Additional Notes

Topic 17: Electromagnetic Induction

Content

A Magnetic Flux and Magnetic Flux Linkage
B Laws of Electromagnetic induction:
Faraday's Law and Lenz's Law
C Induced e.m.f. in a Straight Conductor
D Applications of Electromagnetic induction

Learning Outcomes

Candidates should be able to:

(a) define magnetic flux as the product of an area and the component of the magnetic flux density perpendicular to that area.

(b) recall and solve problems using $\phi = BA$.

(c) define magnetic flux linkage.

(d) infer from appropriate experiments on electromagnetic induction:
  (i) that a changing magnetic flux can induce an e.m.f.,
  (ii) that the direction of the induced e.m.f. opposes the change producing it,
  (iii) the factors affecting the magnitude of the induced e.m.f.

(e) recall and solve problems using Faraday's law of electromagnetic induction and Lenz's law.

(f) explain simple applications of electromagnetic induction.

Demonstrating Science Inquiry Skills

In 1819, Hans Christian Oersted discovered that a magnetic compass experiences a force in the vicinity of an electric current. This was the first evidence of a relationship between electricity and magnetism. Because nature is often symmetric, it led scientists to suspect that magnetic fields could in turn produce electricity. Indeed, experiments conducted by Michael Faraday showed that a changing magnetic field could induce an electric current in a circuit. The results of the experiment led to what we know today as Faraday's law, the application of which led to the production of electrical energy in power generation plants throughout the world.

Additional Notes

Generation of electric current

- Faraday first discovered that current can be induced in a circuit by a changing current in a nearby circuit as shown.

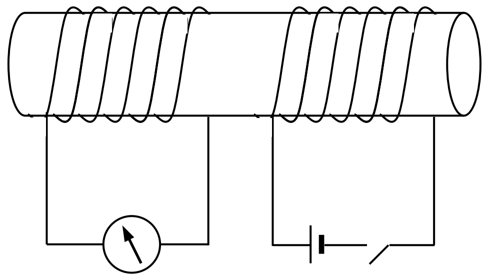


Fig. 17.1

A galvanometer is an apparatus which deflects to indicate the presence of a current passing through it. It is able to distinguish between 2 currents in opposite directions.

Note that there is no e.m.f. source (e.g. battery) in the coil on the left. So any deflection of the galvanometer is surprising.

Action	Observation
Switch is closed	Galvanometer deflects momentarily.
Switch remains closed and current is steady	Galvanometer shows no deflection.
Switch is open	Galvanometer deflects momentarily, but in opposite direction.

- Faraday went on to observe that when a bar magnet is moved near a coil, a similar effect is obtained.

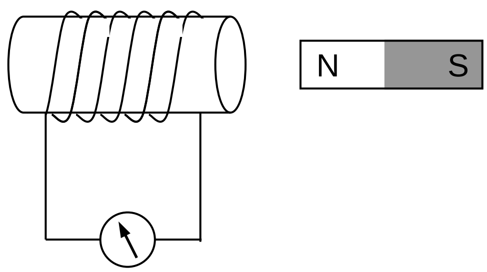


Fig. 17.2

Relative motion of the coil and magnet results in a change in the magnetic field linking the coil.

Action	Observation
Magnet moves towards/ away from coil	Galvanometer deflects momentarily.
Coil moves towards/ away from magnet	Galvanometer deflects momentarily.
Faster relative motion between magnet and coil	Larger deflection by galvanometer.

- Conclusion: (Induced) electric current is generated by a changing magnetic field linking the coil.

Additional Notes

A Magnetic flux and Magnetic Flux Linkage

- Consider a surface in the presence of a uniform magnetic field, *B*.

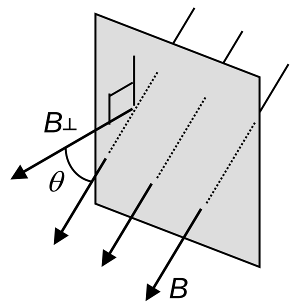


Fig. 17.3

- Magnetic flux ϕ through the surface is:

$$\phi = B_{\perp}A = (B\cos\theta)A$$

where $B_{\perp}$ = component of *B* perpendicular to the surface (T)
A = area of the surface (m^2)
θ = angle between the B-field and the normal to the area

- The SI unit for magnetic flux is weber (Wb).

Magnetic flux is the product of <u>an area</u> and the <u>component of the magnetic flux density perpendicular to that area</u>.

Memorise

- For a coil with area *A* and *N* number of turns, then the <u>flux linkage through the coil</u> $N\phi$ or total flux passing through the loop is:

$$N\phi = NB_{\perp}A = N(B\cos\theta)A$$

The Magnetic Flux Linkage in a coil is the product of the area of the coil and the component of the magnetic flux density perpendicular to that area, and the number of turns in the coil.

Memorise

- The SI unit for magnetic flux linkage is Wb (or Wb-turns).

It is easier to remember $\phi = B_{\perp}A$ and resolve B to obtain $B_{\perp}$ on your own when solving quantitative questions.

Memorizing $\phi = (B\cos\theta)A$ often poses much confusion as to which angle constitutes the required θ.

Area *A* refers only to the area that the B-field passes through.

Additional Notes

Visualising Flux Linkage

The amount of magnetic flux linkage can be visualised in terms of the number of B field lines passing through a coil.

For Fig. 17.4, coil moves from X to Y

- Number of field lines ***linking*** it increases from 3 to 5
- Or the coil ***cuts*** 2 lines in moving from X to Y.

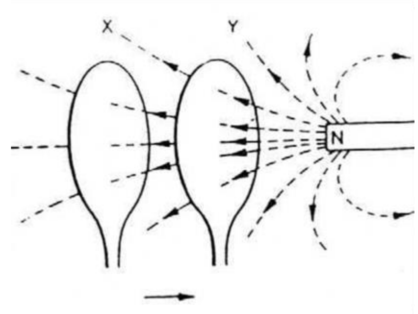
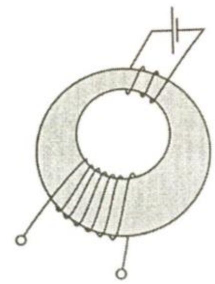


Fig. 17.4

<u>Check Your Understanding 1</u>

A soft iron ring of variable cross-section has two coils wound around it. One coil has 7 turns. The other, of 3 turns is connected to a d.c. supply. Which quantity is the same inside each coil?



A. Magnetic field B. Magnetic flux

C. Magnetic flux density D. Magnetic flux linkage

B Laws of Electromagnetic Induction

B.1 Faraday's Law

Induced e.m.f. is only formed when there is a change in flux wrt time, not when there is flux.

Faraday determined through experiments that when the magnetic flux linking a circuit is changing, an induced e.m.f. is set up in the circuit.

Faraday's Law of Electromagnetic Induction states that the e.m.f. induced in a conductor is proportional to the rate of change of magnetic flux linkage (or rate of cutting of the flux).

- For a coil of N turns, the induced e.m.f., $E \propto \frac{d(N\phi)}{dt}$

$$E = -N\frac{d\phi}{dt}$$

(Units of E: Volt (V))

where the negative sign is a manifestation of <u>Lenz's Law</u>, which will be discussed in the following section.

Magnitude of induced e.m.f. depends on the rate of change of flux, not the magnitude of the change.

- The magnitude of E depends on how fast (the rate) the flux linkage changes.

Since $E = -\frac{dN\phi}{dt} = -\frac{d}{dt}(NBA\cos\theta)$, E depends on

Additional Notes

- $\dfrac{dB}{dt}$ (rate of change of magnetic flux density perpendicular to area)
- $\dfrac{dA}{dt}$ (rate of change of area perpendicular to magnetic field)
- $\dfrac{d\left(\cos\theta\right)}{dt}$ (factor dependent on rate of turn of the coil)

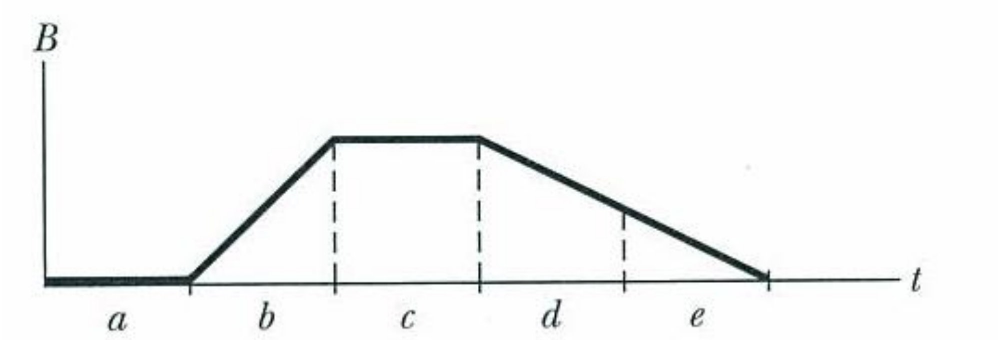
Worked Example

The uniform flux density between the poles of a magnet is 0.080 T. A small coil of area of cross-section 6.5 cm^2 has 250 turns and is placed with its plane normal to the magnetic field. The coil is withdrawn from the field in a time of 0.26 s. Determine the average e.m.f. induced in the coil whilst it is being withdrawn.

$$av\ \varepsilon = -\frac{\Delta N\phi}{\Delta t} = -\frac{N(\Delta B)A}{\Delta t} = -\frac{N(B_f - B_i)A}{\Delta t}$$
$$= -\frac{250(0-0.080)(6.5\times10^{-4})}{0.26}$$
$$= 0.050\ \text{V}$$

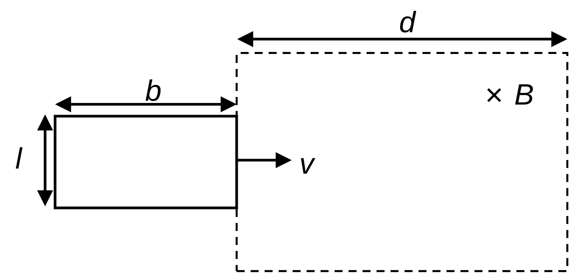
Check Your Understanding 2

A uniform magnetic field that exists throughout a conducting loop, perpendicular to the plane of the loop. The graph shows the variation of the magnitude of the magnetic flux density B with time t. Rank the five regions of the graph according to the magnitude of the e.m.f. induced in the loop, greatest first.



Example 1

The figure shows a rectangular conducting loop of resistance *R*, width *l*, and length *b* being pulled at constant speed *v* through a region of length *d* in which a uniform magnetic field *B* is produced by an electromagnet.
In this example, l = 40 mm, b = 10 cm, d = 15 cm, R = 1.6 Ω, B = 2.0 T, and v = 1.0 cm s^{-1}.



(a) Sketch the variation of magnetic flux ϕ through the loop with time *t*, where *t* = 0 is when the loop is about to enter the field.

(b) Sketch the variation of induced e.m.f. *E* with time *t*.

Additional Notes

B.2 Lenz's Law

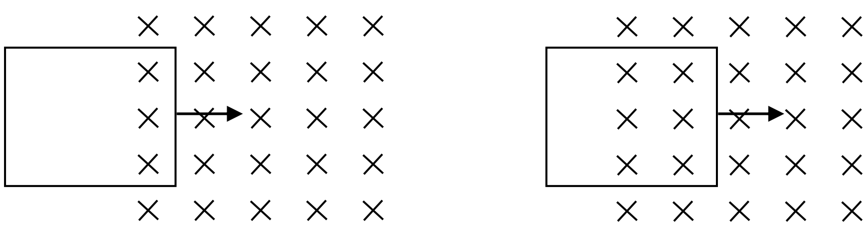
Lenz's Law states that the direction of the induced e.m.f. is such that it tends to produce effects to oppose the change causing it.

Memorise

Induced e.m.f. does not oppose the change directly. It is the effect caused by it that opposes the change.

B.2.1Using Right Hand Grip Rule to determine Direction of Induced Current

In the figure below, a rectangular coil is pulled across a uniform magnetic field with the field lines perpendicular to the plane of the coil.



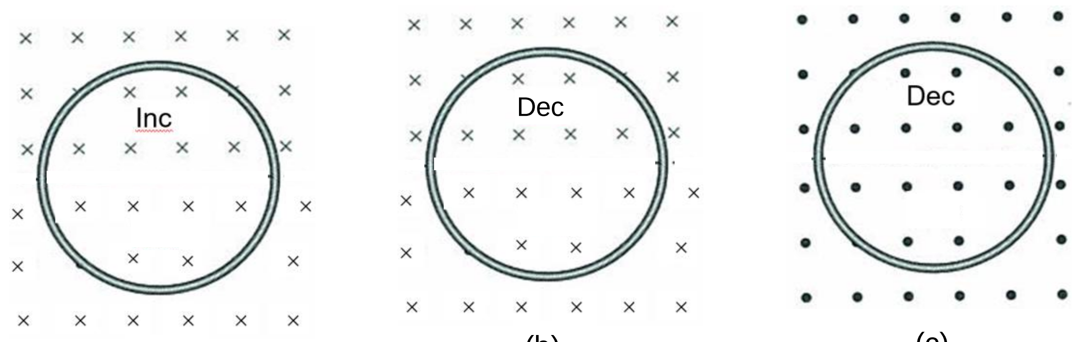
As the coil moves into the field, it experiences a changing magnetic flux linkage and hence e.m.f. is induced. For this case, the induced current flowing in the coil can be determined using Right Hand Grip Rule.

As the coil experiences increasing amount of crosses (flux into page). By Lenz's Law, induced current in coil produces effects to try and maintain amount of crosses, i.e. produce dots (flux out of page) to cancel effect of increasing crosses. By Right Hand Grip Rule, the induced current flows anticlockwise.

Check Your Understanding 3

The figure shows three situations in which identical circular conducting loops are in uniform magnetic fields that are either increasing (Inc) or decreasing (Dec).

Determine the direction of induced current in each case.



(a) (b) (c)

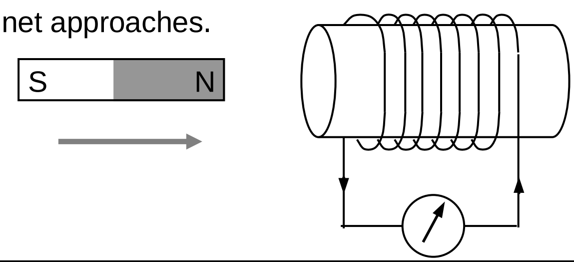
Additional Notes

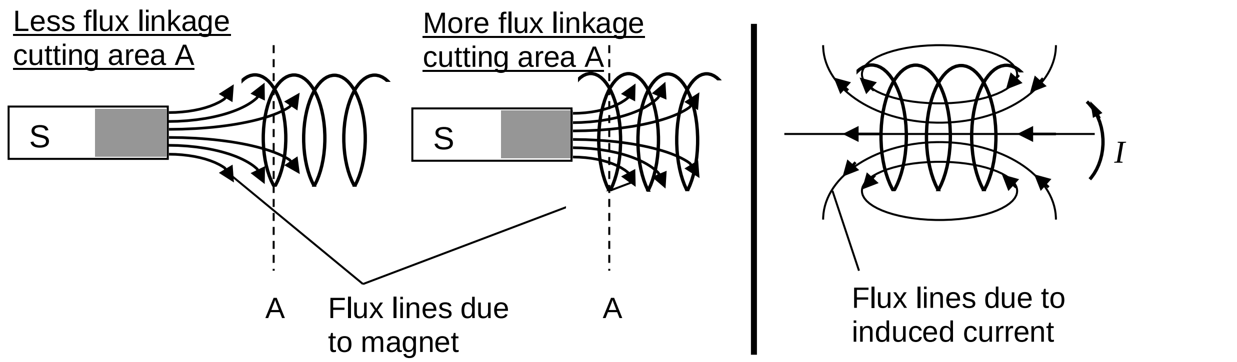
B.3 How to Answer Questions involving Direction of Induced Current/e.m.f.

1. **Determine object of concern.**
2. **State the CAUSE:**
   A. Increase/decrease/change in number of turns of coil
   B. Increase/decrease /change in magnetic flux density experienced by coil
   C. Increase/decrease/change in area of coil perpendicular to magnetic field
   D. Change in angle between magnetic flux density and normal to plane of coil
3. **State the EFFECT:**
   A. Increase/decrease/change in magnetic flux (linkage) (DIRECTION) experienced by coil
   B. **[Magnitude]** (By Faraday's Law): induces an emf in the coil and (if there is a closed circuit) hence an induced current.
   C. **[Direction]** (By Lenz's Law): the induced current flows in a direction (STATE DIRECTION) that will produce a flux to oppose the increase/ decrease.
4. **Effect on Total Mechanical Energy of Object (if applicable)**

Example 2

In the following figure, explain why the galvanometer registers a deflection, and account for its direction when the magnet approaches.





When the N-pole of the magnet is moved towards the coil, the magnetic flux density experienced by the coil ______, causing the magnetic flux linking the coil to ______

- By Faraday's Law, this ______ in flux linkage causes e.m.f. to be induced in the coil giving rise to an induced current in the coil.

- By Lenz's Law, the induced current flows from ______ to ______ through galvanometer (i.e. a deflection) to produce a flux to oppose the effect of this ______ in flux linkage.

Qualitative questions testing on applications of Faraday's and Lenz's laws are very common. Go through a few examples on your own to get comfortable with using them to explain situations of different contexts.

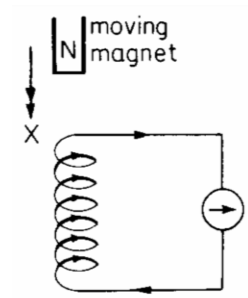
Note that the magnetic flux is from left to right in this case

Additional Notes

B.4 Lenz's Law and the Principle of Conservation of Energy

- An e.m.f. is a source of electrical energy and that energy must have come from somewhere.
- The e.m.f. produces effects which oppose the change.
- Consequently, work has to be done to overcome this opposition and energy is conserved.

Consider the figure on the right.



- When the magnet's North pole is moved towards the solenoid, a North pole is induced at end X of the coil
- Positive work has to be done to move the magnet against the force of repulsion between the North pole of the magnet and the induced North pole at X.
- The mechanical work done is converted to electrical energy of the current.
- This is consistent with the principle of conservation of energy.

To appreciate the opposing force, see that each end of the solenoid acts as a north/ south pole. This results in either a repulsive/ attractive force between the solenoid and magnet.

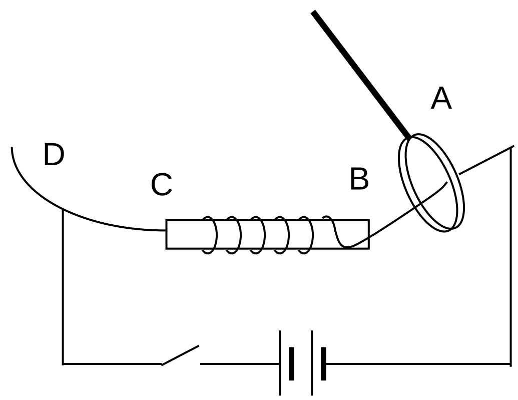
If Lenz's Law is not obeyed, i.e. if a pole is induced in the coil such that it reinforced the change causing it:

- The moving magnet then experiences an attractive force.
- No work needs to be done by the external agent in moving the magnet towards the coil.
- The magnet accelerates and gains kinetic energy as it approaches the coil. This results in larger change in flux linkage and hence a larger induced current. The attractive force thus becomes stronger.
- Energy of the system will continue to increase on its own accord – energy is created, violating the principle of conservation of energy.
- Conclusion: the induced pole in the coil cannot reinforce the change causing it.

Additional Notes

Worked Example

The metal ring is free to oscillate through the electromagnet when the switch is open. What happens when the switch is closed?



- As the ring approaches B, the magnetic flux linking the ring increases due to increases in magnetic flux density. By Faraday's Law, this increase in flux linkage causes e.m.f. to be induced in the ring giving rise to an induced current in the ring.

- By Lenz's Law, the induced current in the ring flows in a direction that will produce a flux to oppose the increase. This causes the ring to lose mechanical energy as it approaches B.

- As the ring passes from B to C, there is minimal change in the magnetic flux linkage (except at the ends). Hence, there is no significant loss in mechanical energy.

- As the ring leaves C, the decrease in flux linkage causes e.m.f. and current to be induced in the ring in the opposite direction from previously. This causes the ring to similarly lose mechanical energy as it leaves C.

- Since current is induced in the ring, it implies that part of the total mechanical energy of the ring is converted into electrical energy (and subsequently thermal energy) in the ring. The process continues until all the initial total mechanical energy of the ring decreases to zero, i.e. the ring comes to a rest.

Note: Losing energy in this case does not necessarily imply slowing down because object is converting potential energy to kinetic energy and electrical energy.

C Induced e.m.f. in a straight conductor

- Consider a straight conductor CD of length l moving with a velocity v at right angles to a uniform magnetic field B.

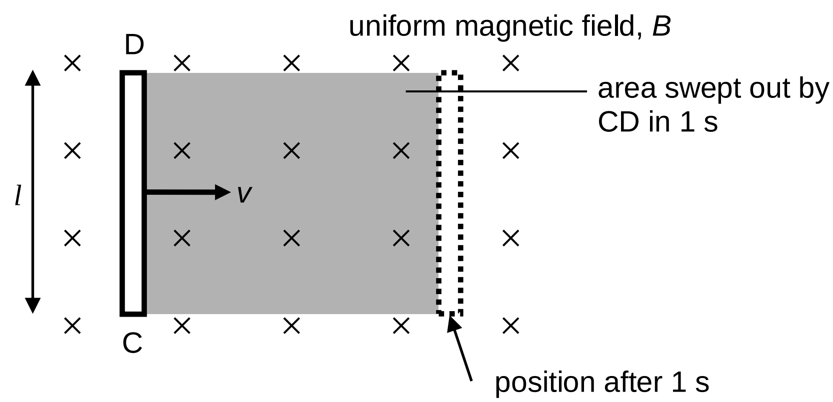


Fig. 17.5

- Using Faraday's Law,
  Area swept out by CD in 1 s, $\Delta A = lv$
  Flux cut by CD in 1 s, $\phi = B\Delta A = Blv$
  Induced e.m.f. E across CD = rate of flux being cut = Blv

  In general, $E = Blv$

Note that earlier on, Right Hand Grip Rule has been introduced to determine direction of induced current in a coil.

- The direction of the induced e.m.f. can be determined by:

C.1 Fleming's Right Hand Rule (see Appendix 1 for microscopic explanation)

See Appendix 2 for alternate method of derivation.

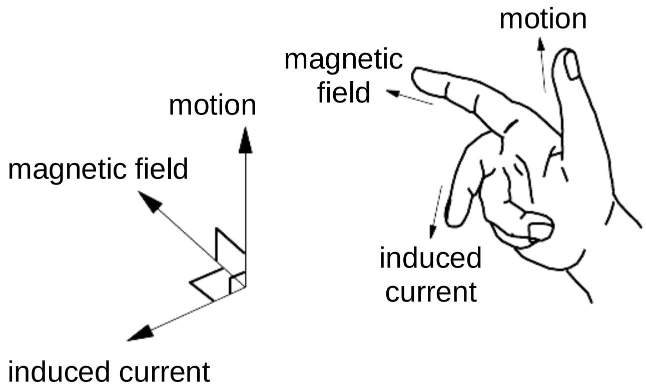


Fig. 17.6

- The flux-cutting conductor CD shown in Fig. 17.5 acts like a source of e.m.f. which is capable of driving a current through an external circuit outside the field connected across its ends.

Additional Notes

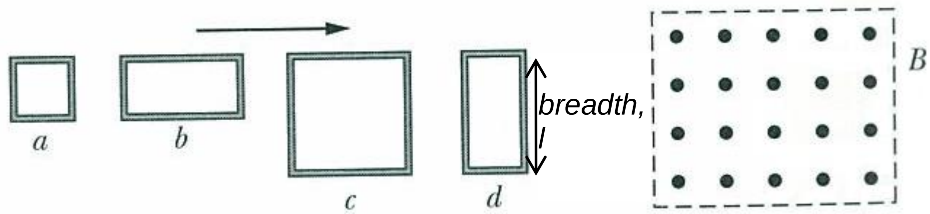
- Using Fleming's Right Hand Rule, a current will flow from C to D in the conductor.

- Important note: since the conductor CD functions like a source of e.m.f., D is at a higher potential than C.

- Note that the components of B, l and v are perpendicular to one another, i.e. $B \perp l$, $B \perp v$ and $l \perp v$.

Check Your Understanding 4

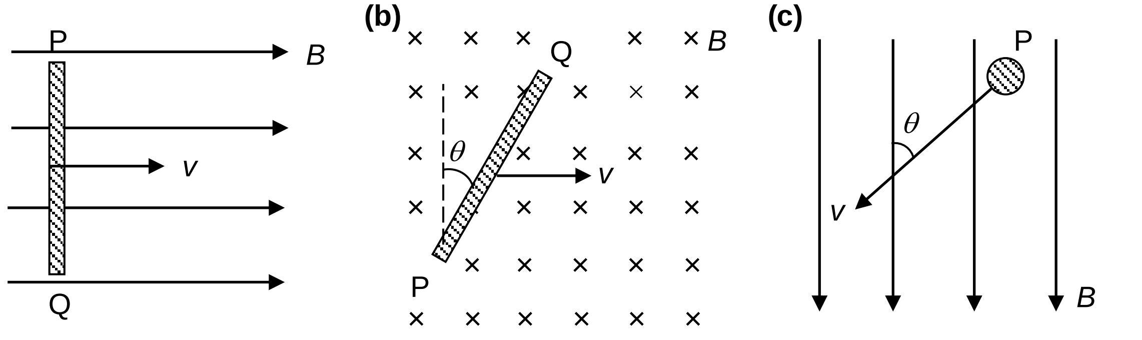
The figure shows four wire loops, with edge lengths of either L or $2L$. All four loops will move through a region of uniform magnetic field B (directed out of the page) at the same constant velocity. Rank the four loops according to the maximum magnitude of the e.m.f. induced as they move through the field, greatest first.



Example 3

A straight conductor PQ of length l moves with velocity v in a uniform magnetic field of magnetic flux density B.

(a) **(b)** **(c)**



(cross section of conductor is shown here. End P is nearer to the reader while end Q is further away from the reader)

For each of the cases,

(i) determine the magnitude of the induced e.m.f.,

(ii) state which end is at a higher potential, where applicable.

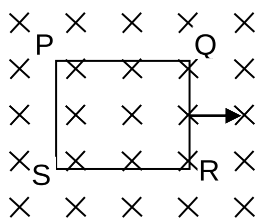
Additional Notes

Worked Example

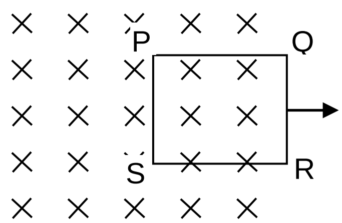
(Determination of current direction using both Right Hand Grip Rule and Fleming's Right Hand Rule)

A rectangular coil PQRS is pulled with constant speed across a uniform magnetic field with the field lines perpendicular to the plane of the coil. In each of the positions (a) and (b), determine the direction of the induced current in the coil.

(a)



(b)



Position (a)

- Using Lenz's Law and Right Hand Grip Rule

  Since there is no change in flux through the coil as it moves to the right (same area exposed to constant *B* field), net e.m.f. is zero.

- Using Fleming's Right Hand Rule
  - Sides PQ and RS do not cut the field lines, hence no e.m.f. is induced in them.
  - Sides PS and QR cut across the field lines, so that equal and opposite e.m.f. is induced in them. (Q higher potential than R and P higher potential than S)
  - The net e.m.f. in the coil is zero.

Position (b)

- Using Lenz's Law and Right Hand Grip Rule

  Since there is a decrease in flux through the coil as it moves to the right, the induced current flows clockwise to produce magnetic flux to prevent the decrease in flux into the page passing through the coil. (i.e. induced current produces magnetic field into the page)

- Using Fleming's Right Hand Rule
  - Sides PQ and SR do not cut the field lines, hence no e.m.f. is induced in them.
  - Side QR does not cut across any field line. Hence no e.m.f. is induced in it.
  - Side PS cuts across the field lines. Hence an e.m.f. (such that induced current will flow from S to P with P at a higher potential) is induced in it.
  - Since the coil is closed, a clockwise current flows in the loop.

D Applications of electromagnetic induction

(1) Faraday's Disc

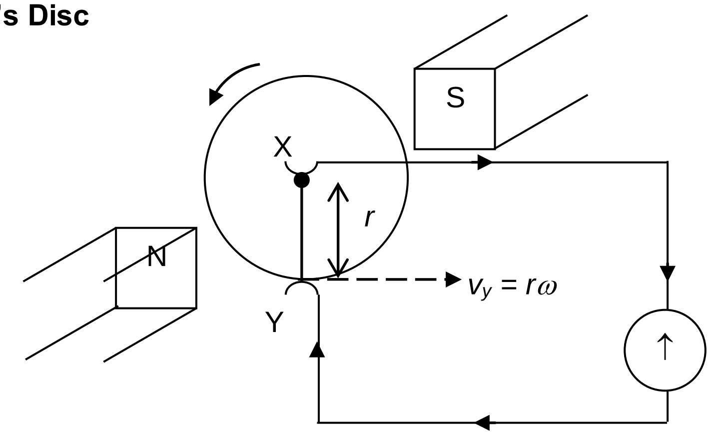


Fig. 17.7

- The components:
  - Copper disc of radius *r*, which rotates with a constant frequency *f*.
  - 2 magnetic poles which produce the magnetic flux, *B*.
  - External circuit connecting axle X to the rim Y.

- Derivation of induced e.m.f. *E* across XY:

$$E = -\frac{dN\phi}{dt}$$

$$|E| = \frac{d}{dt}(BA) \quad \text{since } N = 1\text{, and } B \text{ is already} \perp A$$

$$= B\frac{dA}{dt} \quad \text{since } B = \text{constant}$$

$$= B\frac{\pi r^2}{T}$$

$$\therefore \boxed{|E| = B\pi r^2 f}$$

- Alternative derivation of induced e.m.f. *E* across XY:

$$E = -\frac{dN\phi}{dt} = Blv$$

$$|E| = Brv_{ave} \quad \text{since } v \text{ varies along the length of the radius}$$

$$= Br\frac{(0 + r\omega)}{2} \quad \text{since } v_{centre} = 0 \text{ and } v_{rim} = r\omega$$

$$= \frac{1}{2}Br^2\omega$$

$$= \frac{1}{2}Br^2(2\pi f)$$

$$\therefore |E| = B\pi r^2 f$$

Additional Notes

(2) A.C. Generator

- Consider a coil of N turns and area A rotating with uniform angular velocity ω in a uniform magnetic field of flux density B. At a certain instant, the normal to the plane of the coil make an angle θ with the direction of the magnetic field as shown in Fig. 17.8(a).

- The variations of magnetic flux linkage Nϕ with time, and the induced e.m.f. E with time are shown in Fig. 17.8(b).

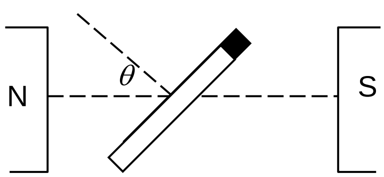


Fig. 17.8a

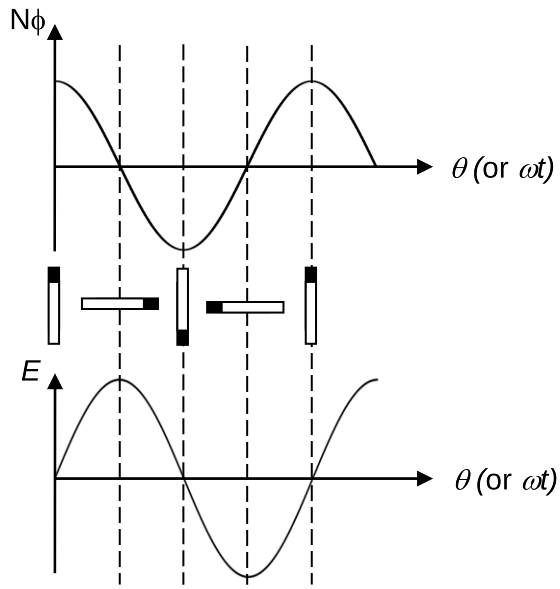


Fig. 17.8b

E can be obtained from the negative gradient of $N\phi$ - t graph.

- Induced e.m.f. $E = -\dfrac{d(NBA\cos\omega t)}{dt}$

$$= -NBA\frac{d(\cos\omega t)}{dt}$$

$$\therefore \boxed{E = \omega NBA\sin(\omega t)}$$

(3) Induction stove

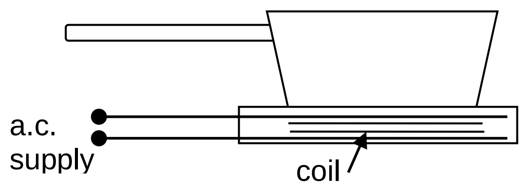


Fig. 17.9

- An alternating current flows through a conducting coil which lies below the cooking surface.
- The changing magnetic field produced in turn induces currents in the base of the conducting cooking pan.
- The electrical energy dissipated due to these induced currents is converted into thermal energy to cook the food.

These induced currents are known as <u>eddy currents</u>.

See Appendix 3 for further explanation.

(4) Electromagnetic brakes in cars

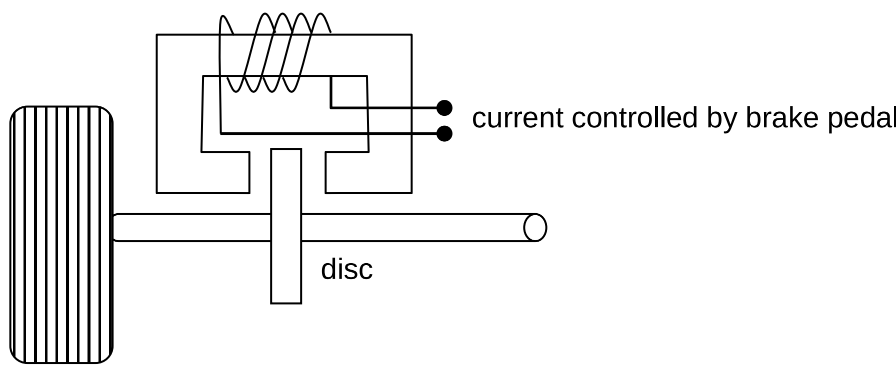
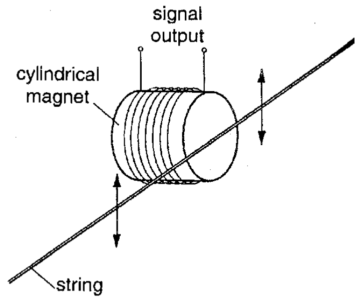


Fig. 17.10

- A conducting braking disc is fixed to the axle of the wheel.
- Part of the braking disc is placed between the poles of an electromagnet.
- As the disc rotates, every radial segment of the disc continuously cuts the magnetic flux, causing induced eddy currents within it.
- These induced currents create a magnetic force which opposes the turning motion of the disc, and hence opposing the turning motion of the wheel too.
- The extent of braking effect can be controlled by adjusting the magnitude of current via the brake pedal.

Additional Notes

(5) Electric Guitar

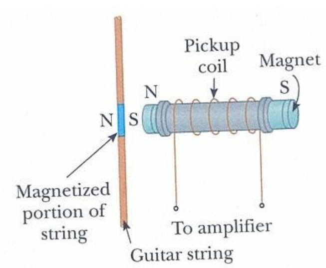


The pick-up on an electric guitar produces an electrical signal from the vibrations of the guitar strings. The pick-up consists of a small coil of insulated wire wound round a small cylindrical bar magnet as shown.

The strings of the guitar are made of steel. When a string vibrates, an electrical signal is generated between the terminals of the coil.

Steel is a magnetic material and steel guitar strings can be magnetized. A permanent magnet inside the pickup coil magnetizes the portion of the string nearest the coil.

How it Works: The magnetic field of the magnet produces a north and south pole in the section of the steel string just above the magnet. That section then has its own magnetic field. When the string is plucked and thus made to oscillate, its motion relative to the coil changes the flux linkage through the coil, this would cause an emf to be induced in the coil.

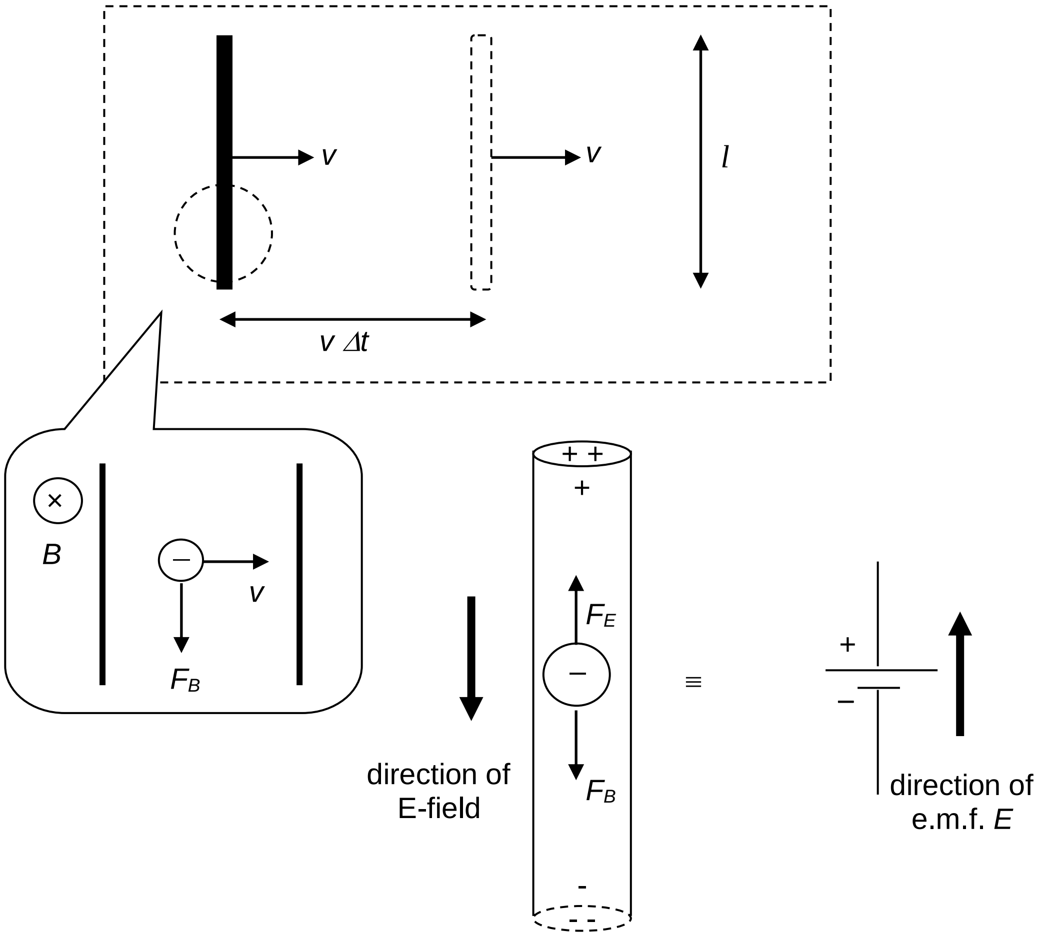


Amplification of signal: The electrical signal which is generated must be amplified before connection to a loudspeaker. This is because the magnetic field due to the string is weak and the flux linking the coil is small. The rate of change of flux linkage is very small and so the magnitude of the induced e.m.f. will be very small. Hence the signal (the induced e.m.f.) must be amplified before connecting to a loudspeaker.

(YouTube Video: How Electric Guitar Works)

Appendix 1

Flow of electrons in a straight conductor moving in a uniform magnetic field



Suppose we have a straight conductor of length l placed in magnetic field of flux density B. If the conductor moves at velocity v at right angles to the field, then the electrons in it will also be moving at velocity v at right angles to the field. By Fleming's Left Hand Rule, each electron will experience a magnetic force, forcing it to migrate to the lower end of the conductor.

The movement of the electrons results in an accumulation of negative charges at one end (bottom) and positive charges at the other end (upper). This produces an electric field E along the rod, which resists the downward migration of the electrons.

The electrons will stop piling up when the forces on each electron due to the E-field and B-field are balanced (i.e. $F_B = F_E$). An e.m.f. E is eventually induced between the ends of the conductor. This can also be used to explain Hall effect.

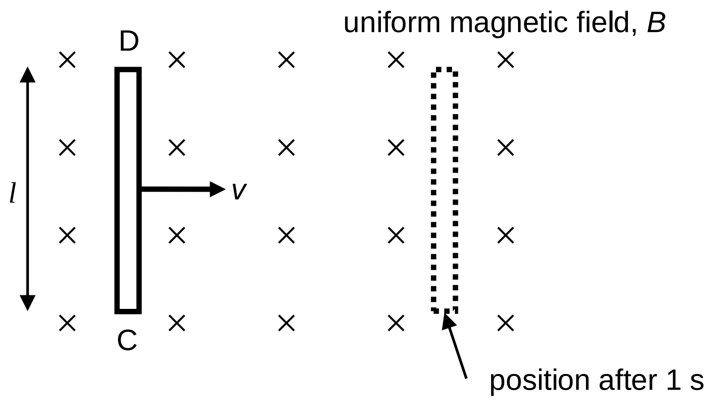
(Theory: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/hall.html)
(Simulation: https://www.youtube.com/watch?v=poqe8Vn5AiQ)

Additional Notes

Appendix 2

Induced e.m.f. in a straight conductor
Alternative method of derivation (using conservation of energy)

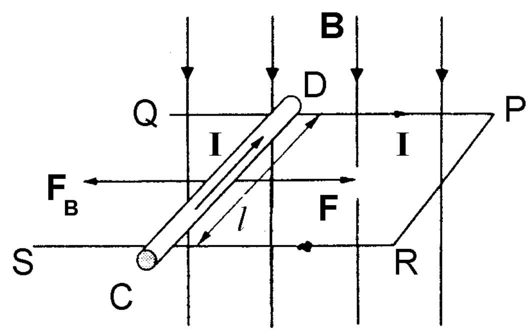
Consider a straight conductor of length l moving with a velocity v at right angles to a uniform magnetic field B.



Consider CD being pulled by an external agent with a force F along the metal rails PQ and RS at a steady velocity v across the B field.

CD cuts the magnetic flux and causes a change of flux linkage in the area PRCD.

An e.m.f. is induced in the circuit. The induced e.m.f. will drive a current clockwise (by Fleming's Right Hand Rule) in the circuit.



This induced current in turn causes a magnetic force F_B to act (to the left by Fleming's Left Hand Rule) on the conductor opposing F.

When the conductor CD moves with uniform velocity v, we have
$F = F_B = BIl$

By the law of conservation of energy,

rate of work done by external agent = rate at which electrical energy is generated

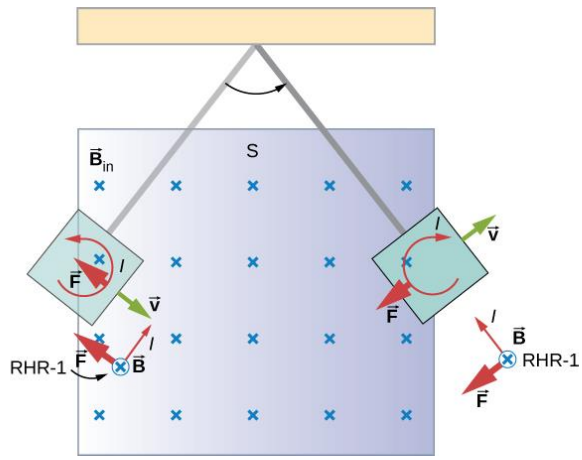
$$BIlv = EI$$

Hence, $$E = Blv$$

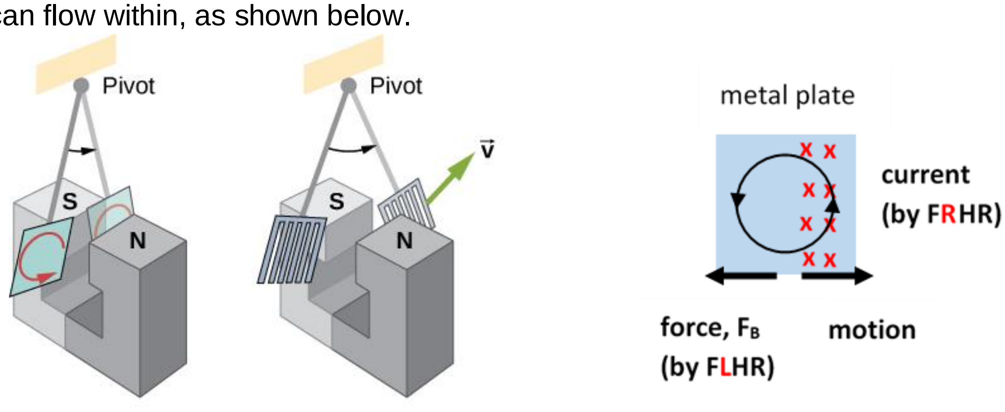
Appendix 3

Eddy currents

- Eddy currents are induced currents.
- Eddy currents refer to loops of currents induced within large bodies of conductors as a result of a changing magnetic field across the conductors.
- In the figure below, as a conducting plate enters and leaves the field, the change in flux produces an eddy current in the plate. Hence, a magnetic force – due to the current loop and magnetic field – is produced which opposes the motion.
- There is no current and no magnetic force when the plate is completely inside the uniform field.



- The effects of eddy current can be reduced by reducing the area where eddy current can flow within, as shown below.



(a) (b) (c)

(a) The motion of a metal (conducting) plate between the poles of a magnet is quickly damped by the action of eddy currents.
(b) There is little effect on the motion of a slotted metal plate, implying that eddy currents are made less effective.
(c) The flow of eddy current when the plate in (a) is **just** between the poles is such that it produces an electromagnetic force F_B which opposes the motion.
What will happen when the plate starts to leave the poles?

Additional Notes

Key Formulae

Term	Equation	Where
Magnetic flux, ϕ	$\phi = B_{\perp}A = (B\cos\theta)A$	$B_{\perp}$ = component of B perpendicular to the plane of the loop (T) A = area of the loop cut by B (m^2) θ = angle enclosed by B and A
Magnetic flux linkage, $N\phi$	$N\phi = NB_{\perp}A = N(B\cos\theta)A$	$B_{\perp}$ = component of B perpendicular to the plane of the loop (T) A = area of the loop cut by B (m^2) θ = angle enclosed by B and A N = number of turns of coil
Faraday's Law	$E \propto \dfrac{d(N\phi)}{dt}$	E = induced e.m.f.(V) N = number of turns of coil ϕ = magnetic flux (T)
Induced e.m.f. in a straight conductor, E	$E = Blv$	E = induced e.m.f.(V) B = magnetic flux density (T) l = length of conductor v = component of velocity of straight conductor perpendicular to B-field ($m\ s^{-1}$)

Glossary

Magnetic flux	Magnetic flux is the product of an area and the component of the magnetic flux density perpendicular to that area.
Magnetic flux linkage	Magnetic flux linkage in a coil is the product of the area of the coil and the component of the magnetic flux density perpendicular to that area, and the number of turns in the coil.
Faraday's Law	**Faraday's Law** of Electromagnetic Induction states that the e.m.f. induced in a conductor is proportional to the rate of change of magnetic flux linkage (or rate of cutting of the flux).
Lenz's Law	**Lenz's Law** states that the direction of the induced e.m.f. is such that it tends to produce effects to oppose the change causing it.

Solutions to Examples

Example 1

(a) For $0 < t < 10$ s and $15 \text{ s} < t < 25$ s,

$\phi = BA$

$= B(lx)$ where x is the length of coil in the magnetic field

⇨ $\phi \propto x$ since B, l const wrt t

Since $x \propto t$ (v constant)

⇨ $\phi \propto t$

At $t = 10$ s,

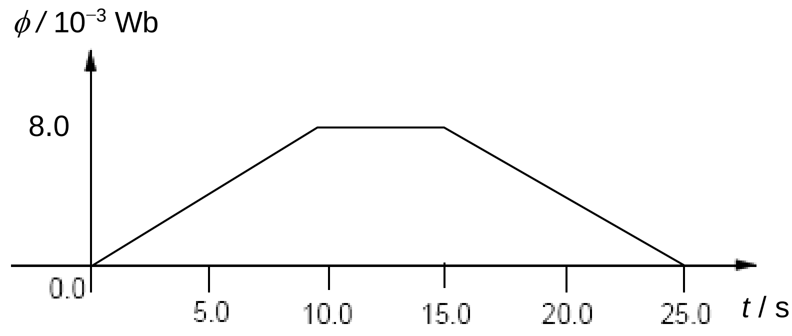
$\Phi_{max} = BA_{max}$

$= 2.0 \times 40 \times 10^{-3} \times 0.10$

$= 8.0 \times 10^{-3}$ Wb

For 10 s < t < 15 s,

ϕ remains constant at ϕ_{max}



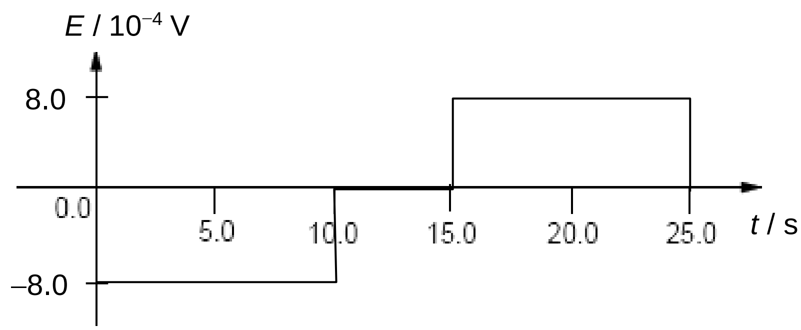
(b)

Since $E = -\dfrac{d\phi}{dt}$

$|E_{max}| = \dfrac{\Delta\phi}{\Delta t}$

$= \dfrac{8.0 \times 10^{-3}}{10}$

$= 8.0 \times 10^{-4}$ V



Example 2

When the N-pole of the magnet is moved towards the coil, the magnetic flux density experienced by the coil increases, causing the magnetic flux linking the coil to increase.

- By Faraday's Law, this increase in flux linkage causes e.m.f. to be induced in the coil giving rise to an induced current in the coil.
- By Lenz's Law, the induced current flows from left to right through galvanometer (i.e. a deflection) to produce a flux to oppose the effect of this increase in flux linkage.

Example 3

(a)(i) There is no cutting of the B-field lines. Induced e.m.f. = 0.

(ii) Not applicable.

(b)(i) v is already perpendicular to B, but l is not.

$\therefore$ l must be resolved to determine the effective length.

Induced e.m.f. $E = B(l\cos\theta)v = Blv\cos\theta$

(ii) By Fleming's Right Hand Rule, induced current (if any) flows from P to Q. Hence Q is at a higher potential.

(c)(i) l is already perpendicular to B, but v is not => v must be resolved.

Induced e.m.f. $E = B(l\sin\theta)v = Blv\sin\theta$

(ii) By Fleming's Right Hand Rule, induced current (if any) flows from Q to P. Hence P is at a higher potential.