

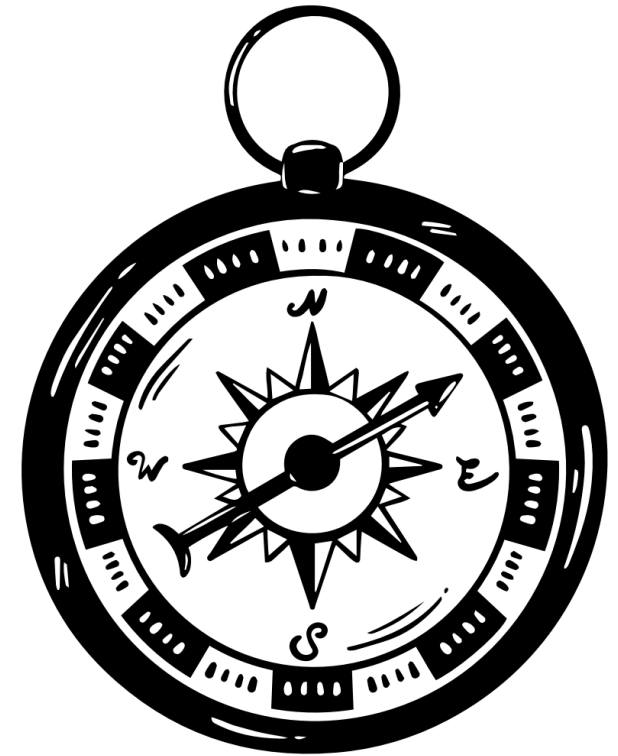


Chapter 9

Electromagnetic Induction

Revision Paper

9.1 FARADAY'S EXPERIMENTS 9.2 FARADAY'S LAW OF INDUCTION 9.3 LENZ'S LAW 9.4 GENERATORS AND MOTORS 9.5 INDUCED ELECTRIC FIELD 9.6 INDUCTANCE OF A SOLENOID 9.7 SELF-INDUCTION AND MUTUAL INDUCTION 9.8 RL CIRCUITS 9.9 ENERGY OF A MAGNETIC FIELD



Faraday's Law of Induction

Chapter 9
Lesson 2 – Revision Paper

9.2 – Faraday's Law of Induction

- A solenoid is an **electromagnet** that can be used to produce a constant magnetic field with a large volume.

The magnitude of the magnetic field inside an ideal solenoid is

$$\begin{aligned} \mathbf{B} &= \mu_0 \mathbf{n} i \\ &= \frac{\mu_0 \mathbf{N} i}{L} \end{aligned}$$

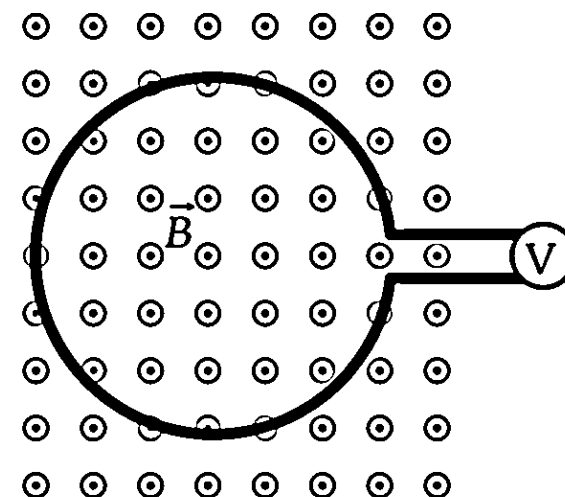
9.2 – Faraday's Law of Induction

$$\begin{aligned}\Phi_B &= BA \cos \theta \\ 1 \text{ Wb} &= 1 \text{ T m}^2 \\ \Delta V_{ind} &= -\frac{d\Phi_B}{dt} \\ &= -A \cos \theta \frac{dB}{dt} \\ &= -B \cos \theta \frac{dA}{dt} \\ &= \omega AB \sin \theta\end{aligned}$$

Self-Test Opportunity 9.1

01

The plane of the circular loop shown in the figure is perpendicular to a magnetic field with magnitude $B = 0.500 \text{ T}$. The magnetic field goes to zero at a constant rate in 0.250 s . The induced voltage in the loop is 1.24 V during that time. What is the radius of the loop?



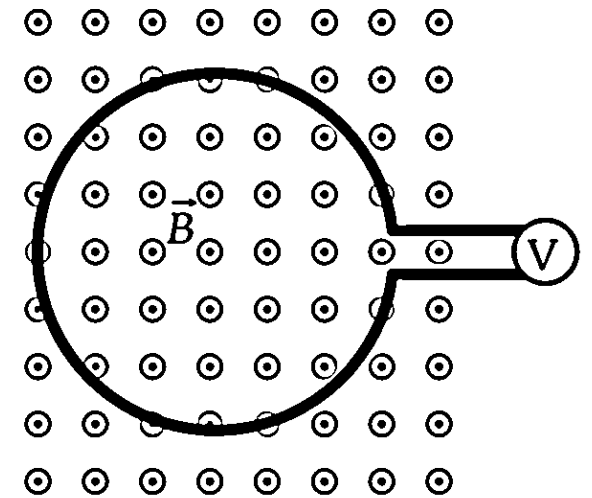
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$$\frac{dB}{dt} = - \frac{0.500 \text{ T}}{0.250 \text{ s}} = - 2.00 \text{ T/s}$$

$$\Delta V_{\text{ind}} = - \frac{d\Phi_B}{dt} = - \frac{d(BA)}{dt} = - \pi r^2 \frac{dB}{dt}$$

$$r = \sqrt{\frac{|\Delta V_{\text{ind}}|}{\pi |dB/dt|}} = \sqrt{\frac{1.24 \text{ V}}{\pi (2.00 \text{ T/s})}} = 0.444 \text{ m.}$$



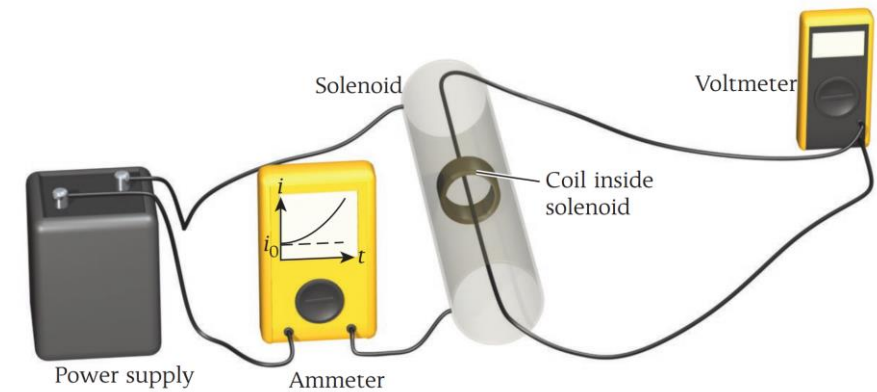
شرح السؤال



Example 9.1

02

A current of **600 mA** is flowing in an ideal solenoid, resulting in a magnetic field of **0.025 T** inside the solenoid. Then the current increases with time, t , according to $i(t) = i_0 \left[1 + (2.4 \text{ s}^{-2})t^2 \right]$. If a circular coil of radius **3.4 cm** with $N = 200$ windings is located inside the solenoid with its normal vector parallel to the magnetic field, what is the induced potential difference in the coil at $t = 2.0 \text{ s}$?



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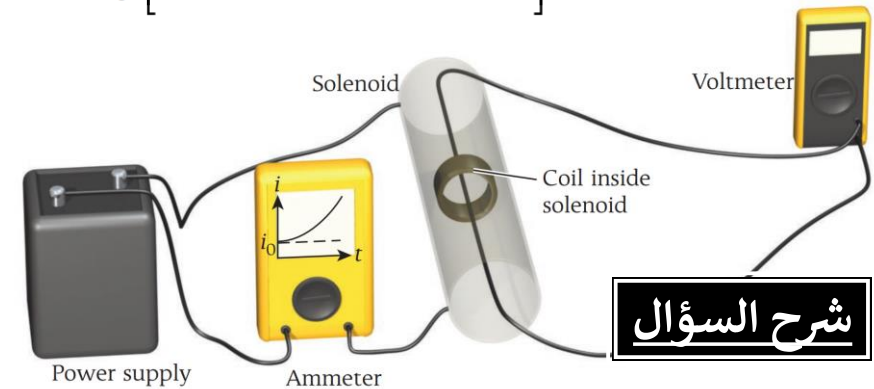
$$\begin{aligned}\Delta V_{\text{ind}} &= - A \cos \theta \frac{dB}{dt} \\ &= - A \cos \theta \frac{d}{dt} [B_0 (1 + (2.4 \text{ s}^{-2})t^2)] \\ &= - AB_0 \cos \theta (2(2.4 \text{ s}^{-2})t) \\ &= - (0.73 \text{ m}^2)(0.025 \text{ T})(\cos 0^\circ)(4.8 \text{ s}^{-2})t \\ &= (-0.088 \text{ V/s})t.\end{aligned}$$

At time $t = 2.0 \text{ s}$, the induced potential difference in the coil is $\Delta V_{\text{ind}} = -0.18 \text{ V}$.

$$A = N\pi R^2 = 200\pi(0.034 \text{ m})^2 = 0.73 \text{ m}^2.$$

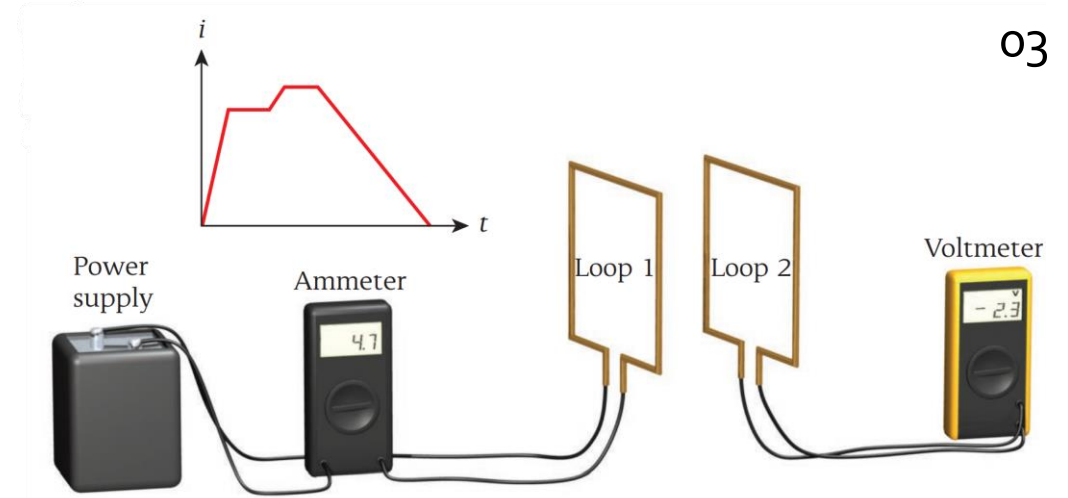
Because the magnetic field is proportional to the current, we immediately obtain for the time dependence of the magnetic field in this case

$$B(t) = B_0 [1 + (2.4 \text{ s}^{-2})t^2],$$

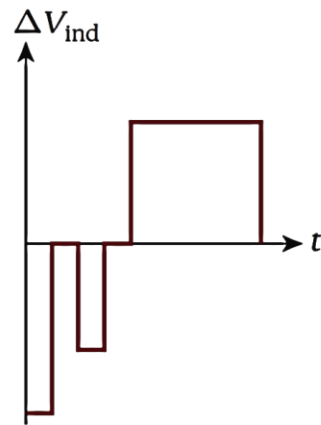


Concept Check 9.2

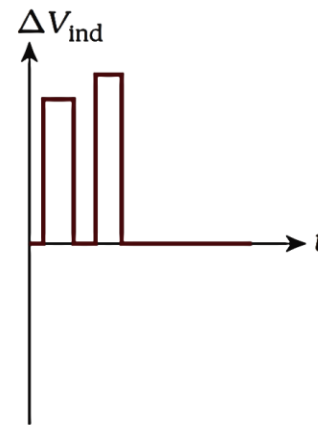
A power supply is connected to **loop 1** and an ammeter as shown in the figure. **Loop 2** is close to loop 1 and is connected to a **voltmeter**. A graph of the current i through loop 1 as a function of time, t , is also shown in the figure. Which graph best describes the induced potential difference, ΔV_{ind} , in loop 2 as a function of time, t ?



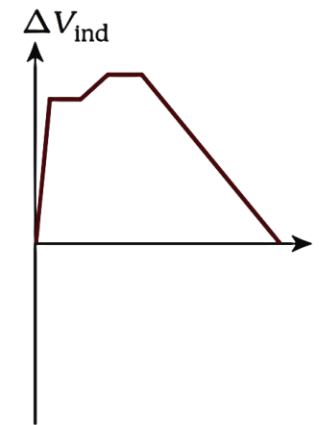
- a) graph 1
- b) graph 2
- c) graph 3
- d) graph 4



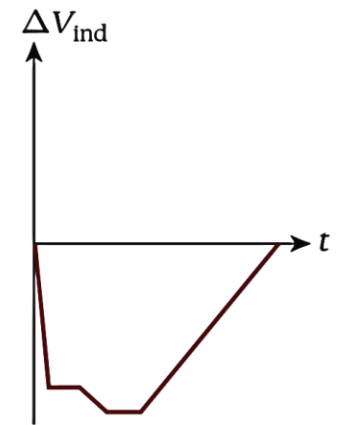
Graph 1



Graph 2



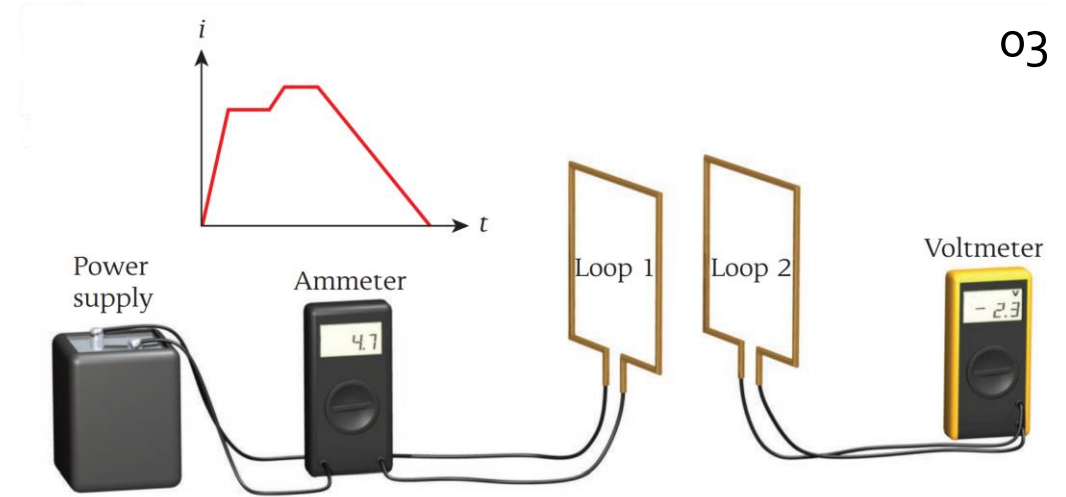
Graph 3



Graph 4

Concept Check 9.2

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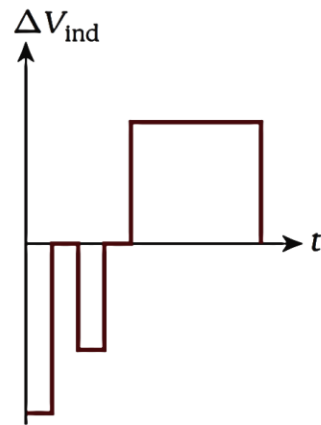


a) graph 1

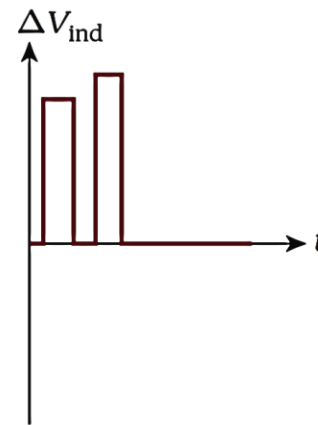
b) graph 2

c) graph 3

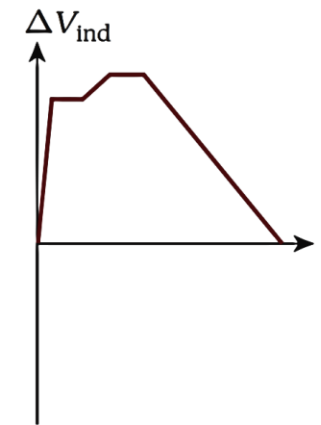
d) graph 4



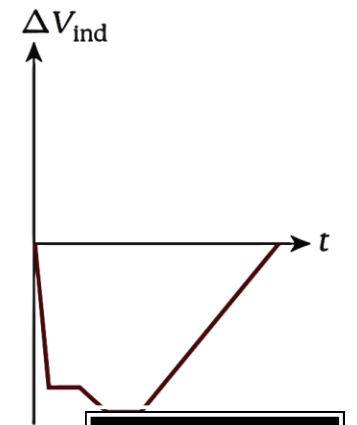
Graph 1



Graph 2



Graph 3

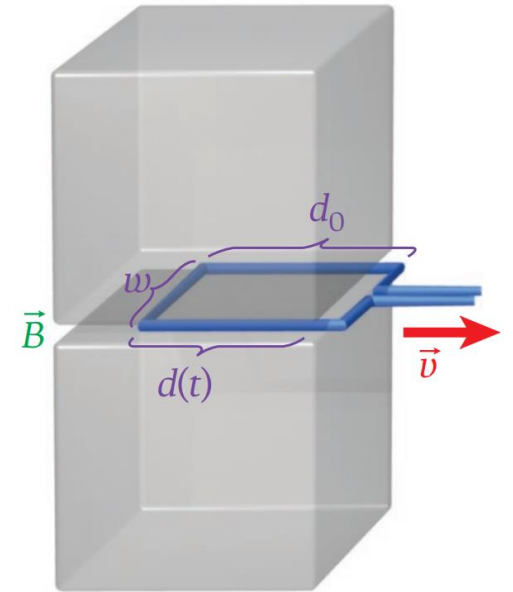


شرح السؤال

Example 9.2

04

A rectangular wire loop of width $w = 3.1 \text{ cm}$ and depth $d_0 = 4.8 \text{ cm}$ is pulled out of the gap between two permanent magnets. A magnetic field of magnitude $B = 0.073 \text{ T}$ is present throughout the gap. If the loop is removed at a constant speed of 1.6 cm/s , what is the induced voltage in the loop as a function of time?



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$$\Delta V_{\text{ind}} = -B \cos \theta \frac{dA}{dt}$$

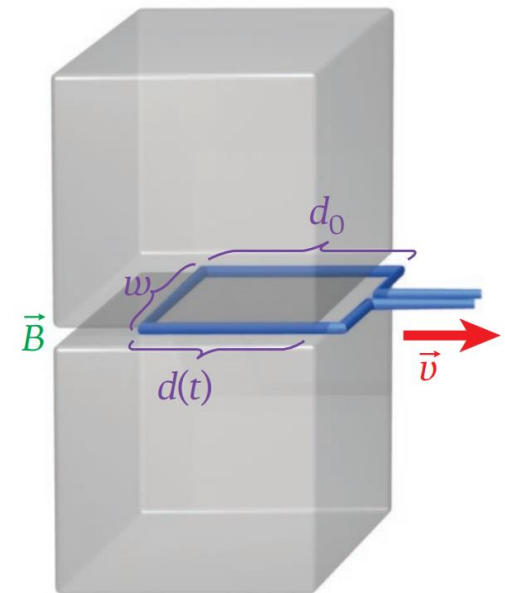
$$A(t) = (w)(d(t)) = w(d_0 - vt).$$

$$= -B \cos \theta \frac{d}{dt}[w(d_0 - vt)]$$

$$= wvB \cos \theta$$

$$= (0.031 \text{ m})(0.016 \text{ m/s})(0.073 \text{ T}) \cos 0^\circ$$

$$= 3.6 \times 10^{-5} \text{ V}.$$



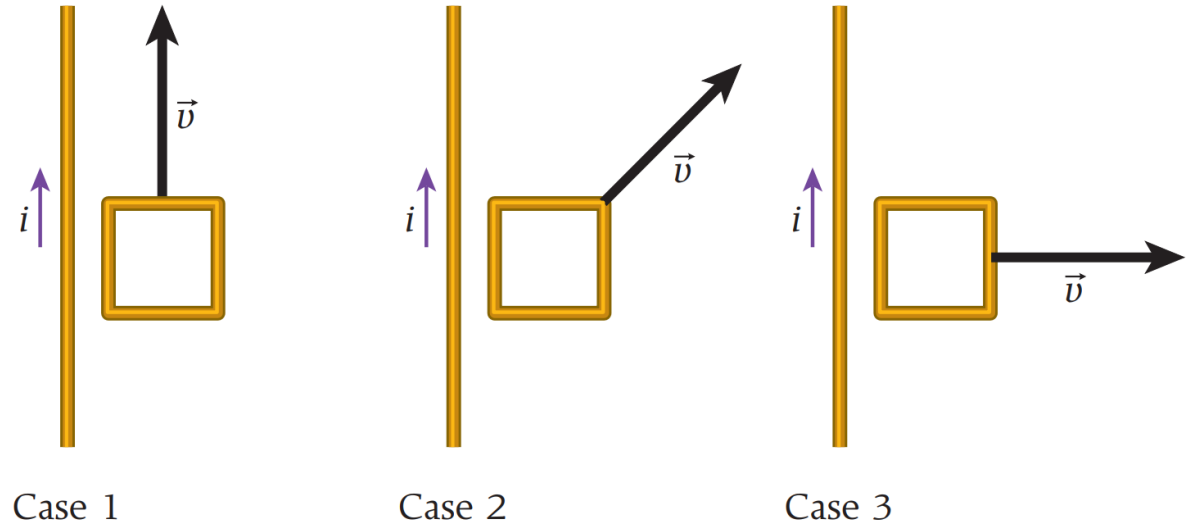
شرح السؤال

Concept Check 9.3

05

A long wire carries a current, i , as shown in the figure. A square loop moves in the same plane as the wire, as indicated. In which cases will the loop have an induced current?

- a) cases 1 and 2
- b) cases 1 and 3
- c) cases 2 and 3
- d) None of the loops will have an induced current.
- e) All of the loops will have an induced current.

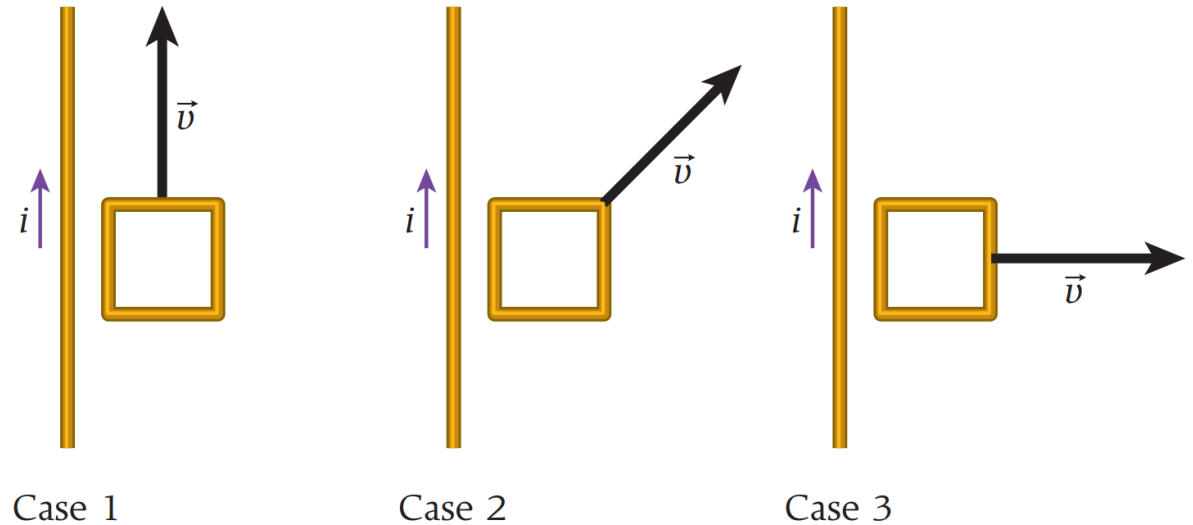


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- b) cases 1 and 3
- c) **cases 2 and 3**
- d) None of the loops will have an induced current.
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شرح السؤال



Multiple Choice Questions 9.1

A solenoid with **200 turns** and a cross-sectional area of **60 cm²** has a magnetic field of **0.60 T** along its axis. If the field is confined within the solenoid and changes at a rate of **0.20 T/s**, the magnitude of the induced potential difference in the solenoid will be

- a) 0.0020 V.
- b) 0.02 V.
- c) 0.001 V.
- d) 0.24 V.

Multiple Choice Questions 9.1

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d) 0.24 V.

$$\begin{aligned}
 \Delta V_{\text{ind}} &= -N \frac{d\Phi_B}{dt} \\
 &= -NA \cos \theta \frac{dB}{dt} \\
 &= -(200)(60 \times 10^{-4}) \cos 0 (0.2) \\
 &= -0.24
 \end{aligned}$$

شرح السؤال

Multiple Choice Questions 9.3

Which of the following will induce a current in a loop of wire in a uniform magnetic field?

- a) decreasing the strength of the field
- b) rotating the loop about an axis parallel to the field
- c) moving the loop within the field
- d) all of the above
- e) none of the above

Multiple Choice Questions 9.3

Which of the following will induce a current in a loop of wire in a uniform magnetic field?

- a) **decreasing the strength of the field**
- b) rotating the loop about an axis parallel to the field
- c) moving the loop within the field
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- e) none of the above

شرح السؤال

Multiple Choice Questions 9.4

Faraday's Law of Induction states that

- a) a potential difference is induced in a loop when there is a change in the magnetic flux through the loop.
- b) the current induced in a loop by a changing magnetic field produces a magnetic field that opposes this change in magnetic field.
- c) a changing magnetic field induces an electric field.
- d) the inductance of a device is a measure of its opposition to changes in current flowing through it.
- e) magnetic flux is the product of the average magnetic field and the area perpendicular to it that it penetrates.

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Multiple Choice Questions 9.8

09

You have a light bulb, a bar magnet, a spool of wire that you can cut into as many pieces as you want, and nothing else. How can you get the bulb to light up?

- a) You can't. The bulb needs electricity to light it, not magnetism.
- b) You cut a length of wire, connect the light bulb to the two ends of the wire, and pass the magnet through the loop that is formed.
- c) You cut two lengths of wire and connect the magnet and the bulb in series.

Multiple Choice Questions 9.8

09

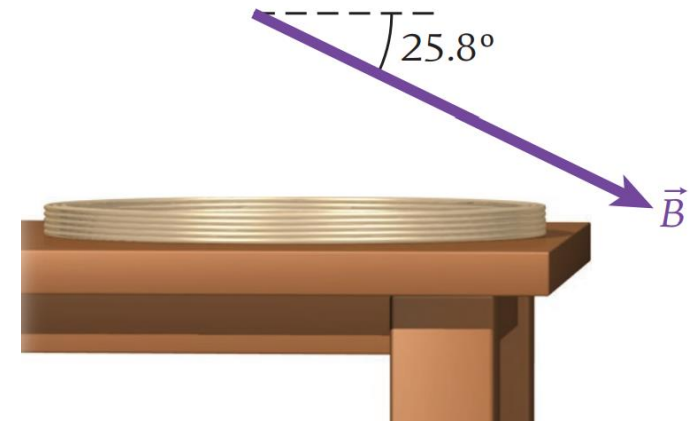
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Exercise 9.28

10

A circular coil of wire with **20 turns** and a radius of **40.0 cm** is laying flat on a horizontal tabletop as shown in the figure. There is a uniform magnetic field extending over the entire table with a magnitude of **5.00 T** and directed to the north and downward, making an angle of **25.8°** with the horizontal. What is the magnitude of the magnetic flux through the coil?

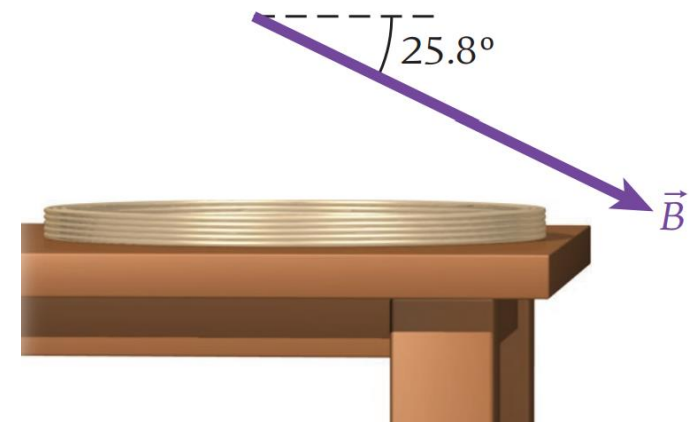


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$$\Phi = NBA \cos \theta = 20(5.00 \text{ T})\pi(0.400 \text{ m})^2 \cos(90^\circ - 25.8^\circ) = 21.9 \text{ T m}^2$$



شرح السؤال



Exercise 9.29

When a magnet in an MRI is abruptly shut down, the magnet is said to be quenched. Quenching can occur in as little as 20.0 s. Suppose a magnet with an initial field of **1.20 T** is quenched in **20.0 s**, and the final field is approximately **zero**. Under these conditions, what is the average induced potential difference around a conducting loop of radius **1.00 cm** (about the size of a wedding ring) oriented perpendicular to the field?

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The potential difference around the loop is:

$$V_{\text{emf}} = -\frac{d\Phi}{dt} \approx -\frac{\Delta\Phi}{\Delta t} = -\frac{\Delta(AB)}{\Delta t} = -A \frac{\Delta B}{\Delta t} = -\pi r^2 \frac{\Delta B}{\Delta t} = -\pi (0.0100 \text{ m})^2 \left(\frac{0 \text{ T} - 1.20 \text{ T}}{20.0 \text{ s}} \right) = 1.89 \cdot 10^{-5} \text{ V}.$$

Note that the area of the ring is perpendicular to the field. Thus, the normal of the area is parallel to the field and $\cos \theta = 1$.

شرح السؤال

Exercise 9.30

12

An **8-turn** coil has square loops measuring **0.200 m** along a side and a resistance of **3.00 Ω** . It is placed in a magnetic field that makes an angle of **40.0°** with the plane of each loop. The magnitude of this field varies with time according to **$B = 1.50t^3$** , where **t** is measured in seconds and **B** in teslas. What is the induced current in the coil at **$t = 2.00$ s**?

Exercise 9.30

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If the angle between the B -field and the plane of the loop is 40° , then the angle between the B -field and the normal to the loop is $90^\circ - 40^\circ = 50^\circ$, and so the voltage across the loop is given by:

$$V_{\text{ind}} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(NAB \cos \theta) = -NA \cos \theta \frac{dB}{dt} = -NA \cos \theta \frac{d(1.50t^3)}{dt} = -NL^2 (\cos 50.0^\circ) 4.50t^2.$$

The current induced if the loop has a resistance of $R = 3.00 \Omega$ is:

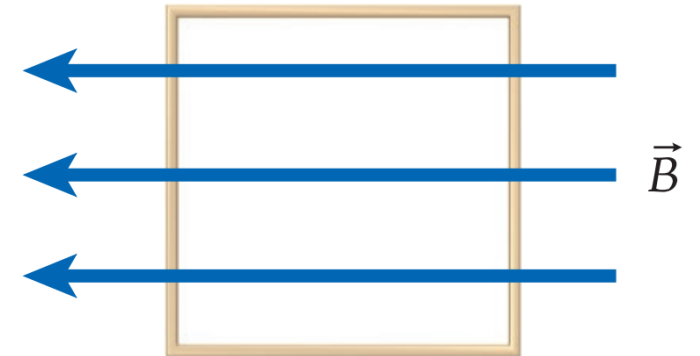
$$i = \frac{|V_{\text{ind}}|}{R} = \frac{NL^2 (\cos 50.0^\circ) 4.50t^2}{R} = \frac{(8)(0.200 \text{ m})^2 (\cos 50.0^\circ) 4.50(2.00 \text{ s})^2}{(3.00 \Omega)} = 1.23 \text{ A}.$$

شرح السؤال

Exercise 9.31

13

A metal loop has an area of **0.100 m²** and is placed flat on the ground. There is a uniform magnetic field pointing due west, as shown in the figure. This magnetic field initially has a magnitude of **0.123 T**, which decreases steadily to **0.075 T** during a period of **0.579 s**. Find the potential difference induced in the loop during this time.



Exercise 9.31

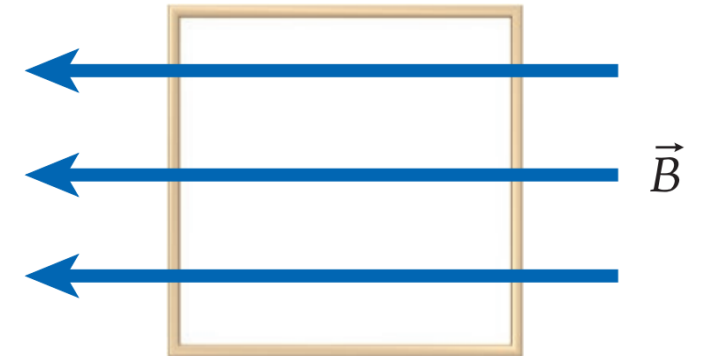
13

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Because the magnetic field is perpendicular to the normal of the loop, there is no flux through the loop:

$$\Phi = AB \cos 90^\circ = 0.$$

Since there is no flux through the loop, there is no induced voltage: $V = -\frac{d\Phi}{dt} = -\frac{d(0)}{dt} = 0.$



شرح السؤال



Exercise 9.32

14

A respiration monitor has a flexible loop of copper wire, which wraps about the chest. As the wearer breathes, the radius of the loop of wire increases and decreases. When a person in the Earth's magnetic field (assume $0.426 \times 10^{-4} \text{ T}$) inhales, what is the average current in the loop, assuming that it has a resistance of $30.0 \, \Omega$ and increases in radius from 20.0 cm to 25.0 cm over 1.00 s ? Assume that the magnetic field is perpendicular to the plane of the loop.

Exercise 9.32

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SIMPLIFY: The induced current in the loop is:

$$i = \frac{V_{\text{ind}}}{R} = \frac{1}{R} \left(-\frac{d\Phi_B}{dt} \right) = -\frac{1}{R} \left(\frac{dAB}{dt} \right) = -\frac{B}{R} \left(\frac{dA}{dt} \right) = -\frac{B}{R} \frac{d\pi r^2}{dt} = -\frac{B\pi}{R} \left(\frac{dr^2}{dt} \right) \approx -\frac{B\pi}{R} \left(\frac{r_f^2 - r_i^2}{\Delta t} \right).$$

CALCULATE:
$$i = -\frac{(4.26 \cdot 10^{-5} \text{ T})\pi}{30.0 \, \Omega} \left(\frac{(0.250 \text{ m})^2 - (0.200 \text{ m})^2}{1.00 \text{ s}} \right) = -1.00374 \cdot 10^{-7} \text{ A}$$

ROUND: The induced current in the loop is $i = -1.00 \cdot 10^{-7} \text{ A}$.

شرح السؤال

Lenz's Law

Chapter 9 Lesson 3 – Revision Paper

9.3 – Lenz's Law

- Lenz's Law states that a changing magnetic flux through a conducting loop **induces** a current in the loop that **opposes** the change in magnetic flux.

$$E = \frac{\Delta V_{\text{ind}}}{l} = vB$$

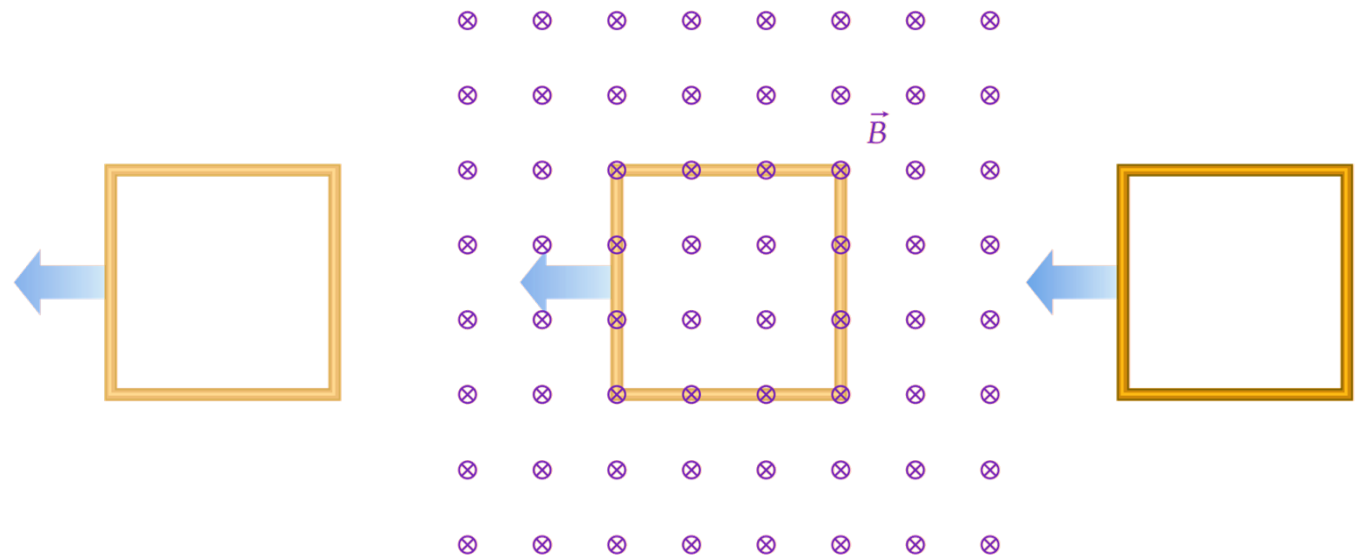
$$\Delta V_{\text{ind}} = lvB$$

$$\Delta V_{\text{ind}} = \frac{B\omega r^2}{2} = \frac{B\pi r^2}{T}$$

Self-Test Opportunity 9.2

01

A square conducting loop with very small resistance is moved at constant speed from a region with no magnetic field through a region of constant magnetic field and then into a region with no magnetic field, as shown in the figure. As the loop enters the magnetic field, what is the direction of the induced current? As the loop leaves the magnetic field, what is the direction of the induced current?

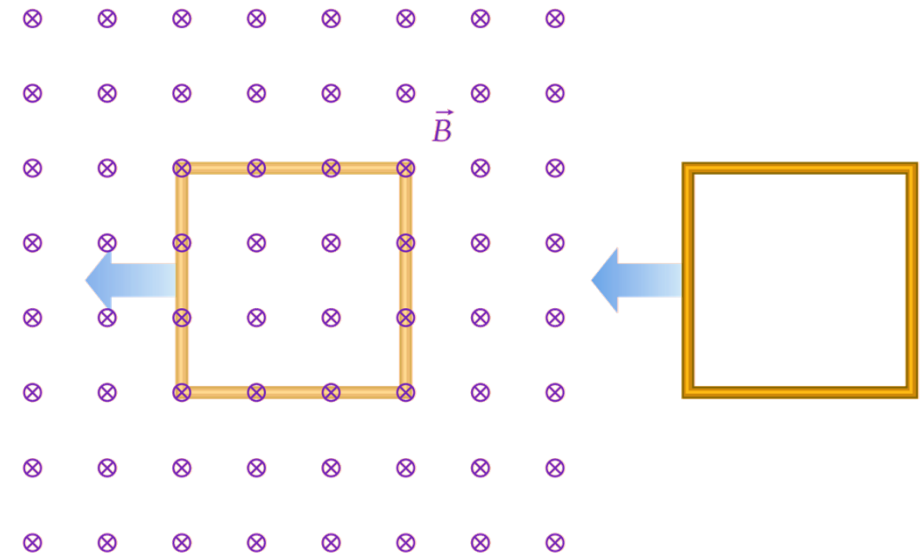


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*As the loop **enters** the magnetic field, the magnetic flux is **increasing**. The current induced in the loop will be in the **counterclockwise** direction to **oppose** the increase in the flux.*



*As the loop **exits** the magnetic field, the magnetic flux is **decreasing**. The current induced in the loop will be in a **clockwise** direction to **oppose** the decrease in the flux.*

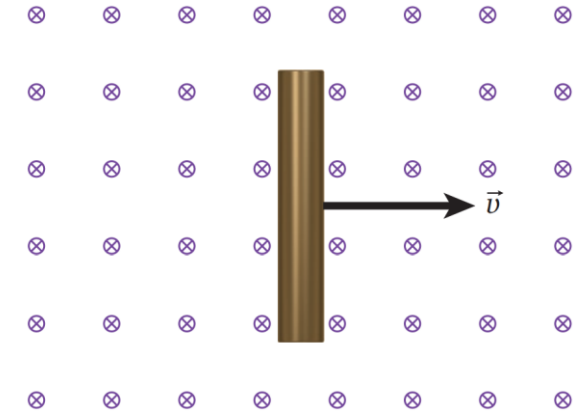
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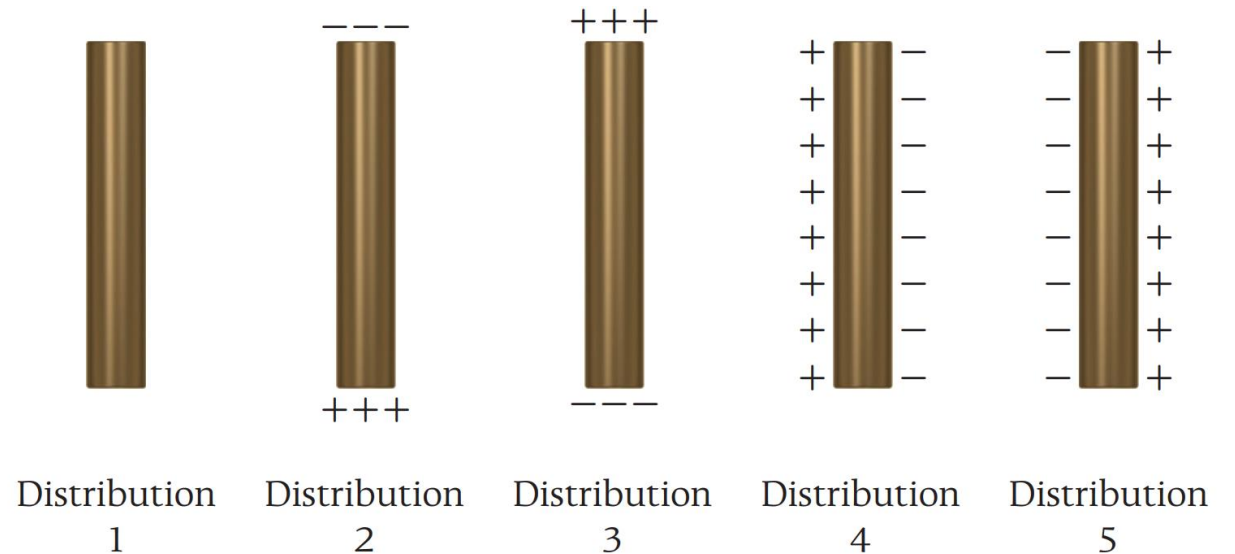
Concept Check 9.4

02

A metal bar is moving with constant velocity $\vec{v}$ through a uniform magnetic field pointing into the page, as shown in the figure. Which of the following most accurately represents the charge distribution on the surface of the metal bar?



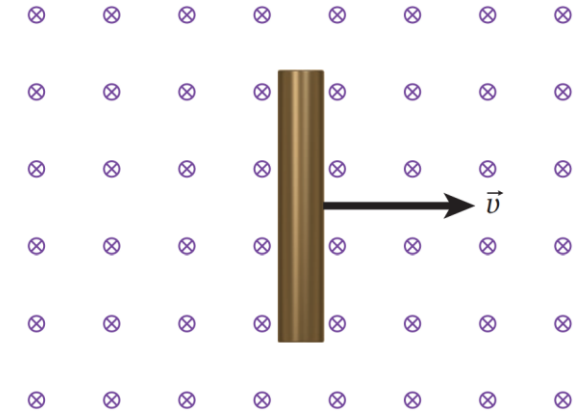
- a) distribution 1
- b) distribution 2
- c) distribution 3
- d) distribution 4
- e) distribution 5



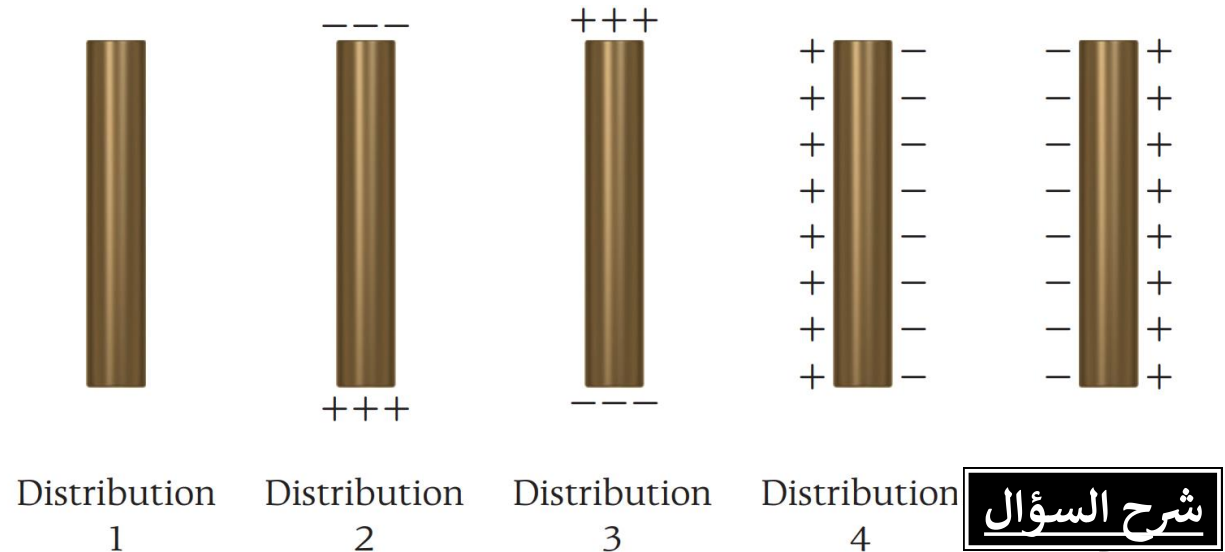
Concept Check 9.4

02

A metal bar is moving with constant velocity $\vec{v}$ through a uniform magnetic field pointing into the page, as shown in the figure. Which of the following most accurately represents the charge distribution on the surface of the metal bar?



- a) distribution 1
- b) distribution 2
- c) **distribution 3**
- d) distribution 4
- e) distribution 5



Example 9.3

In 1996, the Space Shuttle Columbia deployed a tethered satellite on a wire out to a distance of **20. km**. The wire was oriented perpendicular to the Earth's magnetic field at that point, and the magnitude of the field was $\mathbf{B} = 5.1 \times 10^{-5} \text{ T}$. Columbia was traveling at a speed of **7.6 km/s**. What was the potential difference induced between the ends of the wire?

Example 9.3

In 1996, the Space Shuttle Columbia deployed a tethered satellite on a wire out to a distance of **20. km**. The wire was oriented perpendicular to the Earth's magnetic field at that point, and the magnitude of the field was **$B = 5.1 \times 10^{-5} \text{ T}$** . Columbia was traveling at a speed of **7.6 km/s**. What was the potential difference induced between the ends of the wire?

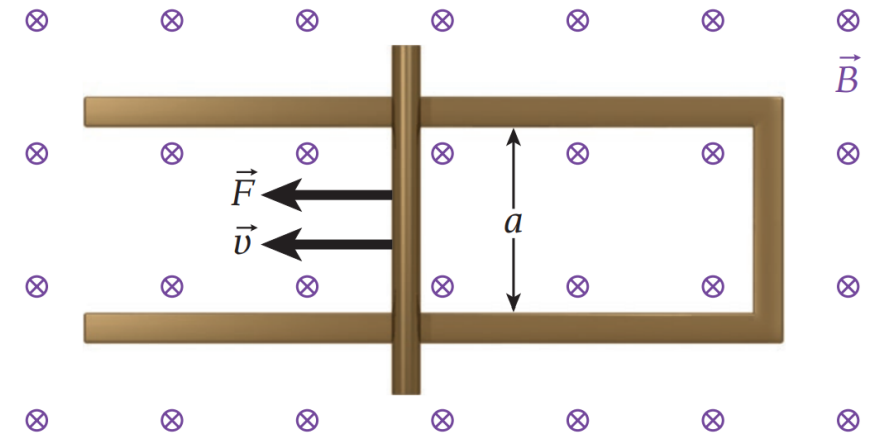
$$\Delta V_{\text{ind}} = vLB = (7.6 \times 10^3 \text{ m/s})(20.0 \times 10^3 \text{ m})(5.1 \times 10^{-5} \text{ T}) = 7.8 \text{ kV.}$$

شرح السؤال

Example 9.4

04

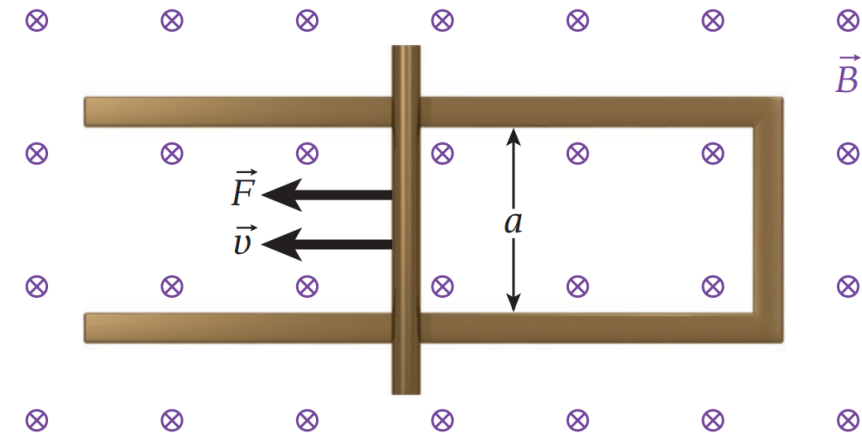
A conducting rod is pulled horizontally by a constant force of magnitude, $F = 5.00 \text{ N}$, along a set of conducting rails separated by a distance $a = 0.500 \text{ m}$. The two rails are connected, and no friction occurs between the rod and the rails. A uniform magnetic field with magnitude $B = 0.500 \text{ T}$ is directed into the page. The rod moves at constant speed, $v = 5.00 \text{ m/s}$. What is the magnitude of the induced potential difference in the loop formed by the connected rails and the moving rod?



Example 9.4

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$$\begin{aligned}\Delta V_{ind} &= lvB \\ &= (0.5)(5)(0.5) \\ &= \mathbf{1.25 \text{ V}}\end{aligned}$$



شرح السؤال

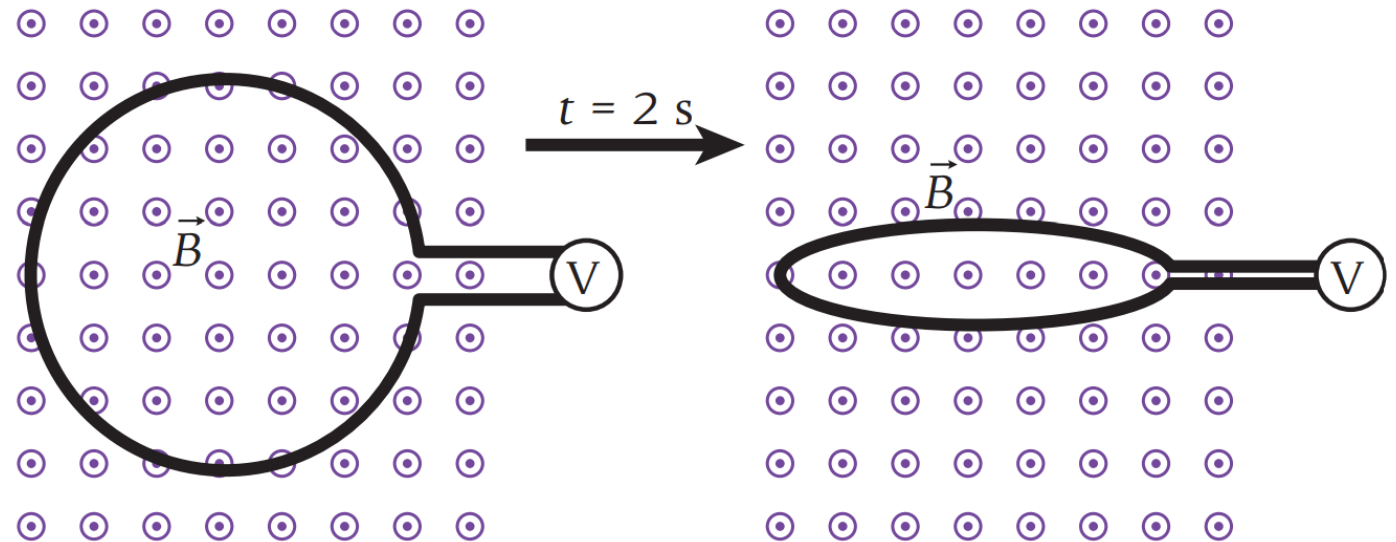


Concept Check 9.5

05

A wire loop is placed in a uniform magnetic field. Over a period of **2 s**, the loop is shrunk. Which statement about the induced potential difference is correct?

- a) There will be some induced potential difference.
- b) There will be no induced potential difference because the loop changes size along one axis and not the other.
- c) There will be no induced potential difference because the loop is not closed.
- d) There will be no induced potential difference because the loop is shrinking.

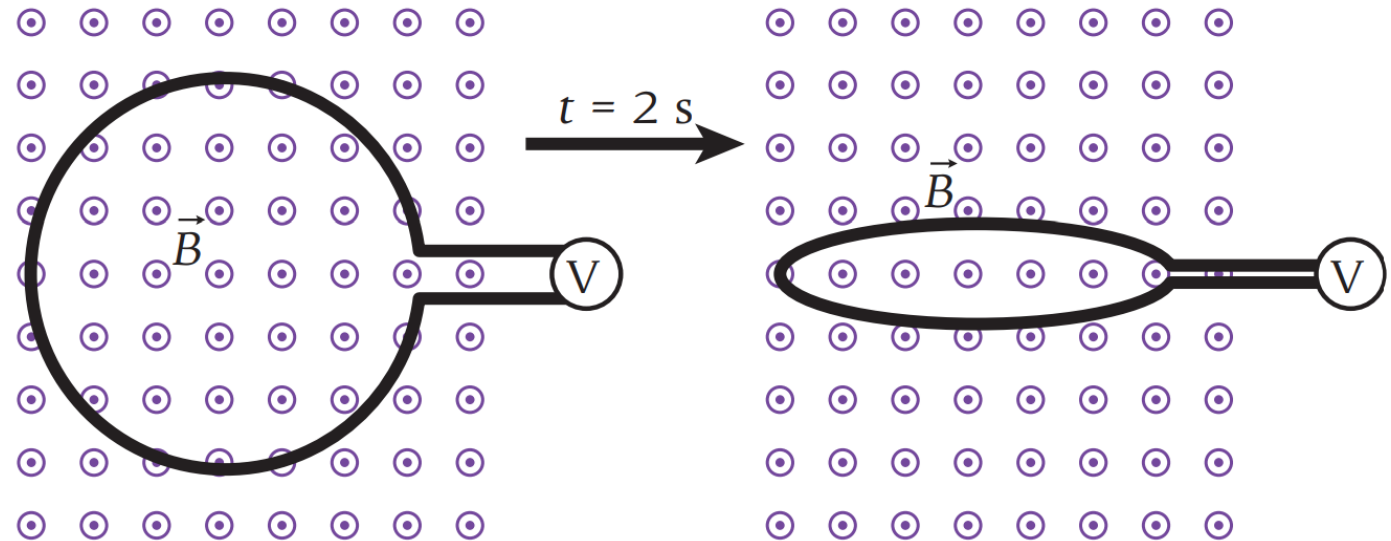


Concept Check 9.5

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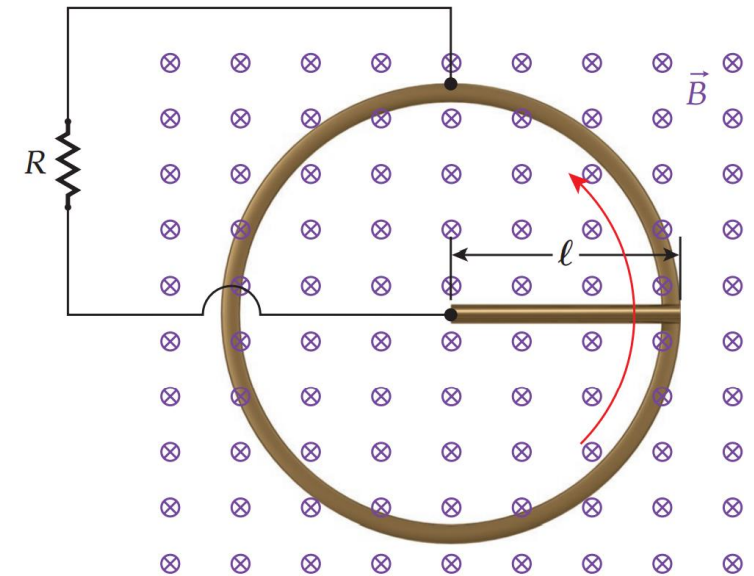
شرح السؤال



Solved Problem 9.1

o6

A conducting rod with length $\ell = 8.17 \text{ cm}$ rotates around one of its ends in a uniform magnetic field that has a magnitude $B = 1.53 \text{ T}$ and is directed parallel to the rotation axis of the rod. The other end of the rod slides on a frictionless conducting ring. The rod makes 6.00 revolutions per second. A resistor, $R = 1.63 \text{ m}\Omega$, is connected between the rotating rod and the conducting ring. What is the power dissipated in the resistor due to magnetic induction?

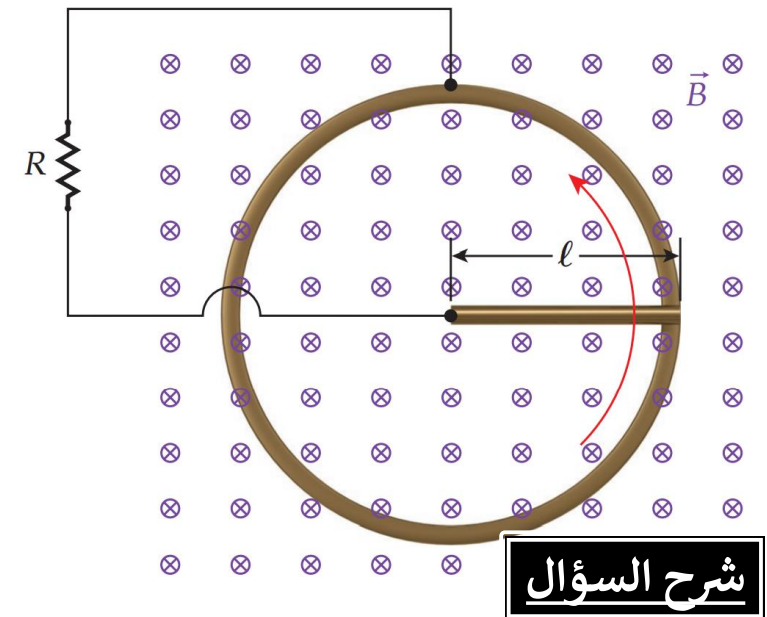


Solved Problem 9.1

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$$\Delta V_{\text{ind}} = \frac{B\pi r^2}{T} = \frac{(1.53)(\pi)(0.0817)^2}{1/6} = 0.1925 \text{ V}$$

$$P = \frac{\Delta V^2}{R} = \frac{(0.1925)^2}{1.63 \times 10^{-3}} = 22.7 \text{ W}$$



Solved Problem 9.1

A conducting rod with length $\ell = 8.17 \text{ cm}$ rotates around one of its ends in a uniform magnetic field that has a magnitude $B = 1.53 \text{ T}$ and is directed parallel to the rotation axis of the rod. The other end of the rod slides on a frictionless conducting ring. The rod makes 6.00 revolutions per second. A resistor, $R = 1.63 \text{ m}\Omega$, is connected between the rotating rod and the conducting ring. What is the power dissipated in the resistor due to magnetic induction?

$$\Delta V_{\text{ind}} = v\ell B. \quad v(r) = \frac{2\pi r}{T}, \quad P = \frac{\Delta V_{\text{ind}}^2}{R}. \quad \text{Textbook Solution}$$

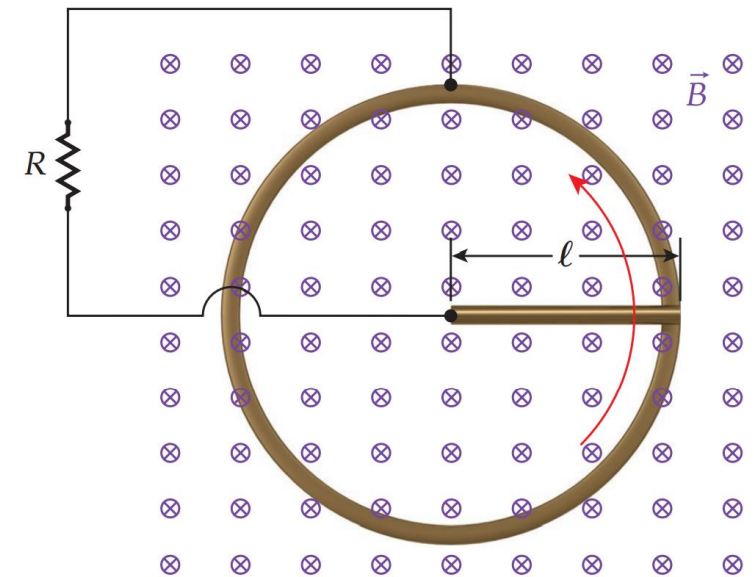
$$\Delta V_{\text{ind}} = \int_0^\ell v(r)Bdr.$$

$$\Delta V_{\text{ind}} = \int_0^\ell \left(\frac{2\pi r}{T} \right) B dr = \frac{2\pi B}{T} \frac{\ell^2}{2} = \frac{\pi B \ell^2}{T}.$$

$$P = \frac{(\pi B \ell^2 / T)^2}{R} = \frac{\pi^2 B^2 \ell^4}{RT^2}.$$

$$P = \frac{\pi^2 B^2 \ell^4}{RT^2} = \frac{\pi^2 (1.53 \text{ T})^2 (0.0817 \text{ m})^4}{(1.63 \times 10^{-3} \Omega) \left(\frac{1}{6.00 \text{ s}} \right)^2} = 22.7345 \text{ W}.$$

9.3 – Lenz's Law

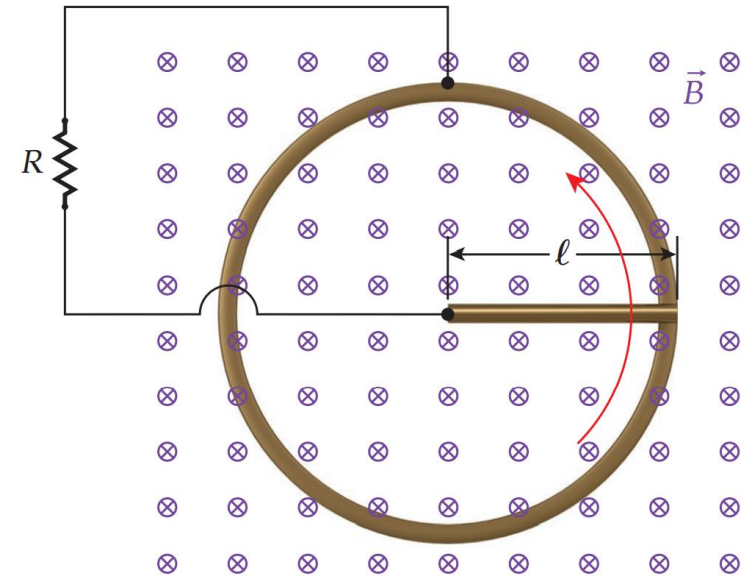


Multiple Choice Questions 9.13

07

Suppose the length of the rotating rod in Solved Problem 9.1 is increased by a factor of **2**. By what factor does the power dissipated in the resistor change?

- a) $1/2$
- b) 2
- c) 4
- d) 8
- e) 16



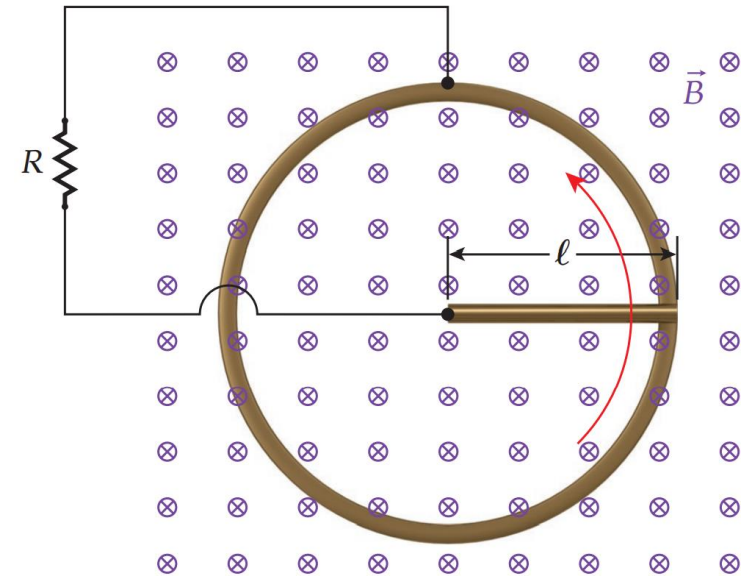
Multiple Choice Questions 9.13

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- a) 1/2
- b) 2
- c) 4
- d) 8
- e) **16**

$$\begin{aligned}\frac{P_1}{P_2} &= \frac{\Delta V_1^2}{\Delta V_2^2} \\ &= \frac{\left(\frac{B\pi r_1^2}{T}\right)^2}{\left(\frac{B\pi r_2^2}{T}\right)^2} \\ &= \frac{r_1^4}{r_2^4} = \frac{r_1^4}{(2r_1)^4} = \frac{1}{16} \\ P_2 &= \mathbf{16P_1}\end{aligned}$$



شرح السؤال

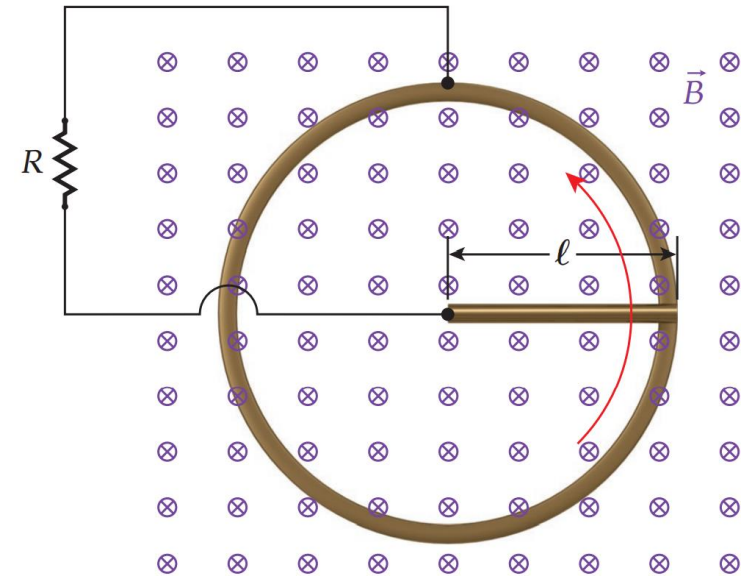


Multiple Choice Questions 9.14

o8

Suppose the resistance of the resistor in Solved Problem 9.1 is increased by a factor of **2**. By what factor does the power dissipated in the resistor change?

- a) $1/2$
- b) 2
- c) 4
- d) 8
- e) 16



Multiple Choice Questions 9.14

o8

Suppose the resistance of the resistor in Solved Problem 9.1 is increased by a factor of **2**. By what factor does the power dissipated in the resistor change?

a) **1/2**

b) 2

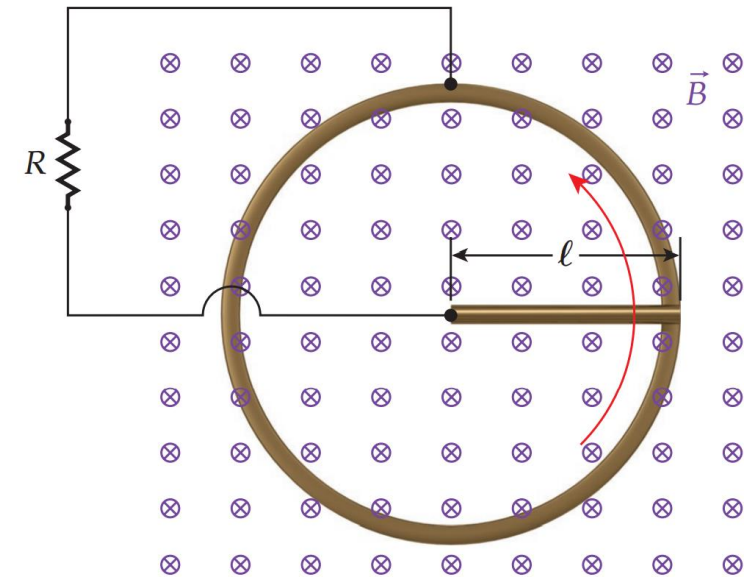
c) 4

d) 8

e) 16

$$\frac{P_1}{P_2} = \frac{R_2}{R_1} = \frac{2R_1}{R_1} = 2$$

$$P_2 = \frac{1}{2} P_1$$



شرح السؤال

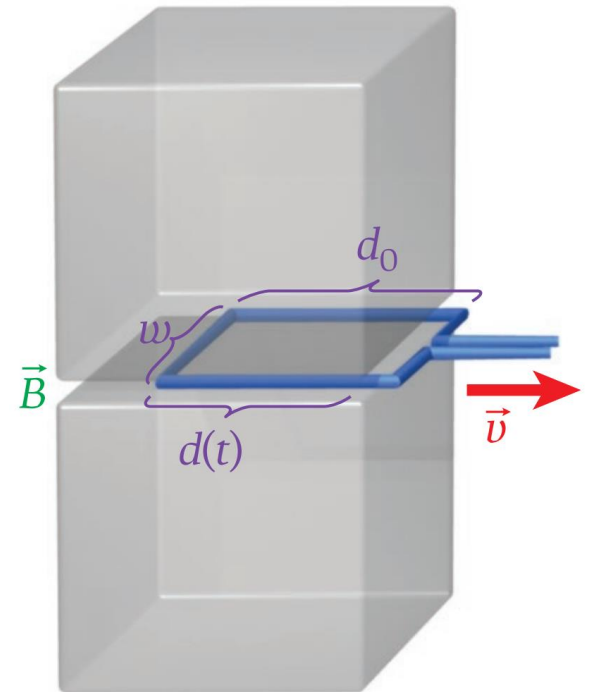


Multiple Choice Questions 9.2

09

The rectangular loop of wire shown in the figure is pulled with a constant acceleration from a region of zero magnetic field into a region of a uniform magnetic field. During this process, the current induced in the loop

- a) will be zero.
- b) will be some constant value that is not zero.
- c) will increase linearly with time.
- d) will increase exponentially with time.
- e) will increase linearly with the square of the time.



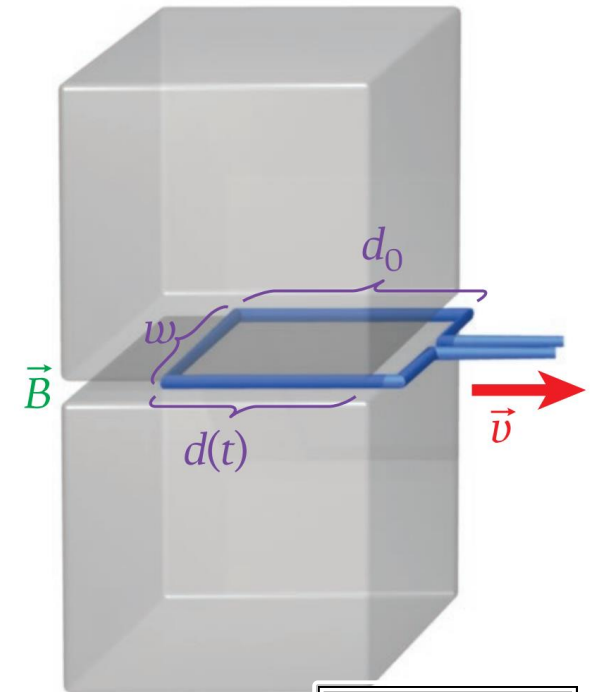
Multiple Choice Questions 9.2

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- c) **will increase linearly with time.**
- d) will increase exponentially with time.
- e) will increase linearly with the square of the time.

$$\Delta V_{\text{ind}} = lv(t)B$$



شرح السؤال

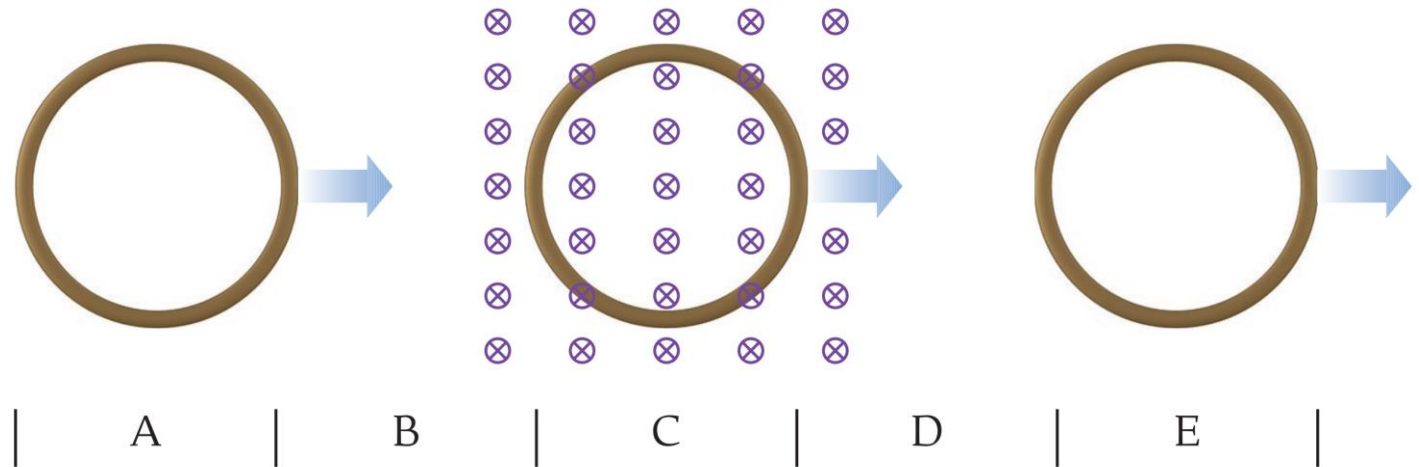


Multiple Choice Questions 9.5

10

A conducting ring is moving from left to right through a uniform magnetic field, as shown in the figure. In which region(s) is there an induced current in the ring?

- a) regions B and D
- b) regions B, C, and D
- c) region C
- d) regions A through E

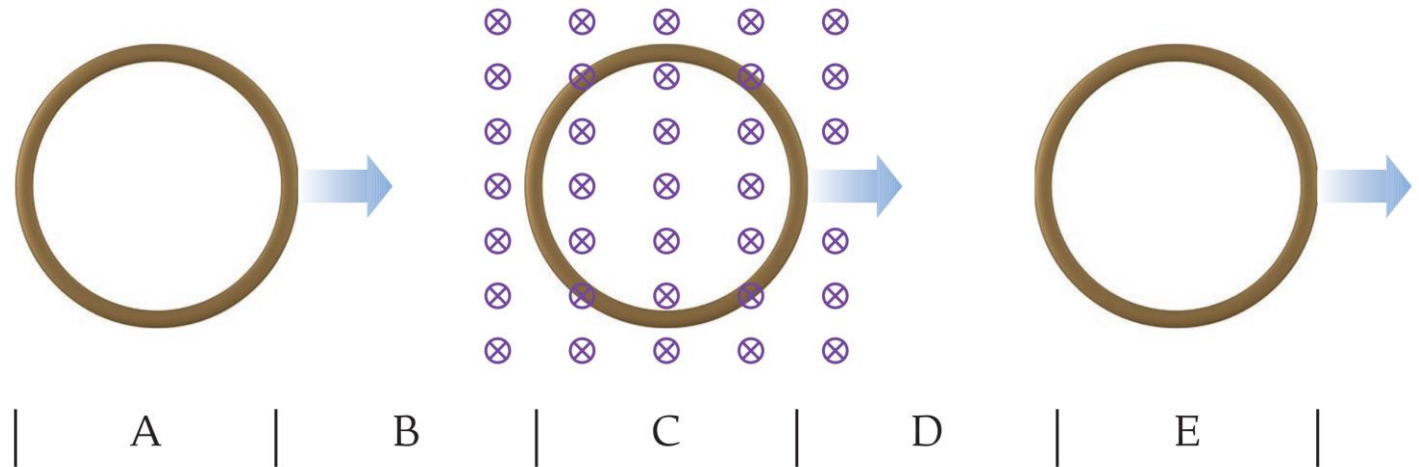


Multiple Choice Questions 9.5

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- b) regions B, C, and D
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شرح السؤال

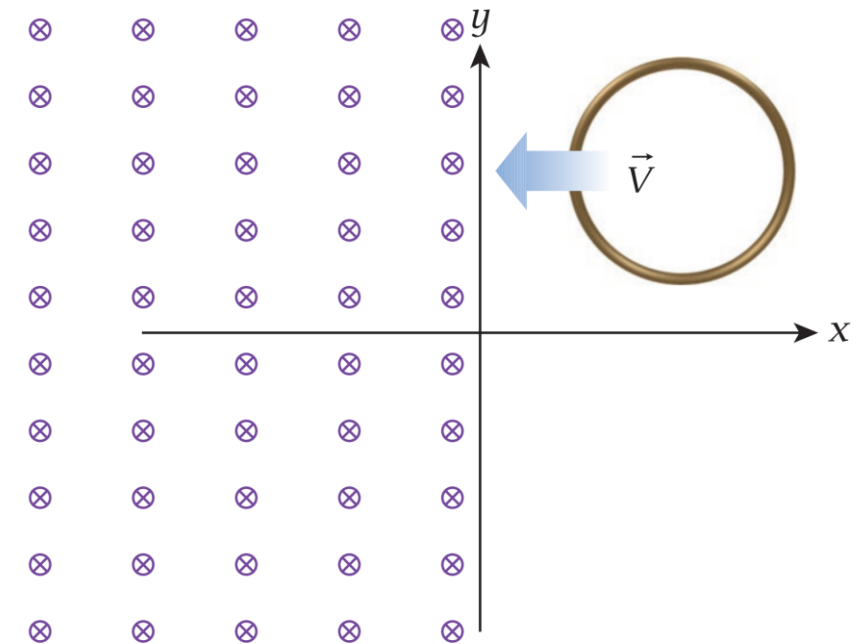


Multiple Choice Questions 9.6

11

A circular loop of wire moving in the xy -plane with a constant velocity in the negative x -direction enters a uniform magnetic field, which covers the region in which $x < 0$, as shown in the figure. The surface normal vector of the loop points in the direction of the magnetic field. Which of the following statements is correct?

- a) The induced potential difference in the loop is at a maximum as the edge of the loop just enters the region with the magnetic field.
- b) The induced potential difference in the loop is at a maximum when one fourth of the loop is in the region with the magnetic field.
- c) The induced potential difference in the loop is at a maximum when the loop is halfway into the region with the magnetic field.
- d) The induced potential difference in the loop is constant from the instant the loop starts to enter the region with the magnetic field.

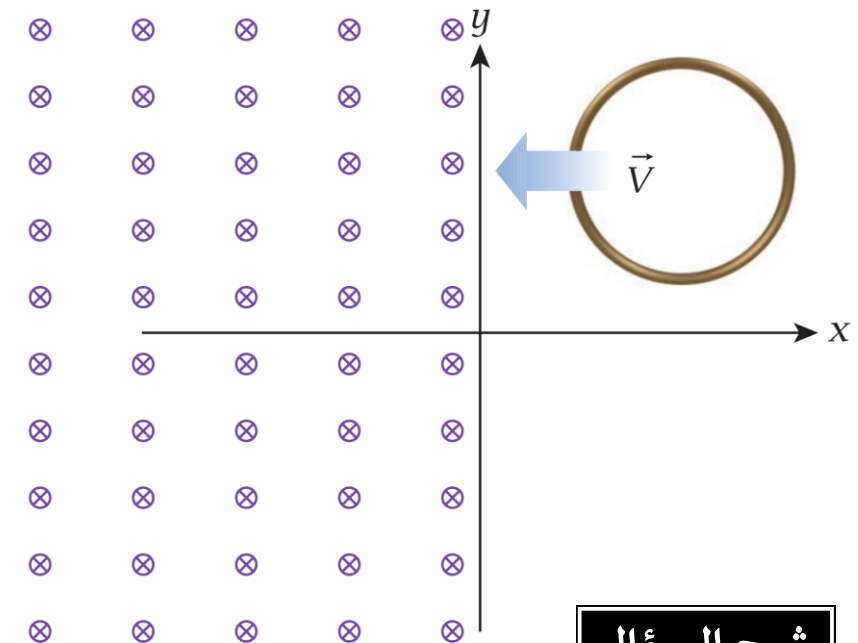


Multiple Choice Questions 9.6

11

A circular loop of wire moving in the xy -plane with a constant velocity in the negative x -direction enters a uniform magnetic field, which covers the region in which $x < 0$, as shown in the figure. The surface normal vector of the loop points in the direction of the magnetic field. Which of the following statements is correct?

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- b) The induced potential difference in the loop is at a maximum when one fourth of the loop is in the region with the magnetic field.
- c) **The induced potential difference in the loop is at a maximum when the loop is halfway into the region with the magnetic field.**
- d) The induced potential difference in the loop is constant from the instant the loop starts to enter the region with the magnetic field.



شرح السؤال



Multiple Choice Questions 9.9

Calculate the potential difference induced between the tips of the wings of a Boeing 747-400 with a wingspan of **64.67 m** when it is in level flight at a speed of **913 km/h**. Assume that the magnitude of the downward component of the Earth's magnetic field is **$B = 5.00 \times 10^{-5} \text{ T}$** .

- a) 0.820 V
- b) 2.95 V
- c) 10.4 V
- d) 30.1 V
- e) 225 V

Multiple Choice Questions 9.9

Calculate the potential difference induced between the tips of the wings of a Boeing 747-400 with a wingspan of **64.67 m** when it is in level flight at a speed of **913 km/h**. Assume that the magnitude of the downward component of the Earth's magnetic field is **$B = 5.00 \times 10^{-5} \text{ T}$** .

a) 0.820 V

$$\Delta V_{\text{ind}} = lvB$$

b) 2.95 V

c) 10.4 V

d) 30.1 V

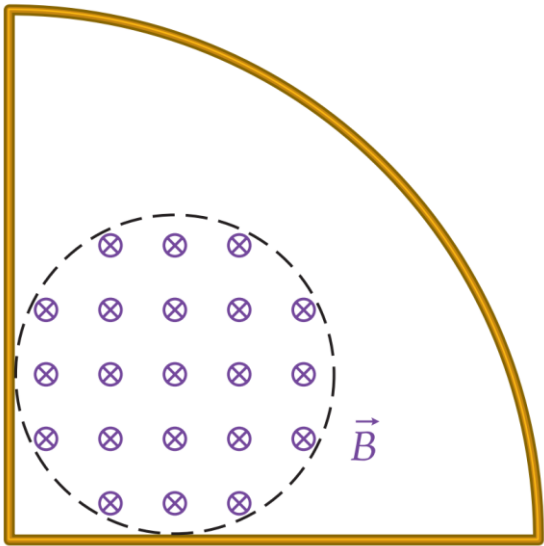
e) 225 V

شرح السؤال

Exercise 9.35

13

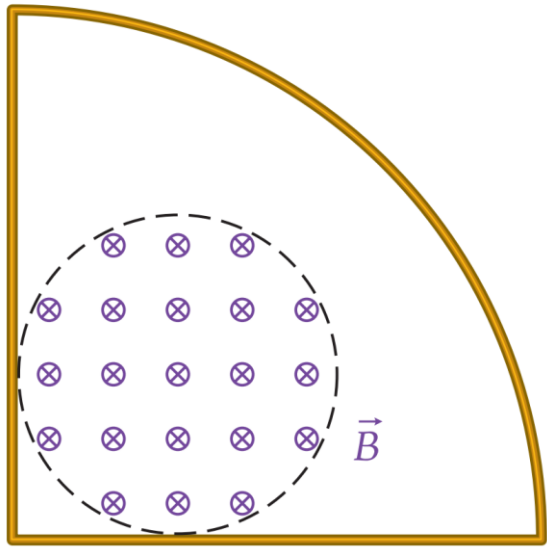
The conducting loop in the shape of a quarter-circle shown in the figure has a radius of **10.0 cm** and a resistance of **0.200 Ω** . The magnetic field strength within the dotted circle of radius **3.00 cm** is initially **2.00 T**. The magnetic field strength then decreases from **2.00 T** to **1.00 T** in **2.00 s**. Find (a) the magnitude and (b) the direction of the induced current in the loop.



Exercise 9.35

13

The conducting loop in the shape of a quarter-circle shown in the figure has a radius of **10.0 cm** and a resistance of **0.200 Ω** . The magnetic field strength within the dotted circle of radius **3.00 cm** is initially **2.00 T**. The magnetic field strength then decreases from **2.00 T** to **1.00 T** in **2.00 s**. Find (a) the magnitude and (b) the direction of the induced current in the loop.



(a) The decreasing B field creates a changing flux through the loop, confined to the area of the dotted circle of radius, $r = 3.00$ cm. The varying flux creates an emf of:

$$\Delta V_{\text{ind}} = -\frac{d\Phi_B}{dt} = -\frac{d(AB)}{dt} = -\frac{d(\pi r^2 B)}{dt} = -\pi r^2 \frac{dB}{dt} \approx -\pi r^2 \frac{\Delta B}{\Delta t} = -\pi r^2 \left(\frac{B_f - B_i}{\Delta t} \right).$$

This corresponds to a current of:

$$i = \frac{V}{R} = -\frac{\pi r^2}{R} \left(\frac{B_f - B_i}{\Delta t} \right) = -\frac{\pi (0.0300 \text{ m})^2}{0.200 \Omega} \left(\frac{1.00 \text{ T} - 2.00 \text{ T}}{2.00 \text{ s}} \right) = 0.00707 \text{ A} = 7.07 \text{ mA}$$

(b) The B field points into the page, thus a decrease in the B field will induce a current corresponding to a B field which points into the page. By the right-hand rule, the induced current flows clockwise.

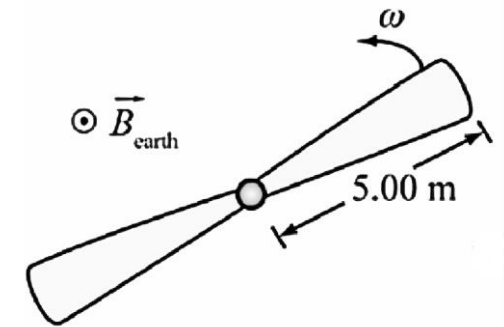
شرح السؤال



Exercise 9.37

14

A helicopter hovers above the north magnetic pole in a magnetic field of magnitude **0.426 G** and oriented perpendicular to the ground. The helicopter rotors are **10.0 m** long, are made of aluminum, and rotate about the hub with a rotational speed of **1.00×10^4 rpm**. What is the potential difference from the hub to the end of a rotor ?



Exercise 9.37

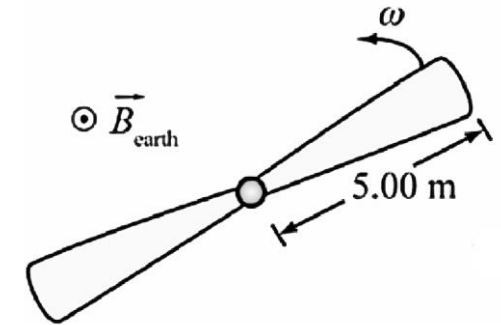
A helicopter hovers above the north magnetic pole in a magnetic field of magnitude **0.426 G** and oriented perpendicular to the ground. The helicopter rotors are **10.0 m** long, are made of aluminum, and rotate about the hub with a rotational speed of **1.00×10^4 rpm**. What is the potential difference from the hub to the end of a rotor ?

RESEARCH: The potential difference across a wire moving in a magnetic field is $\Delta V_{\text{ind}} = vLB$. Each element of the blade travels at a different speed, $v = r\omega$. To calculate the potential difference, the length must be divided into pieces of length, dl , which travel at $v = l\omega$. The value should be integrated over the total length, from 0 to L .

SIMPLIFY:
$$\int \Delta V = \int_0^L vBdl = \int_0^L l\omega Bdl = \frac{1}{2}\omega BL^2$$

In terms of the blade's rpm, the potential difference is
$$V = \frac{1}{2} \left(\frac{2\pi(\text{rpm})}{60 \text{ s}} \right) BL^2.$$

CALCULATE:
$$V = \left(\frac{\pi(1.00 \cdot 10^4 \text{ rpm})}{60.0 \text{ s/rpm}} \right) (0.426 \cdot 10^{-4} \text{ T})(5.00 \text{ m})^2 = 0.557633 \text{ V} \approx 0.558 \text{ V}$$



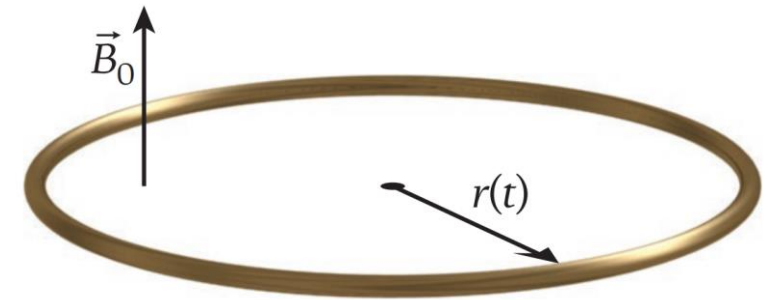
شرح السؤال



Exercise 9.38

15

An elastic circular conducting loop expands at a constant rate over time such that its radius is given by $r(t) = r_0 + vt$, where $r_0 = 0.100 \text{ m}$ and $v = 0.0150 \text{ m/s}$. The loop has a constant resistance of $R = 12.0 \text{ } \Omega$ and is placed in a uniform magnetic field of magnitude $B_0 = 0.750 \text{ T}$, perpendicular to the plane of the loop, as shown in the figure. Calculate the direction and the magnitude of the induced current, i , at $t = 5.00 \text{ s}$.



Exercise 9.38

15

An elastic circular conducting loop expands at a constant rate over time such that its radius is given by $r(t) = r_0 + vt$, where $r_0 = 0.100 \text{ m}$ and $v = 0.0150 \text{ m/s}$. The loop has a constant resistance of $R = 12.0 \Omega$ and is placed in a uniform magnetic field of magnitude $B_0 = 0.750 \text{ T}$, perpendicular to the plane of the loop, as shown in the figure. Calculate the direction and the magnitude of the induced current, i , at $t = 5.00 \text{ s}$.

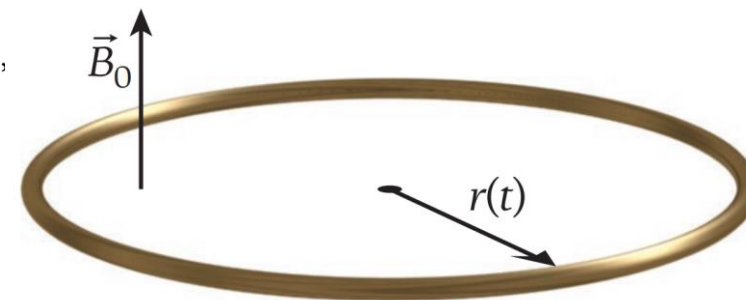
RESEARCH: The flux through the loop is $\Phi_B = AB = \pi r^2 B$. The induced current of the loop is $i = V / R$, where the voltage is given by $V = -d\Phi_B / dt$.

SIMPLIFY: The induced current in the wire is:

$$i = \frac{V}{R} = -\frac{1}{R} \frac{d\Phi_B}{dt} = -\frac{1}{R} \frac{d}{dt}(\pi r^2 B) = -\left(\frac{\pi B}{R}\right) \frac{d}{dt}(r_0 + vt)^2 = -\frac{\pi B 2(r_0 + vt)v}{R} = -\frac{2\pi B}{R} v(r_0 + vt).$$

CALCULATE: The magnitude of the induced current at $t = 5.00 \text{ s}$ is:

$$i = -\frac{2\pi(0.750 \text{ T})}{12.0 \Omega} (0.0150 \text{ m/s}) [0.100 \text{ m} + (0.0150 \text{ m/s})(5.00 \text{ s})] = 0.0010308 \text{ A}.$$



شرح السؤال



Additional Exercises 9.62

A wire of length $\ell = 10.0 \text{ cm}$ is moving with constant velocity in the xy -plane; the wire is parallel to the y -axis and moving along the x -axis. If a magnetic field of magnitude 1.00 T is pointing along the positive z -axis, what must the velocity of the wire be in order for a potential difference of 2.00 V to be induced across it?

Additional Exercises 9.62

A wire of length $\ell = 10.0 \text{ cm}$ is moving with constant velocity in the xy-plane; the wire is parallel to the y-axis and moving along the x-axis. If a magnetic field of magnitude 1.00 T is pointing along the positive z-axis, what must the velocity of the wire be in order for a potential difference of 2.00 V to be induced across it?

The induced voltage is given by:

$$|\Delta V_{\text{ind}}| = \left| -\frac{d\Phi}{dt} \right| = vLB = 2.00 \text{ V} \Rightarrow v = \frac{\Delta V}{BL} = \frac{2.00 \text{ V}}{(0.100 \text{ m})(1.00 \text{ T})} = 20.0 \text{ m/s}.$$

شرح السؤال

Additional Exercises 9.63

17

The magnetic field inside the solenoid in the figure changes at the rate of **1.50 T/s**. A conducting coil with **2000 turns** surrounds the solenoid, as shown. The radius of the solenoid is **4.00 cm**, and the radius of the coil is **7.00 cm**. What is the potential difference induced in the coil?



Additional Exercises 9.63

The magnetic field inside the solenoid in the figure changes at the rate of **1.50 T/s**. A conducting coil with **2000 turns** surrounds the solenoid, as shown. The radius of the solenoid is **4.00 cm**, and the radius of the coil is **7.00 cm**. What is the potential difference induced in the coil?

The potential difference is given by Faraday's law:

$$|\Delta V_{\text{ind}}| = \left| -\frac{d\Phi}{dt} \right| = A \frac{dB}{dt} = \pi R^2 \frac{dB}{dt} = \pi (0.0400 \text{ m})^2 (1.50 \text{ T/s}) = 7.54 \cdot 10^{-3} \text{ V}$$

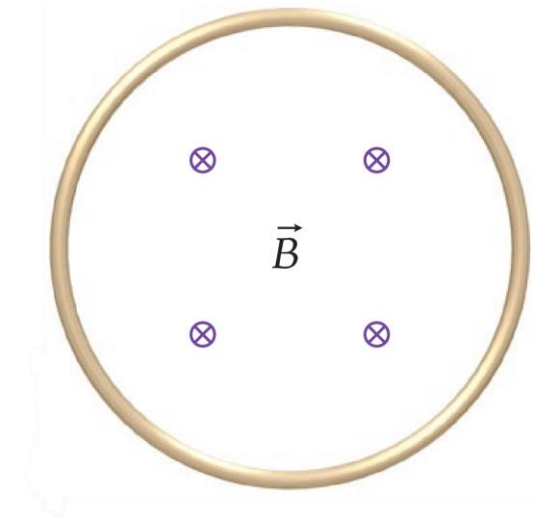
Note that the radius of the coil is irrelevant.



Additional Exercises 9.69

18

A single loop of wire with an area of 5.00 m^2 is located in the plane of the page, as shown in the figure. A time-varying magnetic field in the region of the loop is directed into the page, and its magnitude is given by $\vec{B} = 3.00 \text{ T} + (2.00 \text{ T/s})t$. At $t = 2.00 \text{ s}$, what are the induced potential difference in the loop and the direction of the induced current?

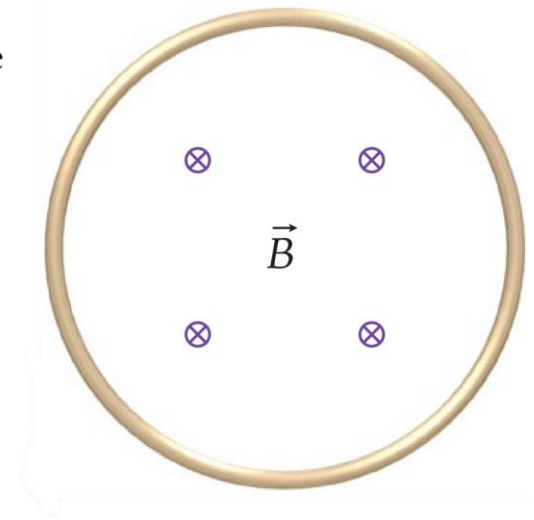


Additional Exercises 9.69

A single loop of wire with an area of 5.00 m^2 is located in the plane of the page, as shown in the figure. A time-varying magnetic field in the region of the loop is directed into the page, and its magnitude is given by $\vec{B} = 3.00 \text{ T} + (2.00 \text{ T/s})t$. At $t = 2.00 \text{ s}$, what are the induced potential difference in the loop and the direction of the induced current?

Since the normal vector of the loop and the magnetic field is parallel, $\cos\theta = 1$. The negative sign can be dropped and ΔV_{ind} becomes:

$$\Delta V_{\text{ind}} = A \frac{dB}{dt} = A \frac{d}{dt}(3.00 \text{ T} + 2.00t \text{ T/s}) = A(2.00 \text{ T/s}) = (5.00 \text{ m}^2)(2.00 \text{ T/s}) = 10.0 \text{ V}.$$



شرح السؤال



Generators and Motors

Chapter 9 Lesson 4 – Revision Paper

9.4 – Generators and Motors

- Lenz's Law states that a changing magnetic flux through a conducting loop **induces** a current in the loop that **opposes** the change in magnetic flux.

$$\Delta V_{\text{ind}} = NAB\omega \sin \theta$$

$$V_{\text{max}} = NAB\omega$$

$$i_{\text{effective}} = \frac{i_{\text{max}}}{\sqrt{2}}$$

Self-Test Opportunity 9.4

A generator is operated by rotating a coil of N turns in a constant magnetic field of magnitude B at a frequency f . The resistance of the coil is R , and the cross-sectional area of the coil is A . Which of the following statements is true?

- a) The average induced potential difference doubles if the frequency, f , is doubled.
- b) The average induced potential difference doubles if the resistance, R , is doubled.
- c) The average induced potential difference doubles if the magnetic field's magnitude, B , is doubled.
- d) The average induced potential difference doubles if the area, A , is doubled.

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- b) The average induced potential difference doubles if the resistance, R , is doubled.
- c) The average induced potential difference doubles if the magnetic field's magnitude, B , is doubled.
- d) The average induced potential difference doubles if the area, A , is doubled.

$$\begin{aligned}\Delta V_{\text{ind}} &= -NAB\omega \\ &= -NAB(2\pi f)\end{aligned}$$

Exercise 9.43

A simple generator consists of a loop rotating inside a constant magnetic field. If the loop is rotating with frequency f , the magnetic flux is given by $\Phi(t) = BA\cos(2\pi ft)$. If $B = 1.00 \text{ T}$ and $A = 1.00 \text{ m}^2$, what must the value of f be for the maximum induced potential difference to be **110. V**?

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$$V_{\max} = NAB\omega$$

$$= NAB(2\pi f)$$

$$f = \frac{V_{\max}}{NAB2\pi} = \frac{110}{(1)(1)(1)(2\pi)} = 17.5 \text{ Hz}$$

$$\Phi(t) = BA \cos(2\pi ft), \quad \Delta V_{\text{ind}} = \frac{d\Phi}{dt} = -2\pi fBA \sin(2\pi ft). \quad \text{The maximum occurs when } |\sin(2\pi ft)| = 1.$$

$$\Delta V_{\text{ind,max}} = 2\pi fBA = 110. \text{ V. Substitute the values to obtain: } f = \frac{110. \text{ V}}{2\pi BA} = \frac{110. \text{ V}}{2\pi(1.00 \text{ T})(1.00 \text{ m}^2)} = 17.5 \text{ Hz.}$$

شرح السؤال

Exercise 9.44

A motor has a single loop inside a magnetic field of magnitude **0.870 T**. If the area of the loop is **300. cm²**, find the maximum angular speed possible for this motor when connected to a source of emf providing **170. V**.

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$$V_{\max} = NAB\omega$$

$$\omega = \frac{V_{\max}}{NAB} = \frac{170}{(1)(300 \times 10^{-4})(0.870)} = 6.51 \times 10^3 \text{ rad/s}$$

شرح السؤال

Exercise 9.45

Your friend decides to produce electrical power by turning a coil of 1.00×10^5 circular loops of wire around an axis perpendicular to the Earth's magnetic field, which has a local magnitude of **0.300 G**. The loops have a radius of **25.0 cm**.

- a) If your friend turns the coil at a frequency of **150. Hz**, what peak current will flow in a resistor, **$R = 1.50 \text{ k}\Omega$** , connected to the coil?

Exercise 9.45

Your friend decides to produce electrical power by turning a coil of 1.00×10^5 circular loops of wire around an axis perpendicular to the Earth's magnetic field, which has a local magnitude of 0.300 G . The loops have a radius of 25.0 cm .

- a) If your friend turns the coil at a frequency of $150. \text{ Hz}$, what peak current will flow in a resistor, $R = 1.50 \text{ k}\Omega$, connected to the coil?

$$\begin{aligned} V_{\max} &= NAB\omega \\ &= N(\pi r^2)B(2\pi f) \\ &= (1 \times 10^5)(\pi(0.25)^2)(0.3 \times 10^{-4})(2\pi(150)) = 555 \text{ V} \end{aligned}$$

$$I_{\max} = \frac{V_{\max}}{R} = \frac{555}{1.5 \times 10^3} = 0.370 \text{ A}$$

شرح السؤال

Exercise 9.45

Your friend decides to produce electrical power by turning a coil of 1.00×10^5 circular loops of wire around an axis perpendicular to the Earth's magnetic field, which has a local magnitude of **0.300 G**. The loops have a radius of **25.0 cm**.

- b) The average current flowing in the coil will be **0.7071** times the peak current. What will be the average power obtained from this device?

Exercise 9.45

Your friend decides to produce electrical power by turning a coil of 1.00×10^5 circular loops of wire around an axis perpendicular to the Earth's magnetic field, which has a local magnitude of 0.300 G . The loops have a radius of 25.0 cm .

- b) The average current flowing in the coil will be 0.7071 times the peak current. What will be the average power obtained from this device?

$$P_{\text{avg}} = i_{\text{eff}}^2 R$$

$$= \left(\frac{i_{\text{max}}}{\sqrt{2}} \right)^2 R = \left(\frac{0.370}{\sqrt{2}} \right)^2 (1.5 \times 10^3) = 103 \text{ W}$$

شرح السؤال

Self-Induction and Mutual Induction

Chapter 9
Lesson 7 – Revision Paper

9.7 – Self-Induction and Mutual Induction

- The inductance, L , of a **device** with conducting loops is
- The inductance of a **solenoid** is given by
- The unit of inductance is the **henry** (H)

$$L = \frac{N\Phi_B}{i}$$

$$L = \mu_0 n^2 \ell A = \mu_0 N^2 A / \ell$$

$$1 \text{ H} = \frac{1 \text{ T m}^2}{1 \text{ A}}$$

9.7 – Self-Induction and Mutual Induction

- The **self-induced** potential difference, $\Delta V_{\text{ind},L}$, for any inductor is given by

$$\Delta V_{\text{ind}} = -L \frac{di}{dt}$$

- The **mutual inductance** between two coils is given by

$$M_{1 \rightarrow 2} = \frac{N_2 \Phi_{1 \rightarrow 2}}{i_1}$$

- The potential difference induced by mutual inductance between two coils is given by

$$\Delta V_{\text{ind},2} = -M \frac{di_1}{dt} \quad || \quad \Delta V_{\text{ind},1} = -M \frac{di_2}{dt}$$

Solved Problem 9.2

A long solenoid with a circular cross section of radius $r_1 = 2.80 \text{ cm}$ and $n = 290$ turns/cm is inside and coaxial with a short coil that has a circular cross section of radius $r_2 = 4.90 \text{ cm}$ and $N = 31$ turns. The current in the solenoid is increased at a constant rate from zero to $i = 2.20 \text{ A}$ over a time interval of 48.0 ms . What is the potential difference induced in the short coil while the current is changing?

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$$\begin{aligned}
 \Delta V_{\text{ind},1} &= -M \frac{di_2}{dt} \\
 &= -\left(\frac{N_1 AB}{i_2} \right) \frac{di_2}{dt} \\
 &= -\left(\frac{N_1 (\pi r_1^2) (\mu_0 n i_2)}{i_2} \right) \frac{di_2}{dt} \\
 &= -(N_1 \pi r_1^2 \mu_0 n) \frac{di_2}{dt} \\
 &= -(31)(\pi(0.028)^2)(\mu_0(290 \times 10^2)) \left(\frac{2.2 - 0}{48 \times 10^{-3}} \right) \\
 &= -0.128 \text{ V}
 \end{aligned}$$

Solved Problem 9.2

A long solenoid with a circular cross section of radius $r_1 = 2.80 \text{ cm}$ and $n = 290$ turns/cm is inside and coaxial with a short coil that has a circular cross section of radius $r_2 = 4.90 \text{ cm}$ and $N = 31$ turns. The current in the solenoid is increased at a constant rate from zero to $i = 2.20 \text{ A}$ over a time interval of 48.0 ms . What is the potential difference induced in the short coil while the current is changing?

$$\begin{aligned}
 \Delta V_{\text{ind},1} &= -N_2 A_1 \cos \theta \frac{dB}{dt} && \text{We can also use Faraday's Laws of Induction to solve the problem} \\
 &= -N_2 A_1 \cos \theta \frac{d(\mu_0 n_1 i_2)}{dt} = -N_2 A_1 \mu_0 n_1 \cos \theta \frac{di_2}{dt} \\
 &= -(31)(\pi(0.028)^2)\mu_0 \left(\frac{290}{10^{-2}}\right) \cos 0 \left(\frac{2.2}{48 \times 10^{-3}}\right) \\
 &= -0.128 \text{ V}
 \end{aligned}$$

شرح السؤال

Multiple Choice Questions 9.7

Which of the following statements regarding self-induction is correct?

- a) Self-induction occurs only when a direct current is flowing through a circuit.
- b) Self-induction occurs only when an alternating current is flowing through a circuit.
- c) Self-induction occurs when either a direct current or an alternating current is flowing through a circuit.
- d) Self-induction occurs when either a direct current or an alternating current is flowing through a circuit as long as the current is varying.

Multiple Choice Questions 9.7

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Multiple Choice Questions 9.10

A long solenoid with a circular cross section of radius $r_1 = 2.80 \text{ cm}$ and $n = 290 \text{ turns/cm}$ is inside of and coaxial with a short coil that has a circular cross section of radius $r_2 = 4.90 \text{ cm}$ and $N = 31 \text{ turns}$. Suppose the current in the short coil is increased steadily from zero to $i = 2.80 \text{ A}$ in 18.0 ms . What is the magnitude of the potential difference induced in the solenoid while the current in the short coil is changing?

- a) 0.0991 V
- b) 0.128 V
- c) 0.233 V
- d) 0.433 V
- e) 0.750 V

Multiple Choice Questions 9.10

A long solenoid with a circular cross section of radius $r_1 = 2.80 \text{ cm}$ and $n = 290 \text{ turns/cm}$ is inside of and coaxial with a short coil that has a circular cross section of radius $r_2 = 4.90 \text{ cm}$ and $N = 31 \text{ turns}$. Suppose the current in the short coil is increased steadily from zero to $i = 2.80 \text{ A}$ in 18.0 ms . What is the magnitude of the potential difference induced in the solenoid while the current in the short coil is changing?

a) 0.0991 V

b) 0.128 V

c) 0.233 V

d) 0.433 V

e) 0.750 V

$$\begin{aligned}
 M &= \frac{N_1 AB}{i_2} = \frac{N_1 A \mu_0 n_1 i_2}{i_2} = \mu_0 N_1 n_1 A \\
 &= \mu_0 (31) (290 \times 10^2) (\pi (0.028)^2) = 2.783 \times 10^{-3} \text{ H} \\
 \Delta V_{\text{ind},1} &= -M \frac{di_2}{dt} = -(2.783 \times 10^{-3}) \left(\frac{2.8}{18 \times 10^{-3}} \right) \\
 &= -0.433 \text{ V}
 \end{aligned}$$

شرح السؤال

Exercise 9.46

Find the mutual inductance of the solenoid and the coil described in Example 9.1 and the induced potential difference in the coil at $t = 2.0 \text{ s}$ using the techniques described in Section 9.7. How do the results for the induced potential difference compare?

Example 9.1

A current of 600 mA is flowing in an ideal solenoid, resulting in a magnetic field of 0.025 T inside the solenoid. Then the current increases with time, t , according to $i(t) = i_0 [1 + (2.4 \text{ s}^{-2})t^2]$. If a circular coil of radius 3.4 cm with $N = 200$ windings is located inside the solenoid with its normal vector parallel to the magnetic field (Figure 9.8), what is the induced potential difference in the coil at $t = 2.0 \text{ s}$?

Exercise 9.46

Find the mutual inductance of the solenoid and the coil described in Example 9.1 and the induced potential difference in the coil at $t = 2.0 \text{ s}$ using the techniques described in Section 9.7. How do the results for the induced potential difference compare?

Example 9.1

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$$\text{First solve for } n: B = \mu_0 n i \Rightarrow n = \frac{B}{\mu_0 i} = \frac{0.025 \text{ T}}{(1.2566 \cdot 10^{-6} \text{ m kg s}^{-2} \text{ A}^{-2})(0.60 \text{ A})} = 33158.$$

$$M = N_1 \pi \mu_0 n_2 r_1^2 = 200 \pi (1.2566 \cdot 10^{-6} \text{ m kg s}^{-2} \text{ A}^{-2})(33158)(0.034 \text{ m})^2 = 0.0302 \text{ H}, \quad i(t) = i_0 (1 + (2.4 \text{ s}^{-2})t^2)$$

$$V = -M \frac{di}{dt} = -(0.0302 \text{ H})(2)(0.60 \text{ A})(2.4 \text{ s}^{-2})(2.0 \text{ s}) = -0.17 \text{ V}$$

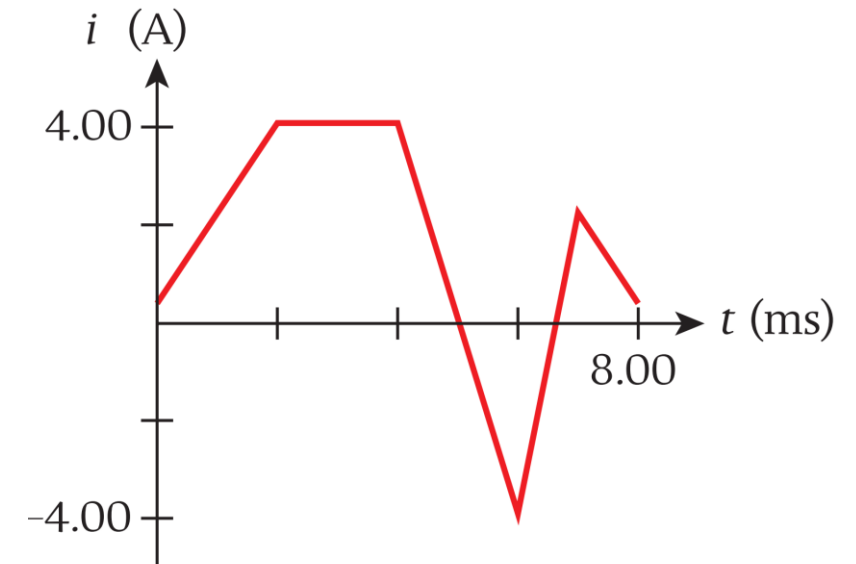
The results match those of the example.

شرح السؤال

Exercise 9.47

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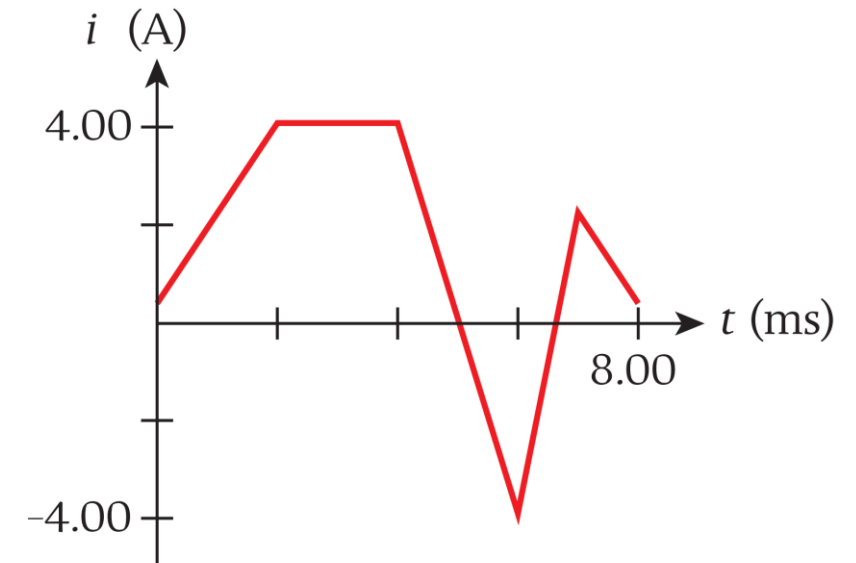
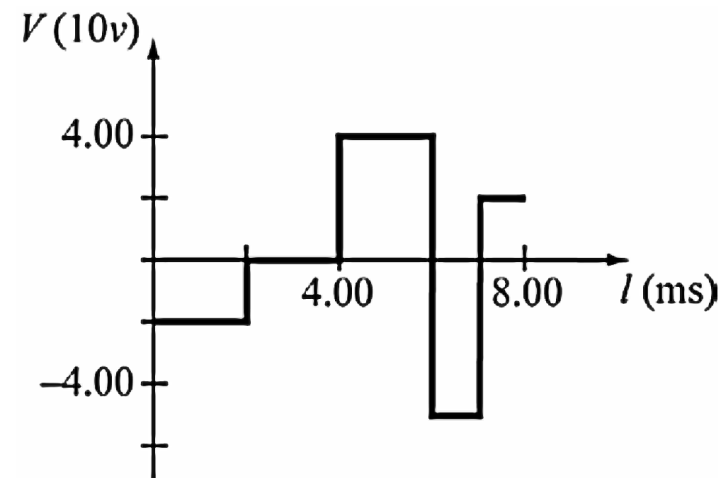
The figure shows the current through a **10.0-mH** inductor over a time interval of **8.00 ms**. Draw a graph showing the self-induced potential difference, ΔV_{ind} , for the inductor over the same interval.



Exercise 9.47

The figure shows the current through a **10.0-mH** inductor over a time interval of **8.00 ms**. Draw a graph showing the self-induced potential difference, ΔV_{ind} , for the inductor over the same interval.

The potential across an inductor is given by: $\Delta V_{\text{ind}} = -L \frac{di}{dt}$, where $\frac{di}{dt}$ is the slope.



شرح السؤال



Exercise 9.48

A short coil with radius $R = 10.0 \text{ cm}$ contains $N = 30.0$ turns and surrounds a long solenoid with radius $r = 8.00 \text{ cm}$ containing $n = 60$ turns per centimeter. The current in the short coil is increased at a constant rate from zero to $i = 2.00 \text{ A}$ in a time of $t = 12.0 \text{ s}$. Calculate the induced potential difference in the long solenoid while the current is increasing in the short coil.

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$$M = \frac{N_1 AB}{i_2} = \frac{N_1 A \mu_0 n_1 i_2}{i_2} = \mu_0 N_1 n_1 A$$

$$= \mu_0 (30)(6000)(\pi(0.08)^2) = 4.55 \times 10^{-3} \text{ H}$$

$$\Delta V_{\text{ind},1} = -M \frac{di_2}{dt} = -(4.55 \times 10^{-3}) \left(\frac{2 - 0}{12} \right)$$

$$= -7.58 \times 10^{-4} \text{ V}$$

شرح السؤال

RL Circuits

Chapter 9 Lesson 8 – Revision Paper

9.8 – RL Circuits

- An **RL circuit** is a circuit that has both a resistor and an **inductor** connected in series to a source of potential difference.

$$V_{emf} = L \frac{di}{dt} + iR$$

$$i(t) = \frac{V_{emf}}{R} (1 - e^{-t/(L/R)})$$

- When a source of emf is suddenly removed from an RL circuit:

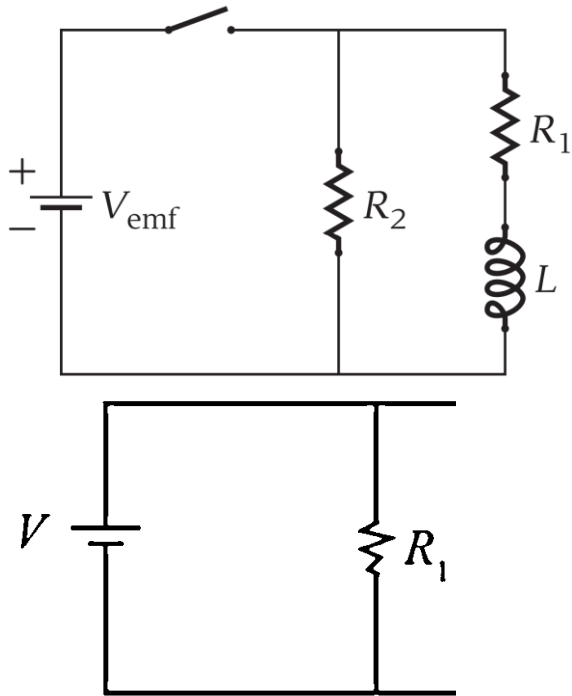
$$L \frac{di}{dt} + iR = 0$$

$$i(t) = i_0 e^{-t/\tau_{RL}}$$

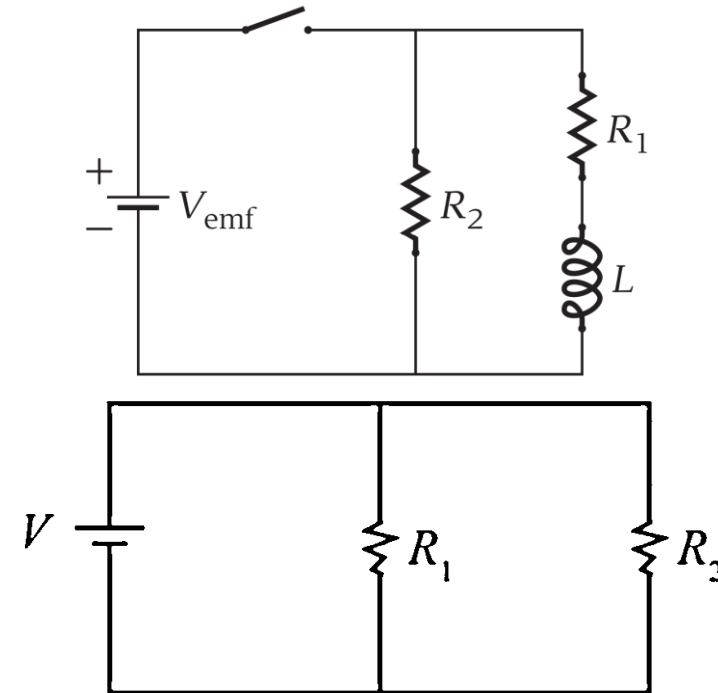
$$\tau_{RL} = \frac{L}{R}$$

9.8 – RL Circuits

- In RL circuits, **immediately** after the switch is closed, the inductor functions as an **open-circuit**.



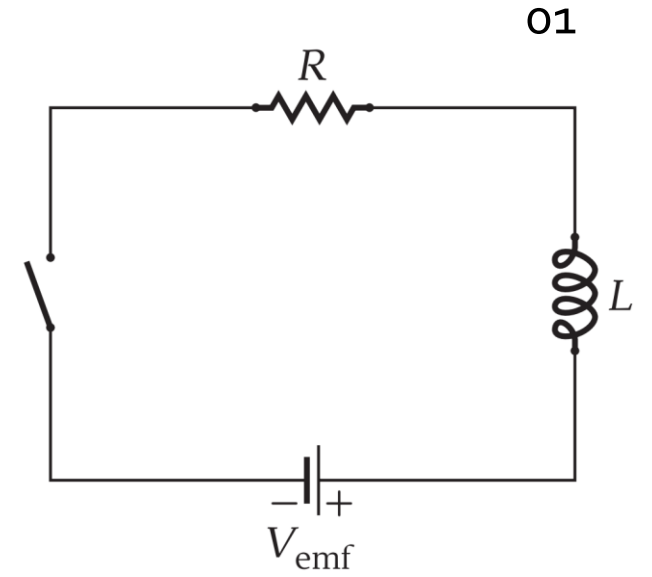
- In RL circuits, a **long** time after the switch is closed, the inductor acts like a **short-circuit**.



Concept Check 9.7

Consider the RL circuit shown in the figure. When the switch is closed, the current in the circuit increases **exponentially** to the value $i = V_{\text{emf}}/R$. If the inductor in this circuit is replaced with an inductor having **three** times the number of turns per unit length, the time required to reach a current of magnitude **0.9*i***

- a) increases.
- b) decreases.
- c) stays the same.

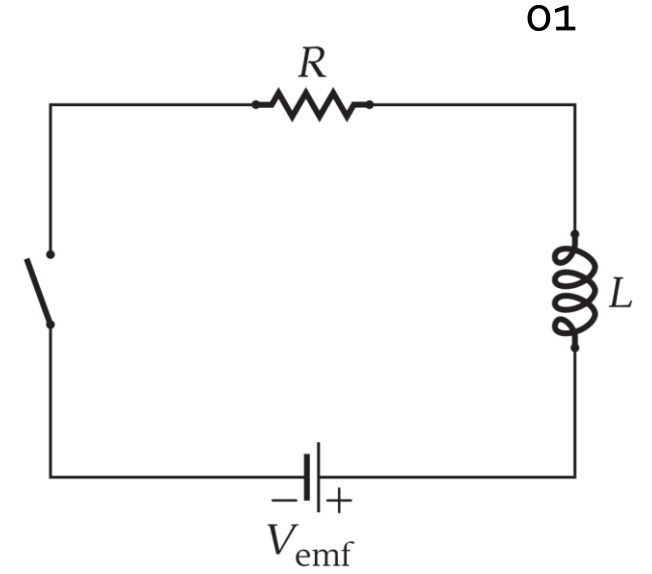


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- a) increases.
- b) decreases.
- c) stays the same.

$$\tau_{\text{RL}} = \frac{L}{R}$$

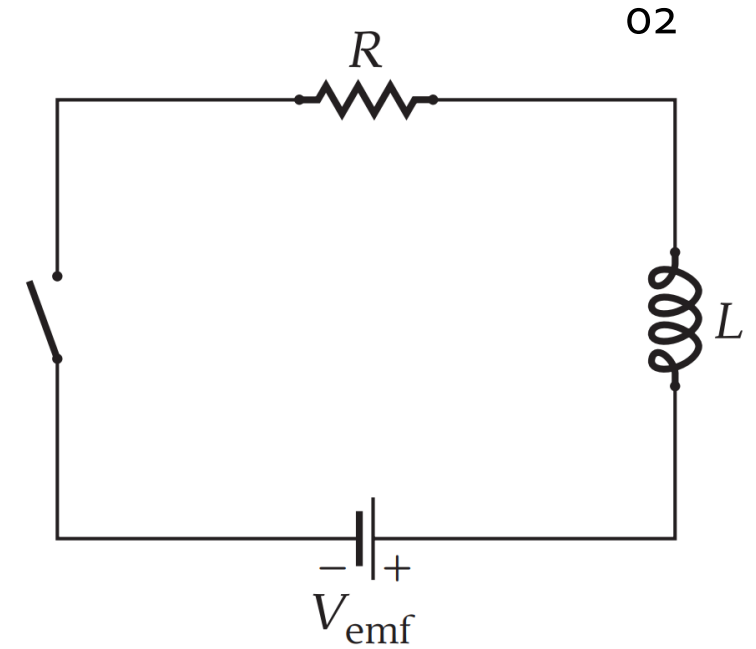


شرح السؤال



Solved Problem 9.3

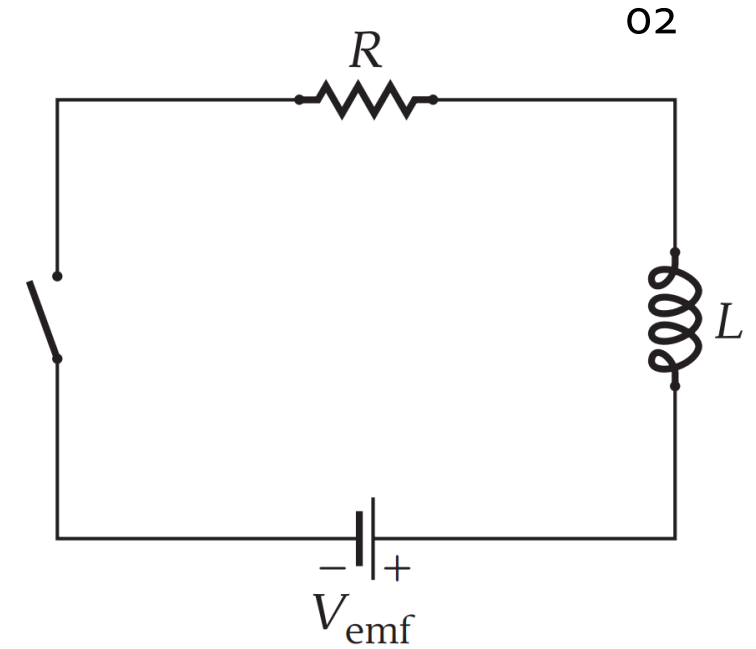
A series circuit contains a battery that supplies $V_{\text{emf}} = 40.0 \text{ V}$, an inductor with $L = 2.20 \text{ H}$, a resistor with $R = 160.0 \text{ } \Omega$, and a switch, connected as shown. The switch is closed at time $t = 0$. How much work is done by the battery between $t = 0$ and $t = 1.65 \times 10^{-2} \text{ s}$?



Solved Problem 9.3

A series circuit contains a battery that supplies $V_{\text{emf}} = 40.0 \text{ V}$, an inductor with $L = 2.20 \text{ H}$, a resistor with $R = 160.0 \Omega$, and a switch, connected as shown. The switch is closed at time $t = 0$. How much work is done by the battery between $t = 0$ and $t = 1.65 \times 10^{-2} \text{ s}$?

$$\begin{aligned} W &= \int_0^T P(t) dt = \int_0^T (V_{\text{emf}})(i_t) dt \\ &= \int_0^T (V_{\text{emf}}) \left(\frac{V_{\text{emf}}}{R} (1 - e^{-t/(L/R)}) \right) dt \\ &= \int_0^{1.65 \times 10^{-2}} (40) \left(\frac{40}{160} (1 - e^{-t/(2.2/160)}) \right) dt = 0.0689 \text{ J} \end{aligned}$$



Solved Problem 9.3

A series circuit contains a battery that supplies $V_{\text{emf}} = 40.0 \text{ V}$, an inductor with $L = 2.20 \text{ H}$, a resistor with $R = 160.0 \Omega$, and a switch, connected as shown. The switch is closed at time $t = 0$. How much work is done by the battery between $t = 0$ and $t = 1.65 \times 10^{-2} \text{ s}$?

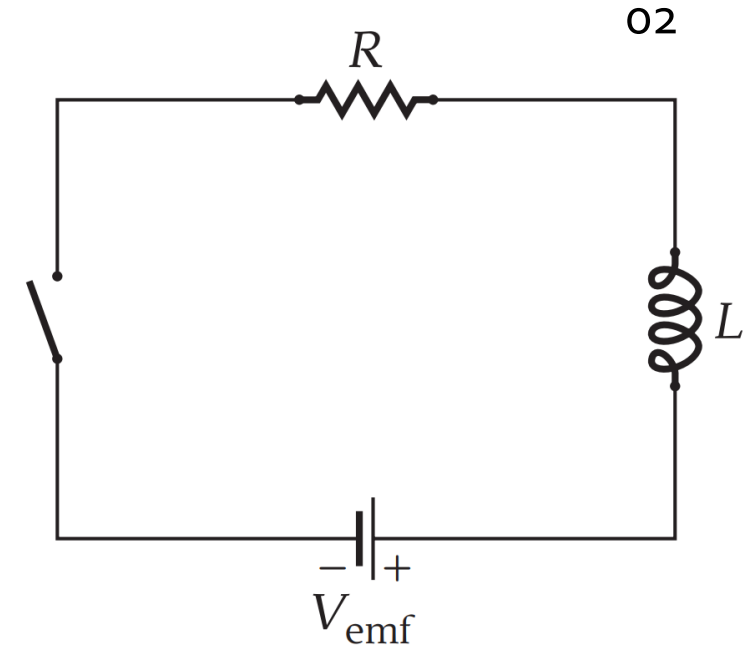
$$P(t) = V_{\text{emf}} i(t),$$

$$i(t) = \frac{V_{\text{emf}}}{R} \left(1 - e^{-t/\tau_{\text{RL}}} \right),$$

$$W = \int_0^T P(t) dt,$$

$$W = \int_0^T \frac{V_{\text{emf}}^2}{R} \left(1 - e^{-t/\tau_{\text{RL}}} \right) dt.$$

$$W = 6.89 \times 10^{-2} \text{ J}.$$



Exercise 9.49

Consider an RL circuit with resistance $R = 1.00 \text{ M}\Omega$ and inductance $L = 1.00 \text{ H}$, which is powered by a 10.0-V battery.

- a) What is the time constant of the circuit?
- b) If the switch is closed at time $t = 0$, what is the current just after that time? After $2.00 \mu\text{s}$? When a long time has passed?

Exercise 9.49

Consider an RL circuit with resistance $R = 1.00 \text{ M}\Omega$ and inductance $L = 1.00 \text{ H}$, which is powered by a 10.0-V battery.

- What is the time constant of the circuit?
- If the switch is closed at time $t = 0$, what is the current just after that time? After $2.00 \mu\text{s}$? When a long time has passed?

$$\tau_{\text{RL}} = \frac{L}{R} = \frac{1}{1 \times 10^6} = 1 \times 10^{-6} \text{ s}$$

$$i(t) = \frac{V_{\text{emf}}}{R} (1 - e^{-t/(L/R)})$$

$$i(0) = \frac{10}{1 \times 10^6} (0) = 0 \text{ A}$$

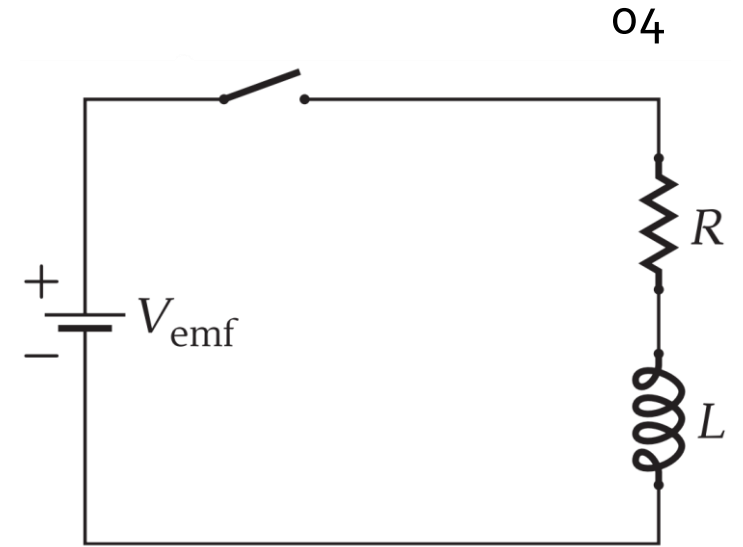
$$i(2 \times 10^{-6}) = \frac{10}{1 \times 10^6} (1 - e^{-2 \times 10^{-6}/1 \times 10^{-6}}) = 8.65 \times 10^{-6} \text{ A}$$

$$i(\infty) = \frac{10}{1 \times 10^6} = 1 \times 10^{-5} \text{ A}$$

شرح السؤال

Exercise 9.50

In the circuit in the figure, $R = 120. \Omega$, $L = 3.00 \text{ H}$, and $V_{\text{emf}} = 40.0 \text{ V}$. After the switch is closed, how long will it take the current in the inductor to reach $300. \text{ mA}$?



Exercise 9.50

In the circuit in the figure, $R = 120. \Omega$, $L = 3.00 \text{ H}$, and $V_{\text{emf}} = 40.0 \text{ V}$. After the switch is closed, how long will it take the current in the inductor to reach $300. \text{ mA}$?

$$i(t) = i_{\text{max}}(1 - e^{-t/\tau})$$

$$\frac{i(t)}{i_{\text{max}}} = 1 - e^{-t/\tau}$$

$$e^{-\frac{t}{\tau}} = 1 - \frac{i(t)}{i_{\text{max}}}$$

$$-\frac{t}{\tau} = \ln\left(1 - \frac{i(t)}{i_{\text{max}}}\right)$$

$$t = -\tau \ln\left(1 - \frac{i(t)}{i_{\text{max}}}\right)$$

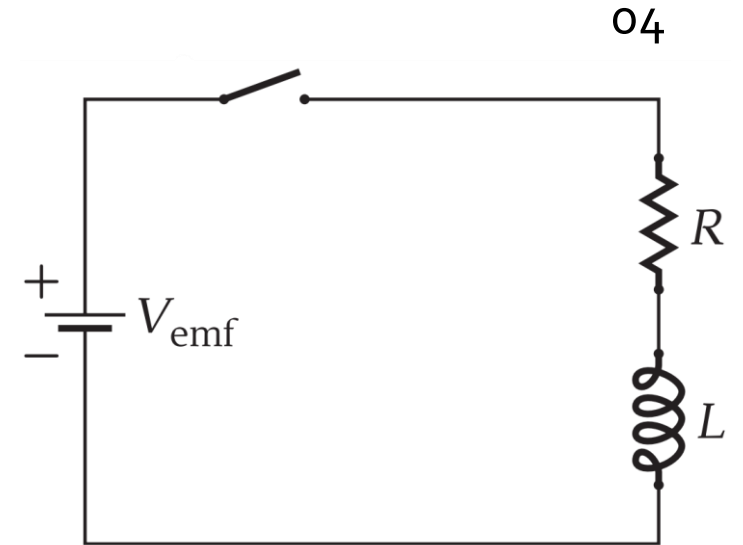
$$t = -\left(\frac{3}{120}\right) \ln\left(1 - \frac{0.3}{40/120}\right) \\ = 0.0576 \text{ s}$$

Or substitute directly in calculator and SHIFT + SOLVE

$$i(t) = \frac{V_{\text{emf}}}{R} (1 - e^{-t/(L/R)})$$

$$0.3 = \frac{40}{120} (1 - e^{-t/(3/120)})$$

$$t = 0.0576 \text{ s}$$



شرح السؤال



Exercise 9.51

The current is increasing at a rate of **3.60 A/s** in an RL circuit with **$R = 3.25 \, \Omega$** and **$L = 440. \text{ mH}$** . What is the potential difference across the circuit at the moment when the current in the circuit is **3.00 A**?

Exercise 9.51

The current is increasing at a rate of **3.60 A/s** in an RL circuit with **$R = 3.25 \Omega$** and **$L = 440. \text{ mH}$** . What is the potential difference across the circuit at the moment when the current in the circuit is **3.00 A**?

$$\begin{aligned}
 V_{emf} &= L \frac{di}{dt} + iR \\
 &= (0.44)(3.6) + (3)(3.25) \\
 &= \mathbf{11.3 \text{ V}}
 \end{aligned}$$

The potential drop is the sum of the potential drop across the resistor and the inductor:

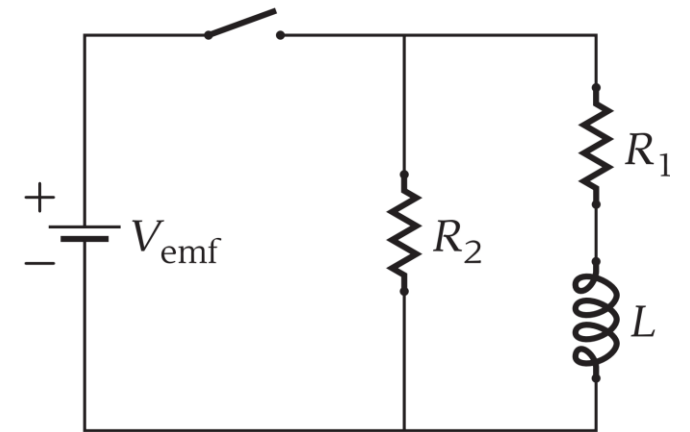
$$\Delta V = iR + L \frac{di}{dt} = (3.0 \text{ A})(3.25 \Omega) + (0.440)(3.6 \text{ A/s}) = 11 \approx 11.3 \text{ V}.$$

شرح السؤال

Exercise 9.52

In the circuit in the figure, a battery supplies $V_{\text{emf}} = 18.0 \text{ V}$ and $R_1 = 6.00 \Omega$, $R_2 = 6.00 \Omega$, and $L = 5.00 \text{ H}$. Calculate each of the following **immediately** after the switch is closed:

- a) the current flowing out of the battery
- b) the current through R_1
- c) the current through R_2
- d) the potential difference across R_1
- e) the potential difference across R_2
- f) the potential difference across L
- g) the rate of current change across R_1



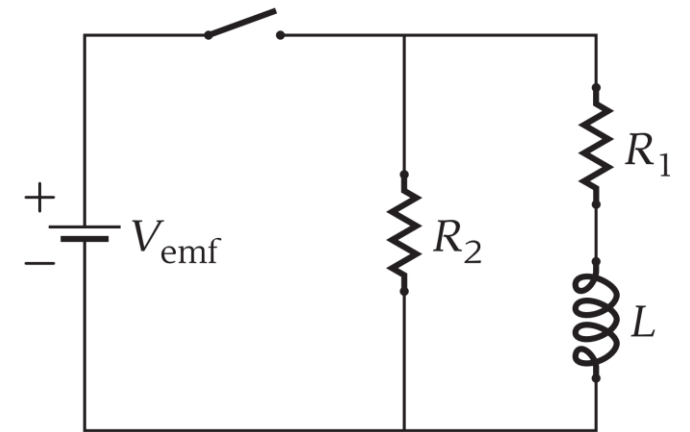
Exercise 9.52

In the circuit in the figure, a battery supplies $V_{\text{emf}} = 18.0 \text{ V}$ and $R_1 = 6.00 \Omega$, $R_2 = 6.00 \Omega$, and $L = 5.00 \text{ H}$. Calculate each of the following **immediately** after the switch is closed:

- the current flowing out of the battery
- the current through R_1
- the current through R_2
- the potential difference across R_1
- the potential difference across R_2
- the potential difference across L
- the rate of current change across R_1

- (a) The inductor functions as an open-circuit, so $i = V_{\text{emf}} / R_2 = 18 \text{ V} / 6.0 \Omega = 3.0 \text{ A}$.
- (b) The inductor acts as an open-circuit, so there is no current across it and hence no current across R_1 .
- (c) The current across R_2 is given by Ohm's Law, $i = V_{\text{emf}} / R$.
- (d) The potential difference across a resistor is also given by Ohm's Law, $\Delta V = iR$.
- (e) Same as (d).
- (f) The sum of the voltages around any loop is zero.
- (g) The rate of current change across R_1 is the same as that of L .

9.8 – RL Circuits



– Continued

شرح السؤال



Exercise 9.52

06

In the circuit in the figure, a battery supplies $V_{\text{emf}} = 18.0 \text{ V}$ and $R_1 = 6.00 \Omega$, $R_2 = 6.00 \Omega$, and $L = 5.00 \text{ H}$. Calculate each of the following **immediately** after the switch is closed:

- a) the current flowing out of the battery
- b) the current through R_1
- c) the current through R_2
- d) the potential difference across R_1
- e) the potential difference across R_2
- f) the potential difference across L
- g) the rate of current change across R_1

c. $i_{R_2} = i_{\text{max}} = \frac{V_{\text{emf}}}{R_2} = \frac{18}{6} = 3 \text{ A}$

d. $\Delta V_{R_1} = 0 \text{ V}$

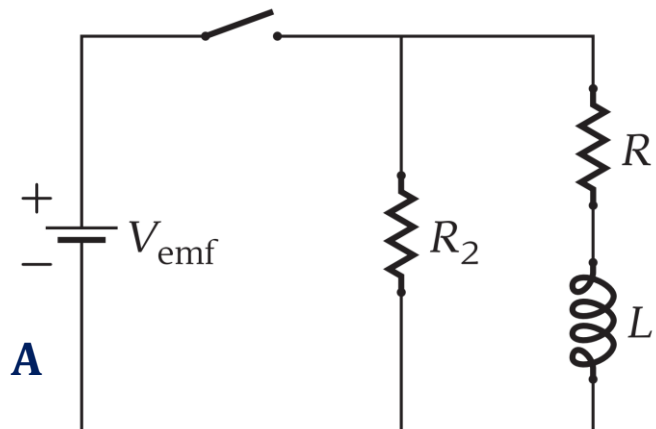
e. $\Delta V_{R_2} = iR_2 = (3)(6) = 18 \text{ V}$

f. $\Delta V_{\text{emf}} - V_L - V_{R_1} = 0 = 18 \text{ V}$

$$V_L = \Delta V_{\text{emf}} - V_{R_1} = 18 - 0 = 18 \text{ V}$$

g. $V_L = L \frac{di}{dt}$

$$\frac{di}{dt} = \frac{V}{L} = \frac{18}{5} = 3.6 \text{ A/s}$$

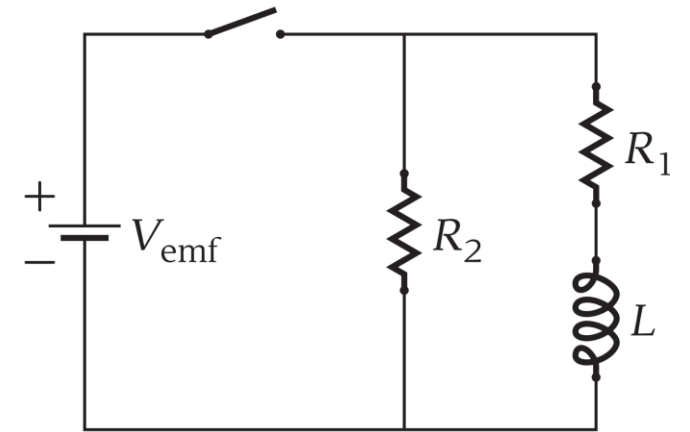


شرح السؤال

Exercise 9.53

In the circuit in the figure, a battery supplies $V_{\text{emf}} = 18.0 \text{ V}$ and $R_1 = 6.00 \Omega$, $R_2 = 6.00 \Omega$, and $L = 5.00 \text{ H}$. Calculate each of the following a **long time** after the switch is closed:

- a) the current flowing out of the battery
- b) the current through R_1
- c) the current through R_2
- d) the potential difference across R_1
- e) the potential difference across R_2
- f) the potential difference across L
- g) the rate of current change across R_1



Exercise 9.53

In the circuit in the figure, a battery supplies $V_{\text{emf}} = 18.0 \text{ V}$ and $R_1 = 6.00 \Omega$, $R_2 = 6.00 \Omega$, and $L = 5.00 \text{ H}$. Calculate each of the following a long time after the switch is closed:

- the current flowing out of the battery
- the current through R_1
- the current through R_2
- the potential difference across R_1
- the potential difference across R_2
- the potential difference across L
- the rate of current change across R_1

$$\text{a. } i_t = \frac{V_{\text{emf}}}{R_{\text{eq}}} = \frac{18}{3} = 6 \text{ A}$$

$$\text{b. } i_{R_1} = \frac{V_{\text{emf}}}{R_1} = \frac{18}{6} = 3 \text{ A}$$

$$\text{c. } i_{R_2} = \frac{V_{\text{emf}}}{R_2} = \frac{18}{6} = 3 \text{ A}$$

$$\text{d. } \Delta V_{R_1} = iR_1 = (3)(6) = 18 \text{ V}$$

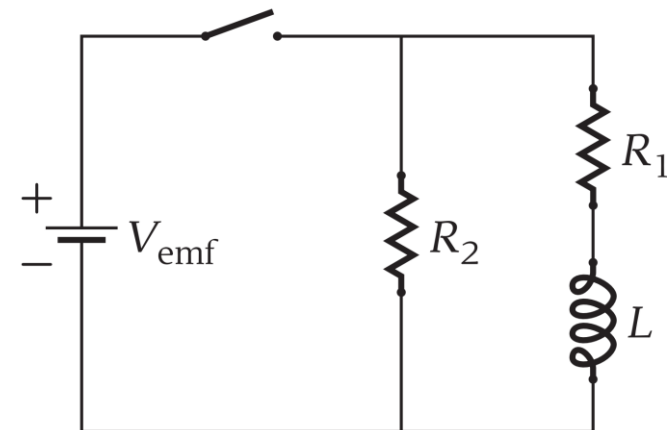
$$\text{e. } \Delta V_{R_2} = iR_2 = (3)(6) = 18 \text{ V}$$

$$\text{f. } \Delta V_{\text{emf}} - V_L - V_{R_1} = 0 = 18 \text{ V}$$

$$V_L = \Delta V_{\text{emf}} - V_{R_1} = 18 - 18 = 0 \text{ V}$$

$$\text{g. } V_L = L \frac{di}{dt}$$

$$\frac{di}{dt} = \frac{V}{L} = \frac{0}{5} = 0 \text{ A/s}$$



شرح السؤال

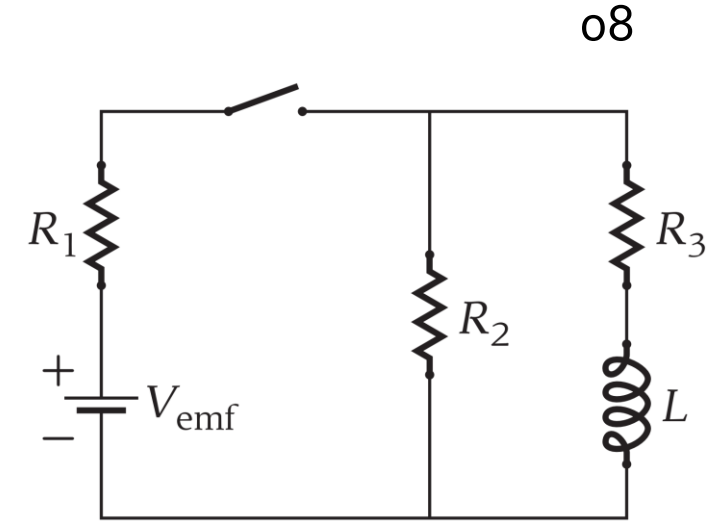
Exercise 9.54

A circuit contains a battery, three identical resistors, and an inductor, as shown in the figure. What will be the current through each resistor

(a) immediately after the switch is closed and

(b) a long time after the switch is closed?

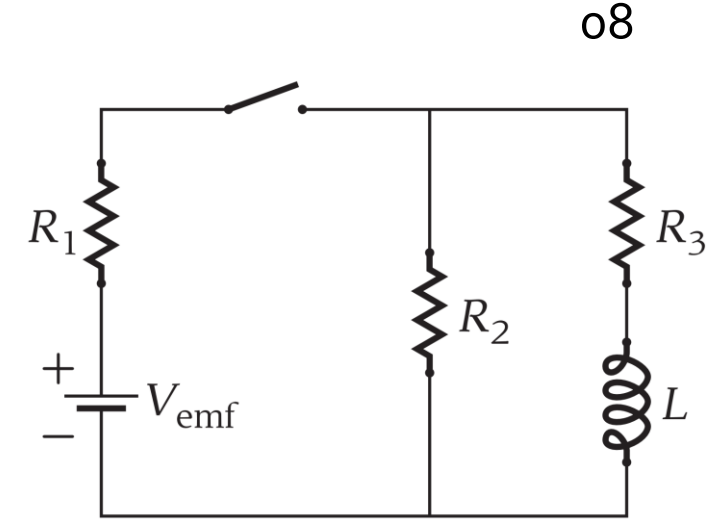
(c) Suppose the switch is reopened a long time after it has been closed. What is the current in each resistor? After a long time?



Exercise 9.54

A circuit contains a battery, three identical resistors, and an inductor, as shown in the figure. What will be the current through each resistor

- (a) immediately after the switch is closed and
- (b) a long time after the switch is closed?
- (c) Suppose the switch is reopened a long time after it has been closed. What is the current in each resistor? After a long time?



If the resistors are identical

- a. $i_t = i_1 = i_2$ $i_3 = 0$
- b. $i_t = i_1$ $i_2 = i_3$
- c. $i_1 = 0$ $i_3 = -i_2$

$$i_1 = i_2 = i_3 = 0$$



Energy and Energy Density of a Magnetic Field

Chapter 9
Lesson 9 – Revision Paper

9.9 – Energy and Energy Density of a Magnetic Field

- Energy is stored in a magnetic field.
- The energy, U_B , stored in the magnetic field of an inductor with an inductance L and carrying a current i is given by

$$U_B = \frac{1}{2} L i^2 = \frac{1}{2} (\mu_0 n^2 \ell A) i^2$$

Concept Check 9.8

A long solenoid has a circular cross section of radius $r = 8.10 \text{ cm}$, a length $\ell = 0.540 \text{ m}$, and $n = 2.00 \times 10^4 \text{ turns/m}$. The solenoid stores **42.5 mJ** of energy when it carries a current i . If the current is doubled, to $2i$, the energy stored in the solenoid

- a) decreases by a factor of 4.
- b) decreases by a factor of 2.
- c) remains the same.
- d) increases by a factor of 2.
- e) increases by a factor of 4.

Concept Check 9.8

A long solenoid has a circular cross section of radius $r = 8.10 \text{ cm}$, a length $\ell = 0.540 \text{ m}$, and $n = 2.00 \times 10^4 \text{ turns/m}$. The solenoid stores **42.5 mJ** of energy when it carries a current i . If the current is doubled, to $2i$, the energy stored in the solenoid

- a) decreases by a factor of 4.
- b) decreases by a factor of 2.
- c) remains the same.
- d) increases by a factor of 2.
- e) **increases by a factor of 4.**

شرح السؤال

Multiple Choice Questions 9.11

A long solenoid has a circular cross section of radius $r = 8.10 \text{ cm}$, a length $\ell = 0.540 \text{ m}$, and $n = 2.00 \times 10^4 \text{ turns/m}$. The solenoid is carrying a current of magnitude $i = 4.04 \times 10^{-3} \text{ A}$. How much energy is stored in the magnetic field of the solenoid?

- a) $2.11 \times 10^{-7} \text{ J}$
- b) $8.91 \times 10^{-6} \text{ J}$
- c) $4.57 \times 10^{-5} \text{ J}$
- d) $6.66 \times 10^{-3} \text{ J}$
- e) $4.55 \times 10^{-1} \text{ J}$

Multiple Choice Questions 9.11

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- d) $6.66 \times 10^{-3} \text{ J}$
- e) $4.55 \times 10^{-1} \text{ J}$

$$U_B = \frac{1}{2} Li^2 = \frac{1}{2} (\mu_0 n^2 \ell A) i^2$$

$$= \frac{1}{2} \left(\mu_0 (2 \times 10^4)^2 (0.54) (\pi (0.081)^2) \right) (4.04 \times 10^{-3})^2$$

$$= \mathbf{4.57 \times 10^{-5} \text{ J}}$$

شرح السؤال

Exercise 9.56

A clinical MRI (magnetic resonance imaging) superconducting magnet can be approximated as a solenoid with a diameter of **1.00 m**, a length of **1.50 m**, and a uniform magnetic field of **3.00 T**. Determine (b) the total energy in the solenoid.

Exercise 9.56

A clinical MRI (magnetic resonance imaging) superconducting magnet can be approximated as a solenoid with a diameter of **1.00 m**, a length of **1.50 m**, and a uniform magnetic field of **3.00 T**. Determine (b) the total energy in the solenoid.

شرح السؤال

Exercise 9.58

An emf of **20.0 V** is applied to a coil with an inductance of **40.0 mH** and a resistance of **0.500 Ω** .

- a) Determine the energy stored in the magnetic field when the current reaches $1/4$ of its maximum value.
- b) How long does it take for the current to reach this value?

Exercise 9.58

An emf of **20.0 V** is applied to a coil with an inductance of **40.0 mH** and a resistance of **0.500 Ω** .

- Determine the energy stored in the magnetic field when the current reaches $1/4$ of its maximum value.
- How long does it take for the current to reach this value?

$$i = \frac{1}{4} i_{\max} = \frac{1}{4} \left(\frac{V_{\text{emf}}}{R} \right) = \frac{1}{4} \left(\frac{20}{0.5} \right) = 10 \text{ A}$$

$$U_B = \frac{1}{2} Li^2 = \frac{1}{2} (40 \times 10^{-3}) (10)^2 = \mathbf{2 \text{ J}}$$

$$i(t) = \frac{V_{\text{emf}}}{R} (1 - e^{-t/(L/R)})$$

$$\begin{aligned} t &= -\tau \ln \left(1 - \frac{i(t)}{i_{\max}} \right) \\ &= -\frac{40 \times 10^{-3}}{0.5} \ln \left(1 - \frac{10}{40} \right) \\ &= \mathbf{0.0230 \text{ s}} \end{aligned}$$

شرح السؤال

Chapter 9 – Revision Paper

Resources

- *Electromagnetic Induction, Chapter 29, from University Physics with Modern Physics, 2e by Bauer and Westfall ©2014*

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