

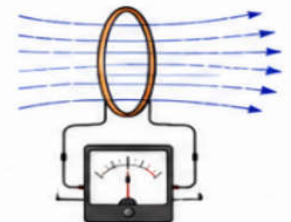
Induced emf acts to **oppose** the decrease.



No change in flux

$$d\Phi_B/dt = 0$$

No induced emf.
 $\mathcal{E} = 0$



Key Takeaway

Whenever the magnetic flux through a loop **changes**, a voltage is induced. The direction of that voltage always **opposes** the change that produced it.



Remember

No change in flux $\rightarrow$ no induced voltage.
Faster change $\rightarrow$ larger induced voltage.



Units

1 weber (Wb) = 1 tesla $\cdot$ m² (T $\cdot$ m²)
1 volt (V) = 1 weber per second (Wb/s)



Electromagnetic Induction

Block V – Magnetic Fields

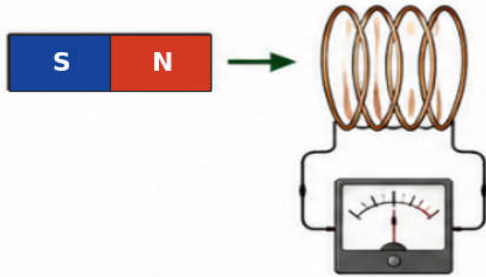


A **changing magnetic field** can **induce a voltage** (and current) in a conductor.

How Does It Happen?

1. Magnet moves

A magnet moves toward a coil of wire.

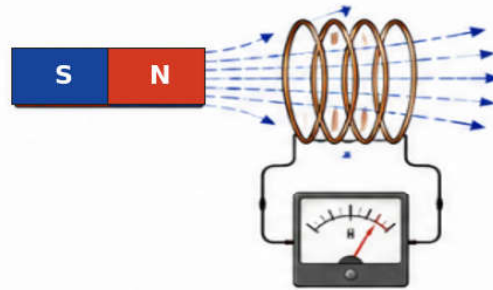


Think:

As the magnet moves, does the magnetic field through the coil change?

2. Magnetic field changes

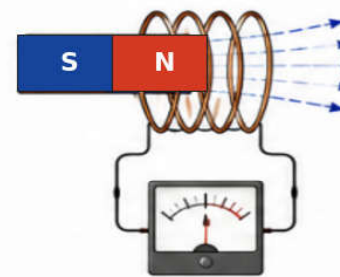
The magnetic **flux** through the coil increases.



Result: A voltage is induced in the coil.
(Current flows if the circuit is closed.)

3. Voltage is induced

A **voltage** appears across the coil while the flux is changing.



If the magnet **stops**, the flux stops changing → the induced voltage disappears.

Key Idea



Any **change** in the magnetic environment of a conductor **induces a voltage**.

Ways to change it:

- Move the magnet
- Move the coil
- Change the strength of the magnetic field
- Change the area or orientation of the coil



Big Picture:

Mechanical motion and magnetism can produce electricity.

This is the fundamental principle behind **generators**, **transformers**, and many **sensors**.



Lenz's Law: The Direction of Induction

Block V – Magnetic Fields



Lenz's Law: The induced current flows in a direction that **opposes** the **change** in **magnetic flux**.

What is Lenz's Law?

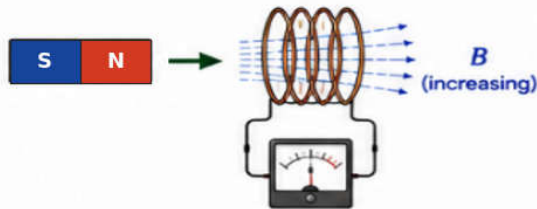
When the magnetic flux through a loop changes, the induced current creates its own magnetic field that **opposes** the **change**.

Why?

This is a consequence of conservation of energy—the system resists the change that caused it.

Examples: A Magnet and a Coil

- 1** Magnet moves toward coil
Flux through coil **increases**.
Coil **opposes** the **increase**.

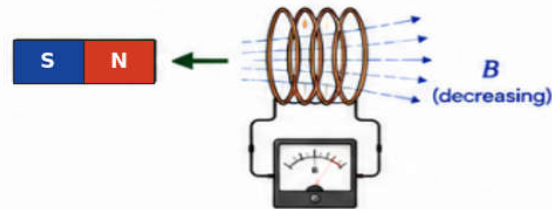


To oppose the increase, the coil's field must point to the **left**.
Therefore, the induced current is **counterclockwise** (viewed from magnet side).

(From magnet side)



- 2** Magnet moves away from coil
Flux through coil **decreases**.
Coil **opposes** the **decrease**.

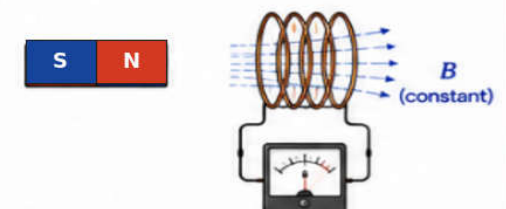


To oppose the decrease, the coil's field must point to the **right**.
Therefore, the induced current is **clockwise** (viewed from magnet side).

(From magnet side)



- 3** Magnet stationary (no motion)
Flux through coil is **constant**.
No change → no induced current.



No change in flux →
no induced voltage →
no current.



Understanding Lenz's Law

The induced current always tries to “push back” against whatever change is happening.

- **Increase** in flux → induced current creates a field to **decrease** it.
- **Decrease** in flux → induced current creates a field to **increase** it.
- **No change** in flux → no induced current.



Key Takeaway

Nature **doesn't like changes!**
Induced currents **oppose** the **change** in flux.



Memory Aid:
“**Oppose** the **change**.”



Real-World Application



Eddy current brakes use Lenz's Law. Moving metal through a magnetic field induces currents that create a force **opposing the motion**—slowing the object down.



Worked Example 1

Block V – Magnetic Fields



A moving charge in a magnetic field experiences a **magnetic force**.

Problem

A proton moves with a speed of
 $v = 2.0 \times 10^6 \text{ m/s}$
through a uniform magnetic field of
 $B = 0.40 \text{ T}$.

The velocity is perpendicular to the magnetic field.

Determine the **magnetic force** acting on the proton.

Given

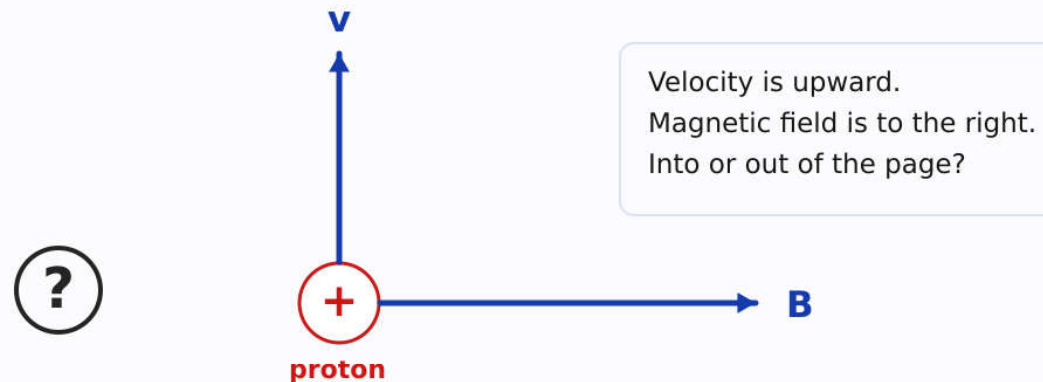
Charge (proton)	$q = 1.60 \times 10^{-19} \text{ C}$
Velocity	$v = 2.0 \times 10^6 \text{ m/s}$
Magnetic field	$B = 0.40 \text{ T}$
Angle	$\theta = 90^\circ$

Required

Find the **magnetic force**.

$$F = ?$$

Diagram



Think First

Before calculating, answer:
Is the force

- (A) Zero
- (B) Very small
- (C) **Maximum**

Hint

Since $\theta = 90^\circ$,
the force should be
maximum.

$$\sin 90^\circ = 1$$

(maximum value)

Key Idea

Always start by identifying the known quantities:

- charge q
- speed v
- magnetic field B
- angle θ

before substituting into the equation $F = qvB \sin \theta$.



Worked Example 1 – Solution

Block V – Magnetic Fields



We use the **magnetic force** on a moving charge: $F = qvB \sin \theta$.



Approach

- 1 Identify the known quantities q , v , B , and θ .
- 2 Substitute into $F = qvB \sin \theta$.
- 3 Calculate and report the result with correct units.



Equation Used

$$F = qvB \sin \theta$$

F = magnetic force (N)
 q = charge (C)
 v = speed (m/s)
 B = magnetic field (T)
 θ = angle between $\vec{v}$ and $\vec{B}$

Solution

- 1 Write the formula.

$$F = qvB \sin \theta$$

- 2 Substitute the values.

$$F = (1.60 \times 10^{-19} \text{ C})(2.0 \times 10^6 \text{ m/s})(0.40 \text{ T}) \sin 90^\circ$$

$$\sin 90^\circ = 1$$

- 3 Calculate.

$$F = (1.60 \times 10^{-19})(2.0 \times 10^6)(0.40)(1)$$

$$F = 1.28 \times 10^{-13} \text{ N}$$

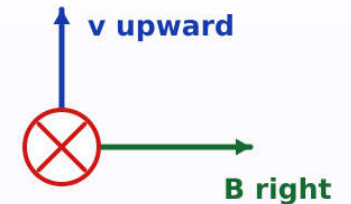
- 4 Round to two significant figures.

$$F = 1.3 \times 10^{-13} \text{ N}$$



Direction Check

For a proton ($q > 0$):



F into the page (⊗)

$$F = q(\vec{v} \times \vec{B})$$



Final Answer

The magnetic force acting on the proton is

$$F = 1.3 \times 10^{-13} \text{ N}$$

Direction: into the page (⊗).



Key Takeaway

For a charge moving perpendicular to a magnetic field ($\theta = 90^\circ$), the magnetic force is **maximum**: $F_{\max} = qvB$.



Worked Example 1 – Discussion

Block V – Magnetic Fields



A moving charge experiences a **magnetic force perpendicular** to both its velocity and the magnetic field.

Result

The magnetic force on the proton is

$$F = 1.3 \times 10^{-13} \text{ N}$$

The force points into the page ($\otimes$).

Check Units

$$\text{N} = \text{C} \cdot \text{m/s} \cdot \text{T} \checkmark$$

Reasonableness

- The force is small ($\approx 10^{-13} \text{ N}$), as expected for a proton.
- It is maximum because $\theta = 90^\circ$.

★ Key Points

- Magnitude: $F = qvB \sin \theta$.
- F is perpendicular to v and B .
- Magnetic force does no work: it changes direction, not speed.
- For v upward and B right, F points into the page ($q > 0$).
- Check the units and physical reasonableness of the result.

Direction (Right-Hand Rule)

For the positive proton:

- 1 Velocity v points upward.
- 2 Magnetic field B points right.
- 3 $v \times B$ points into the page.



$\otimes$ **F into the page ($\otimes$)**

$$\text{For } q > 0: F = q(v \times B)$$



Key Takeaway

For a moving charge in a magnetic field, the **magnetic force** is maximum when the velocity is **perpendicular** to the field and has a direction given by the **right-hand rule**.



Worked Example 2

Force on a Current-Carrying Wire

Block V – Magnetic Fields



A current-carrying wire in a magnetic field experiences a **magnetic force**.

Problem

A straight wire of length $L = 0.50$ m carries a current $I = 3.0$ A to the right.

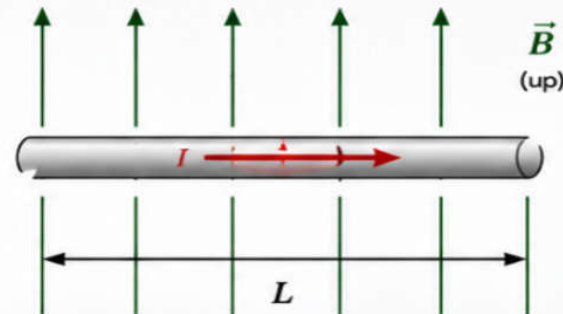
The wire is placed in a uniform magnetic field of $B = 0.80$ T directed **upward**.

The current is perpendicular to the field.

Determine

- the **magnitude** of the magnetic force on the wire.
- the **direction** of the force.

Diagram



What happens?

Use the right-hand rule:

- Thumb: current (right)
- Fingers: magnetic field (up)
- Palm: force (out of the page) $\odot$

Force is out of the page.

Given

Length of wire	$L = 0.50$ m
Current	$I = 3.0$ A
Magnetic field	$B = 0.80$ T
Angle	$\theta = 90^\circ$

? Required

- Find the magnitude of the magnetic force $F = ?$
- Find the direction of the force.

Think First

Before calculating, answer:

For $\theta = 90^\circ$, is the force

- Zero
- Very small
- Maximum**

Key Idea

The magnetic force on a current-carrying wire is given by

$$F = BIL \sin \theta$$

Perpendicular $\rightarrow \sin 90^\circ = 1$
Force is **maximum**.

Quick Calculation

- Use the formula:

$$F = BIL \sin \theta$$

- Substitute the values:

$$F = (0.80 \text{ T})(3.0 \text{ A})(0.50 \text{ m}) \sin 90^\circ$$

- Calculate:

$$F = (0.80)(3.0)(0.50)(1) = 1.20 \text{ N}$$

✓ Answer

- Magnitude of the magnetic force:

$$F = 1.2 \text{ N}$$

- Direction of the force:

Out of the page (toward you)



Key Takeaway

A current-carrying wire in a magnetic field experiences a force given by $F = BIL \sin \theta$.
The direction is found using the **right-hand rule**.



Worked Example 2 – Solution

Block V – Magnetic Fields



The **magnetic force** on a current-carrying wire is $F = BIL \sin \theta$.

Approach

- 1 Identify the known quantities B , I , L , and θ .
- 2 Use $F = BIL \sin \theta$.
- 3 Calculate the magnitude.
- 4 Determine the direction using the **right-hand rule**.

Equation Used

$$F = BIL \sin \theta$$

F = magnetic force (N)

B = magnetic field (T)

I = current (A)

L = length of wire (m)

θ = angle between $\vec{I}$ and $\vec{B}$

Check Units

$$[F] = \text{T} \cdot \text{A} \cdot \text{m} = (\text{N}/(\text{A} \cdot \text{m})) \cdot \text{A} \cdot \text{m} = \text{N}$$

Units are correct! ✓

Solution

- 1 Write the formula.

$$F = BIL \sin \theta$$

- 2 Substitute the values.

$$F = (0.80 \text{ T})(3.0 \text{ A})(0.50 \text{ m}) \sin 90^\circ$$

$$\sin 90^\circ = 1$$

- 3 Calculate.

$$F = (0.80)(3.0)(0.50)(1) \text{ N}$$

$$F = 1.20 \text{ N}$$

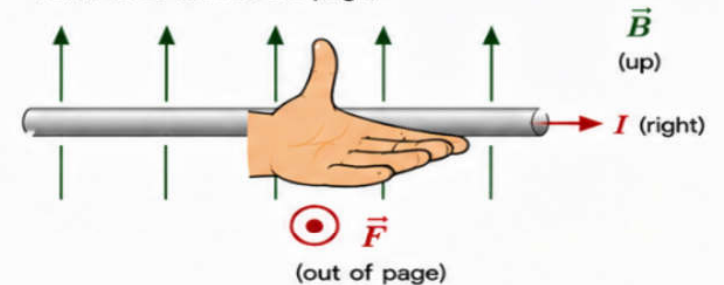
- 4 Round to appropriate significant figures.

$$F = 1.2 \text{ N}$$

Direction (Right-Hand Rule)

Use the right-hand rule:

- Thumb: current (to the right)
- Fingers: magnetic field (upward)
- Palm: force (out of the page)



Therefore, the force is out of the page (toward you).

Final Answer

- (a) Magnitude of the magnetic force: $F = 1.2 \text{ N}$
- (b) Direction of the force: **Out of the page (toward you)**



Discussion

The force is **maximum** because the current is perpendicular to the magnetic field ($\theta = 90^\circ$). If the current were parallel to the field ($\theta = 0^\circ$), the force would be **zero**.



Worked Example 2 – Discussion

Block V – Magnetic Fields



We found both the **magnitude** and the **direction** of the magnetic force on the wire.



What We Found

A straight wire carrying current in a uniform magnetic field experiences a force.

Magnitude:

$$F = 1.2 \text{ N}$$

Direction:

Out of the page (toward you)



Key Takeaways

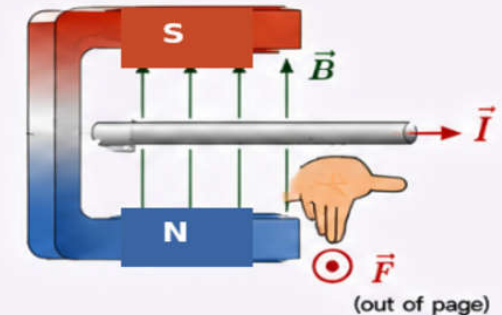
- The magnetic force on a current-carrying wire is given by $F = BIL \sin \theta$.
- The force is **maximum** when the current is perpendicular to the magnetic field ($\theta = 90^\circ$).
- If the current were **parallel** to the field ($\theta = 0^\circ$), then $\sin \theta = 0 \rightarrow$ the force would be **zero**.
- The direction is found using the **right-hand rule**.
- The magnetic force is **perpendicular** to both the current and the magnetic field.



Physical Insight

This principle is used in many engineering devices, such as:

- Electric motors
- Moving-coil meters
- Loudspeakers



Summary

- ✓ We calculated the magnetic force on a current-carrying wire.
- ✓ We used $F = BIL \sin \theta$ with $\theta = 90^\circ$.
- ✓ We determined the direction using the right-hand rule.
- ✓ Result: $F = 1.2 \text{ N}$, **out of the page (toward you)**.



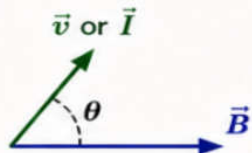
Common Mistakes in Magnetic-Field Problems

Block V – Magnetic Fields

1 Forgetting the angle

$$F = qvB \sin \theta$$

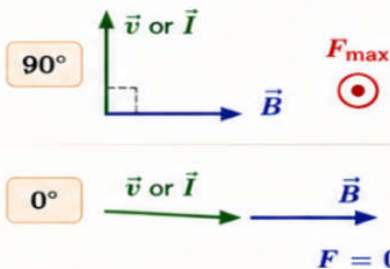
$$F = BIL \sin \theta$$



⚠ Always identify the angle **between** the two directions.

2 Assuming the force is always maximum

$90^\circ \rightarrow$ **maximum** force
 $0^\circ \rightarrow$ **zero** force



⚠ Check the **angle**! It changes the force.

3 Using the right-hand rule incorrectly

First identify the direction of velocity/current and magnetic field.

Right-hand rule (for + charge or current):

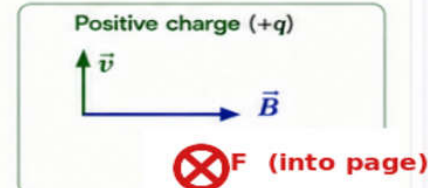
1. Thumb: $\vec{v}$ or $\vec{I}$
2. Fingers: $\vec{B}$
3. Palm: $\vec{F}$



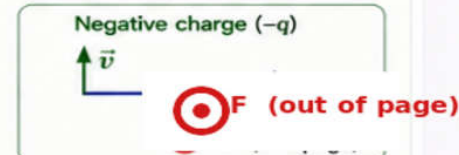
⚠ Swapping directions gives the wrong answer.

4 Forgetting the sign of the charge

For a positive charge (+q), use the right-hand rule.



For a negative charge (-q), the force is opposite.



⚠ Negative charge $\rightarrow$ **opposite** direction!

5 Confusing magnetic force with electric force

Electric field:

$$F = qE$$

(No velocity, no angle)

Magnetic field:

$$F = qvB \sin \theta$$

(Depends on velocity and angle)

⚠ Different equations $\rightarrow$ Different physics!

Problem-Solving Checklist

Before calculating, ask:

1. What is **moving**?
(charge or current)

2. What is the **field** direction? ($\vec{B}$)

3. What is the **angle** θ between them?

4. Which **equation** applies?
($qvB \sin \theta$ or $BIL \sin \theta$)

5. What **direction** should the force have?

Key Message

Most mistakes in basic magnetic-field problems come from **direction** and **geometry**—not from the calculation itself.



Magnetic Fields: Summary

Three Ideas Every Engineer Should Remember

Block V – Magnetic Fields

1 Moving Charges Experience Magnetic Force

$$F = qvB \sin \theta$$

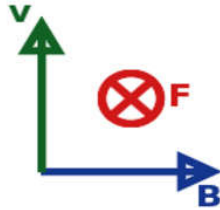
Physical meaning:

A magnetic field can change the direction of motion of a moving charged particle.

Remember:

$v \perp B \rightarrow$ maximum force

$v \parallel B \rightarrow$ zero force



2 Current-Carrying Wires Experience Force

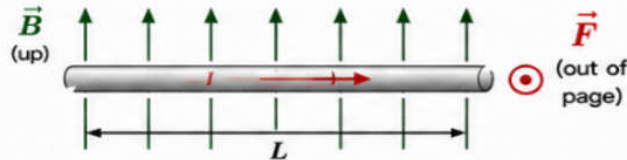
$$F = BIL \sin \theta$$

Physical meaning:

A magnetic field can exert a force on an electric current.

Engineering connection:

Magnetic force $\rightarrow$ torque $\rightarrow$ electric motor



3 Changing Magnetic Flux Produces Voltage

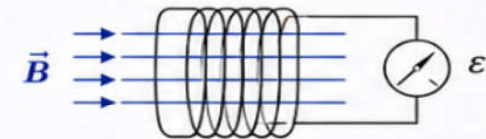
$$\mathcal{E} = - \frac{d\Phi_B}{dt}$$

Physical meaning:

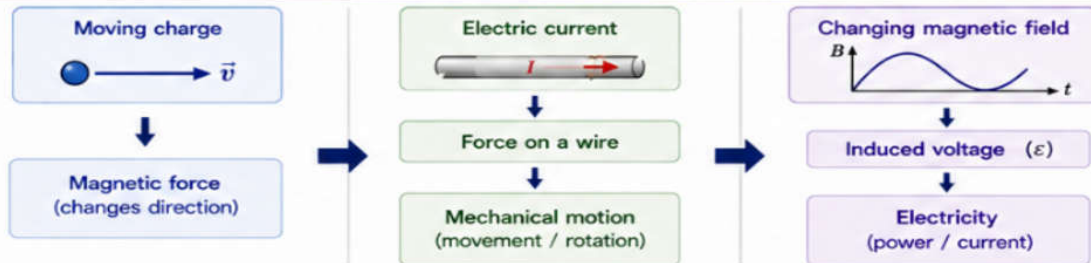
A change in magnetic flux induces a voltage.

The minus sign represents Lenz's law:

The induced effect opposes the change that produced it.



The Big Picture



Engineering Applications



Electric motors



Generators



Loudspeakers



Magnetic sensors



Final Problem-Solving Message



Understand the physical situation **first**.



Choose the equation **second**.



Calculate **last**.



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Lecture 8 | Electric Fields and Magnetic Fields