CHapter 9

ELECTROMAGNETIC INDUCTION

Grade 12 Advanced

T3

29.1 Faraday's Experiments

To understand Faraday's experiments, consider a wire loop connected to an ammeter. A bar magnet is some distance from the loop with its north pole pointing toward the loop. While the magnet is stationary, no current flows in the loop. However,

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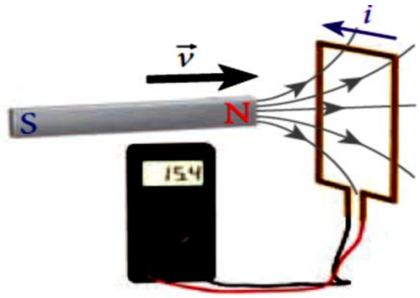
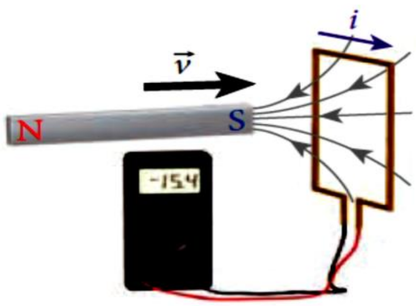


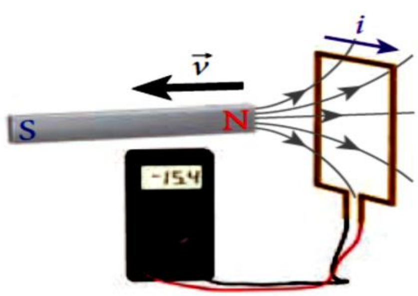
(a)

if the magnet (N pole)is moved toward the loop (Figure 9.2a), a counterclockwise current flows in the loop and (N pole)is brige.
If the magnet is moved toward the loop faster, a larger current is induced in the loop



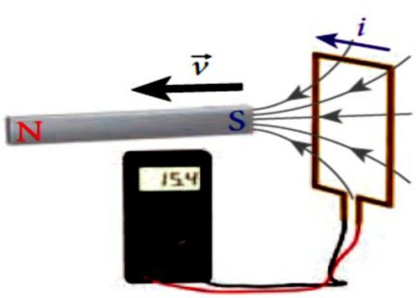
(b)

If the magnet is reversed so the south pole(S pole) points toward the loop (Figure 9.2b) and moved toward the loop, current flows in the clockwise and (N pole)is brige.

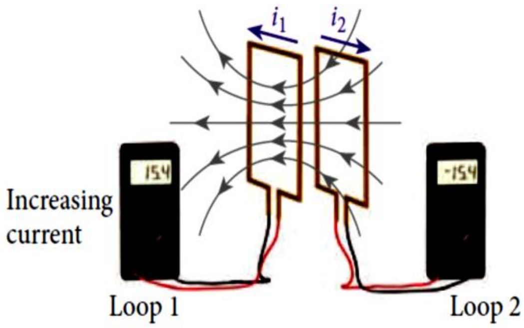


(a)

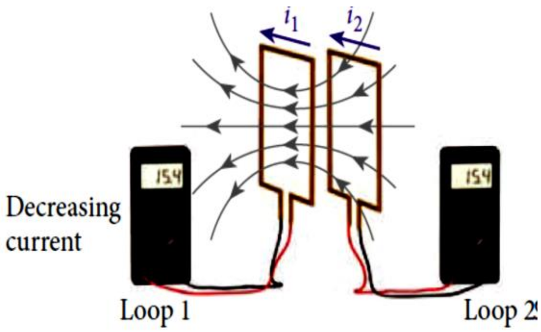
Moving a magnet (N pole)away from a wire loop also induces a clockwise current to flow in the loop the and (S pole)is brige.



Moving a magnet (S pole)away from a wire loop also induces a counterclockwise current to flow in the loop the and (N pole)is brige.



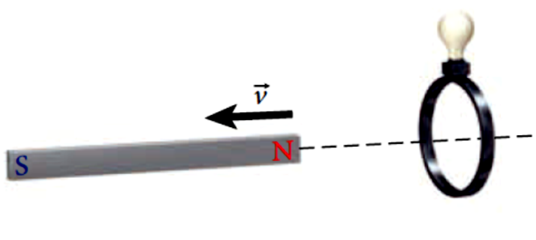
An increasing current in loop 1 induces a current in the opposite direction in loop 2. (The magnetic field lines shown are those produced by the current 1 flowing through loop 1.)



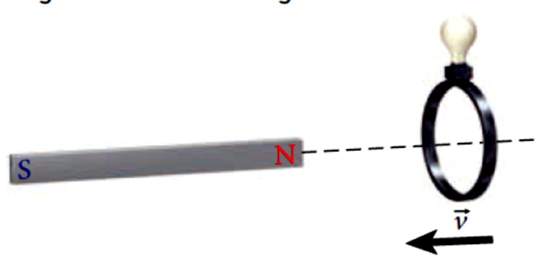
A decreasing current in loop 1 induces a current in the same direction in loop 2.

29.1 In-Class Exercise

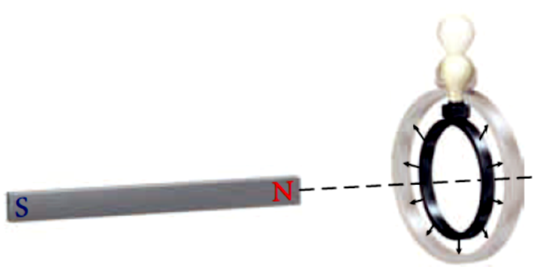
The four figures show a bar magnet and a low-voltage light bulb connected to the ends of a conducting loop. The plane of the loop is perpendicular to the dotted line. In case 1, the loop is stationary, and the magnet is moving away from the loop. In case 2, the magnet is stationary, and the loop is moving toward the magnet. In case 3, both the magnet and loop are stationary, but the area of the loop is increasing. In case 4, the magnet is stationary, and the loop is rotating about its center. In which of these situations will the light bulb be burning?



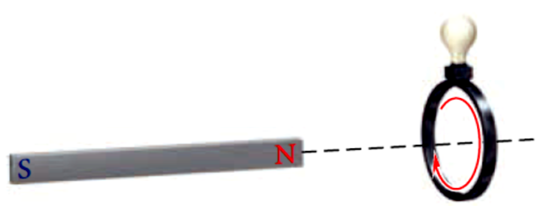
Case 1



Case 2



Case 3



Case 4

a) case 1

b) cases 1 and 2

c) cases 1, 2, and 3

d) cases 1, 2, and 4

e) all four cases

29.2 Faraday's Law of Induction

Changing magnetic field through a loop induces a current in the conductor.

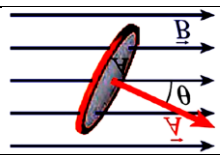
A potential difference is induced in a loop when the number of magnetic field lines passing through the loop changes with time.

> The magnitude of the potential difference, ΔV_{ind}, induced in a conducting loop is equal to the time rate of change of the magnetic flux through the loop

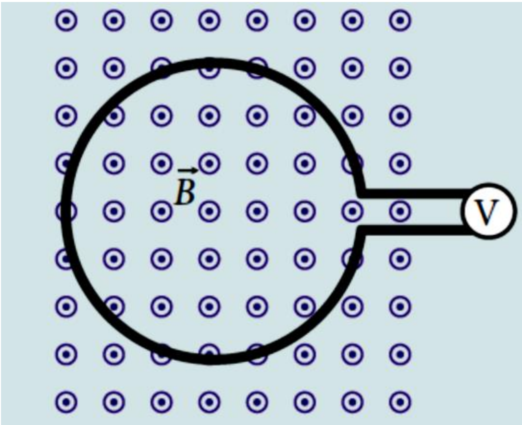
$$\Delta V_{\text{ind}} = -\frac{d\Phi_B}{dt}.$$

The negative sign in equation 29.5 is necessary because the induced potential difference establishes an induced current whose magnetic field tends to oppose the flux change

Induction in a Flat loop inside a Magnetic Field

Magnetic Flux ϕ		$\Phi_B = N B A \cos\theta$
The potential difference, ΔV_{ind}		$\Delta V_{\text{ind}} = -\frac{d\Phi_B}{dt}.$
Equation	**Variable**	**constant**
$\Delta V_{\text{ind}} = -A\cos\theta \frac{dB}{dt}$	**B**	**A و θ**
$\Delta V_{\text{ind}} = \omega AB\sin\theta$	**θ**	**B و A**
$\Delta V_{\text{ind}} = -B\cos\theta \frac{dA}{dt}$	**A**	**B و θ**
If there are more than on turn add N in equation		
$d\Phi = \Phi_f - \Phi_i$	$dA = A_f - A_i$	$dB = B_f - B_i$

9.1 Self-test Opportunity



The plane of the circular loop shown in the figure is perpendicular to a magnetic field with magnitude $B = 0.500$ 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?

Example 9.1

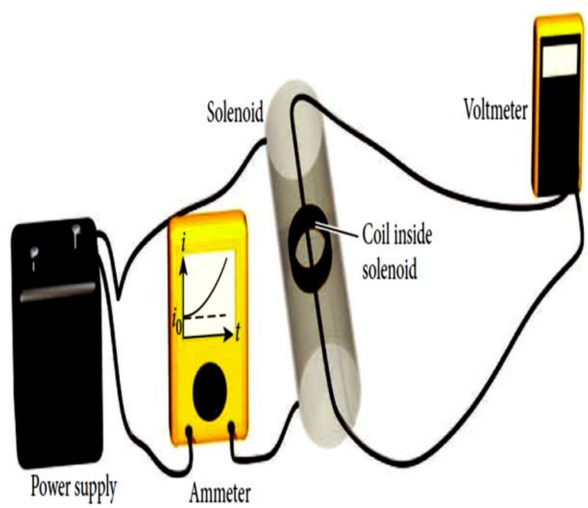
A current of 600 mA is flowing in an ideal solenoid, resulting in a magnetic field of 0.025 T. Then the current increases with time, t, according to.

$$i(t) = i_0\left[1+(2.4\ \text{s}^{-2})t^2\right].$$

Then

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

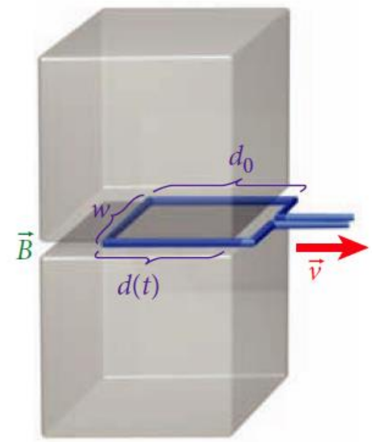
If a circular coil of radius 3.4 cm with $N = 200$ wind- ings is located inside the solenoid with its normal vector parallel to the magnetic field (Figure 29.8), what is the induced potential difference in the coil at $t = 2.0$ s?



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

Example 9.2

Potential Difference induced by a Moving loop A rectangular wire loop of width w = 3.1 cm and depth d0 = 4.8 cm is pulled out of the gap between two permanent magnets. A magnetic field of magnitude B = 0.073 T is present throughout the gap (Figure 9.9). 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?



29.3 In-Class Exercise

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?

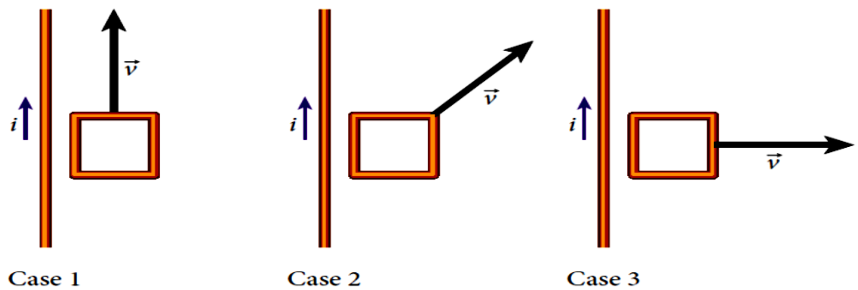
a) cases 1 and 2

b) cases 1 and 3

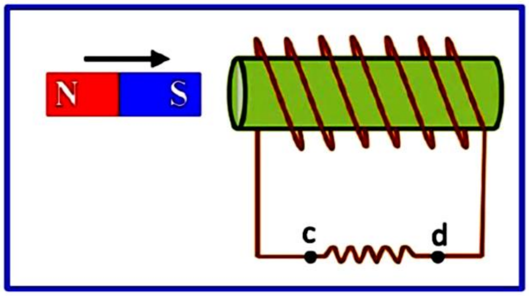
c) cases 2 and 3

d) None of the loops will have an induced current.

e) All of the loops will have an induced current.

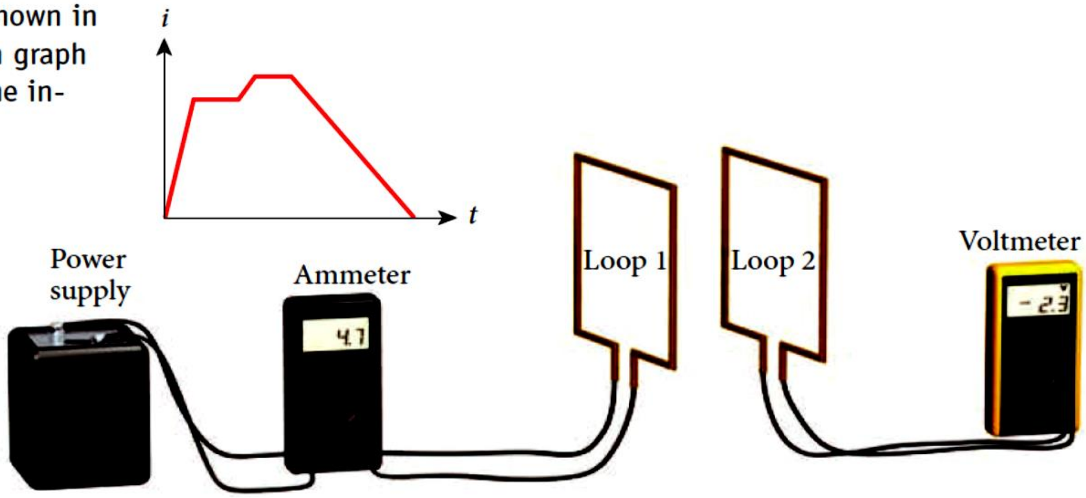


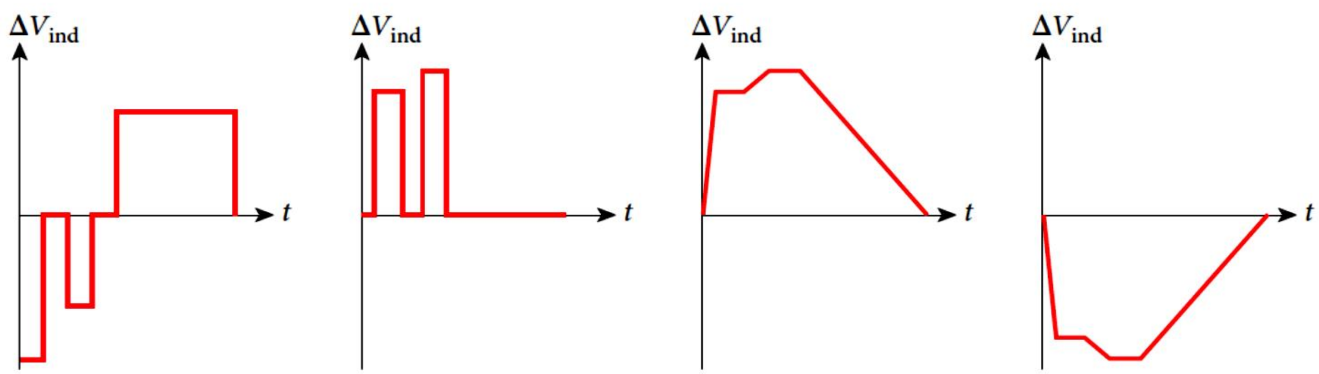
سؤال : حدد على الشكل المجاور اتجاه التيار المستحث المار في المقاومة أثناء تحريك المغناطيس نحو اليمين



29.2 In-Class Exercise

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?



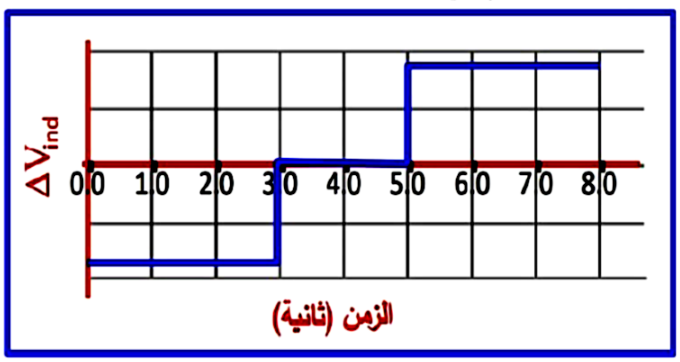


Graph 1 Graph 2 Graph 3 Graph 4

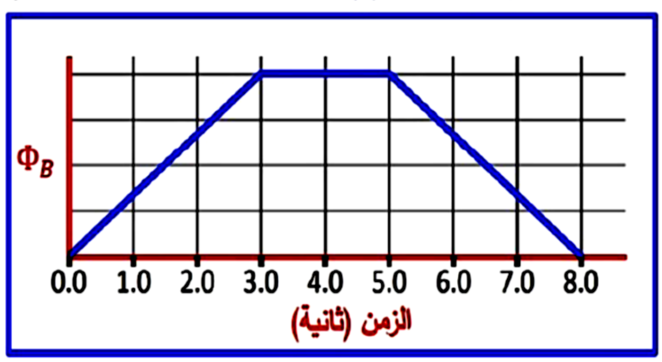
a) graph 1 b) graph 2 c) graph 3 d) graph 4

(2) الرسم التالي الشكل (1) يبين تغيرات التدفق المغناطيسي الذي يجتاز دائرة مغلقة كدالة في الزمن .

ارسم على الشكل (2) تغيرات القوة الدافعة الكهربائية (فرق الجهد المستحث) في الدائرة .



شكل (2)



شكل (1)

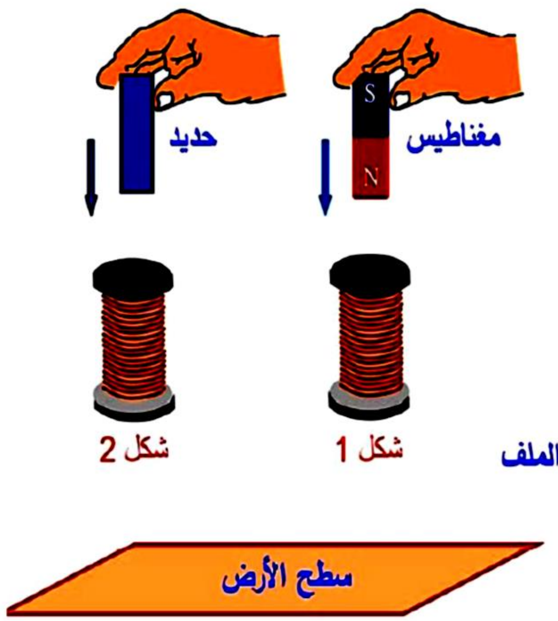
سؤال : في الشكل المجاور كتلة المغناطيس تساوي كتلة قطعة الحديد

و الملفين اللولبيين متماثلين و طويلين .

فإذا ترك كل من المغناطيسي و الحديد ليسقطا سقوطاً

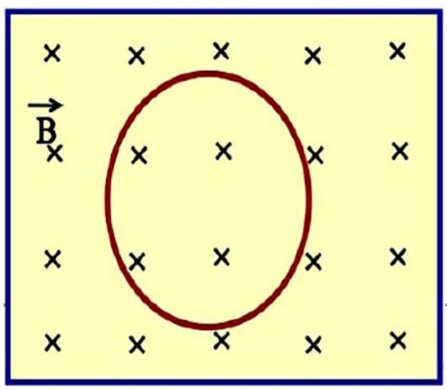
حرار داخل الملف اللولبي . أي من الآتية صحيحة .

- ☐ المغناطيس يصل إلى سطح الأرض قبل الحديد .
- ☐ الحديد يصل إلى سطح الأرض قبل المغناطيس .
- ☐ يصلان معاً في نفس اللحظة .
- ☐ قطعة الحديد تصل إلى سطح الأرض بينما المغناطيس يبقى مكانه الملف



) حلقة فلزية مساحة وجهها ($0.06\ m^2$) تقع في مستوى الصفحة و يؤثر عليها مجال مغناطيسي مقدار شدته (0.4 T) عمودي على الصفحة للداخل تم تدوير الحلقة ليصبح مستواها عمودياً على الصفحة خلال (0.05 S) .

احسب متوسط القوة المحركة الكهربائية المتولدة فيها و حد اتجاهها على الرسم .



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0.48 V (مع دوران عقارب الساعة)

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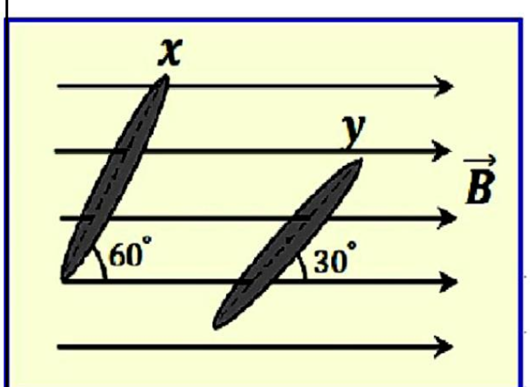
(10) يظهر الشكل المجاور حلقة معدنية عند الوضع (y) مساحة وجهها ($0.05\ m^2$) يجتازهما مجال مغناطيسي منتظم شدته (0.4 T) .

احسب متوسط القوة المحركة الكهربائية المتولدة فيه عندما تدار لتصبح في الوضع (X) خلال زمن قدره (0.02 S) .



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حل اسئلة الكتاب الاختيار من متعدد من (1:6) ص251 و من 28: 33 ص253

Exercises

9.1 A solenoid with 200 turns and a cross-sectional area of 60 cm^2 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. 0.24 V.
D. 0.001 V.

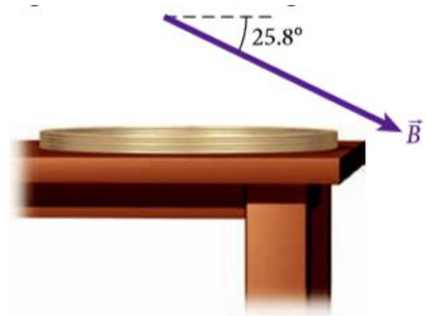
9.3 Which of the following will induce a current in a loop of wire in a uniform magnetic field?

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.

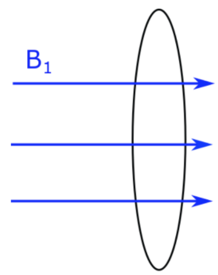
9.5 A conducting ring is moving from left to right through a uniform magnetic field, as shown in the figure. In which regions is there an induced current in the ring?

A. Regions B and D
B. Regions B, C, and D
C. Region C
D. Regions A through E

9.28 A circular coil of wire with 20 turns and a radius of 40.0 cm is lying flat on a horizontal table 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?



9.29 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 oriented perpendicular to the field?

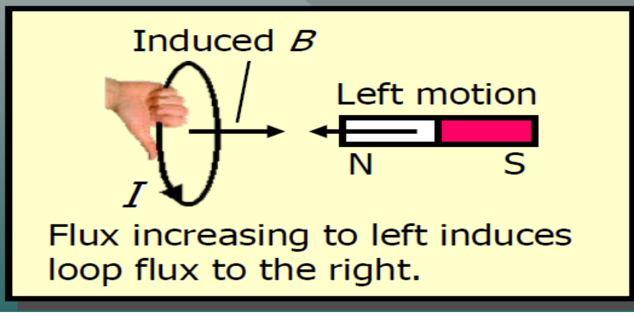


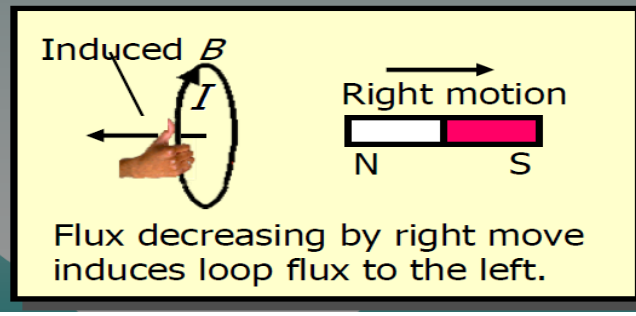
9.30 An 8-turn coil has square loops measuring 0.200 m along a side and a resistance of 3.00 Ω. It is placed in a magnetic field that makes an angle of 40.0° with the plane of each loop. The magnitude of this field varies with time according to $B = 1.50\ t^3$, what is the induced current in the coil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

9.32 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 0.426×10^{-4} T) inhales, what is the average current in the loop, if it has a resistance of 30.0 Ω 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.

29.3 Lenz's Law

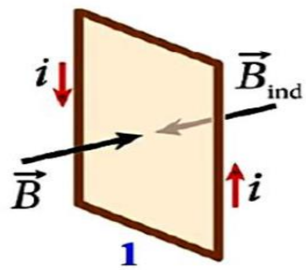
Lenz's law: An induced current will be in such a direction as to produce a magnetic field that will oppose the motion of the magnetic field that is producing it.



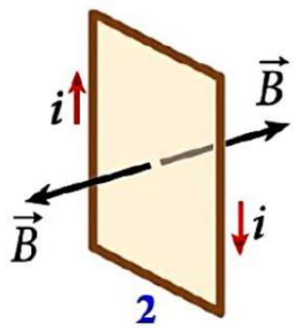


Resulting from that induced current:

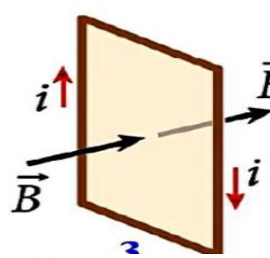
(a) An increasing magnetic field pointing to the right induces a current that creates a magnetic field pointing to the left.



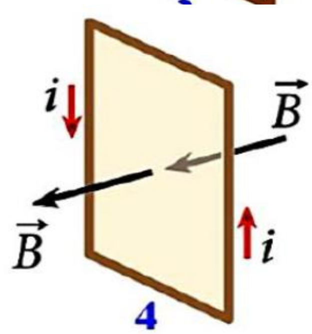
(b) An increasing magnetic field pointing to the left induces a current that creates a magnetic field pointing to the right.



(c) A de- creasing magnetic field pointing to the right induces a current that creates a magnetic field pointing to the right.

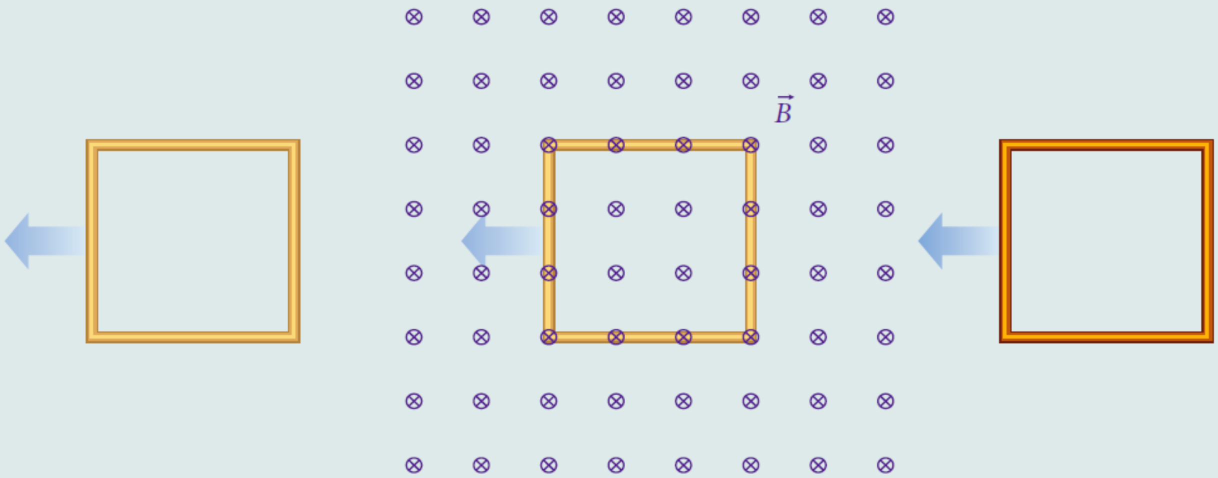


(d) A decreasing magnetic field pointing to the left induces a current that creates a magnetic field pointing to the left.



9.2 Self-test Opportunity:

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?



Eddy Currents

As the pendulum with the solid plate enters the magnetic field between the magnets.

Lenz's Law says that: the changing magnetic flux induces currents that tend to oppose the change in flux.

These currents produce induced magnetic fields opposing the external field that created the currents. These induced magnetic fields interact with the external magnetic field (via their spatial gradients) to stop the pendulum.

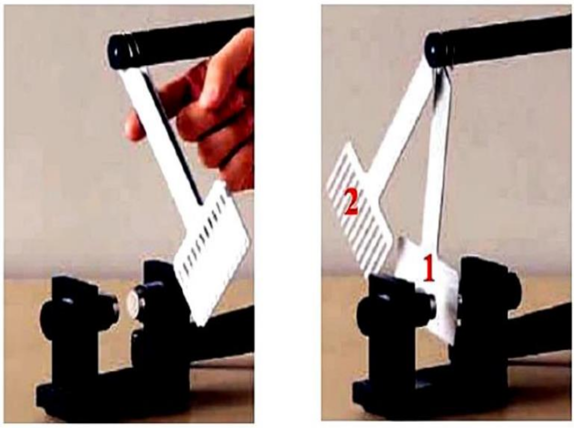
Larger induced currents produce larger induced magnetic fields and thus lead to more rapid deceleration of the pendulum.

In the slotted plate, the induced eddy currents are broken up by the slots, and the slotted plate passes through the magnetic field, only slowing slightly.

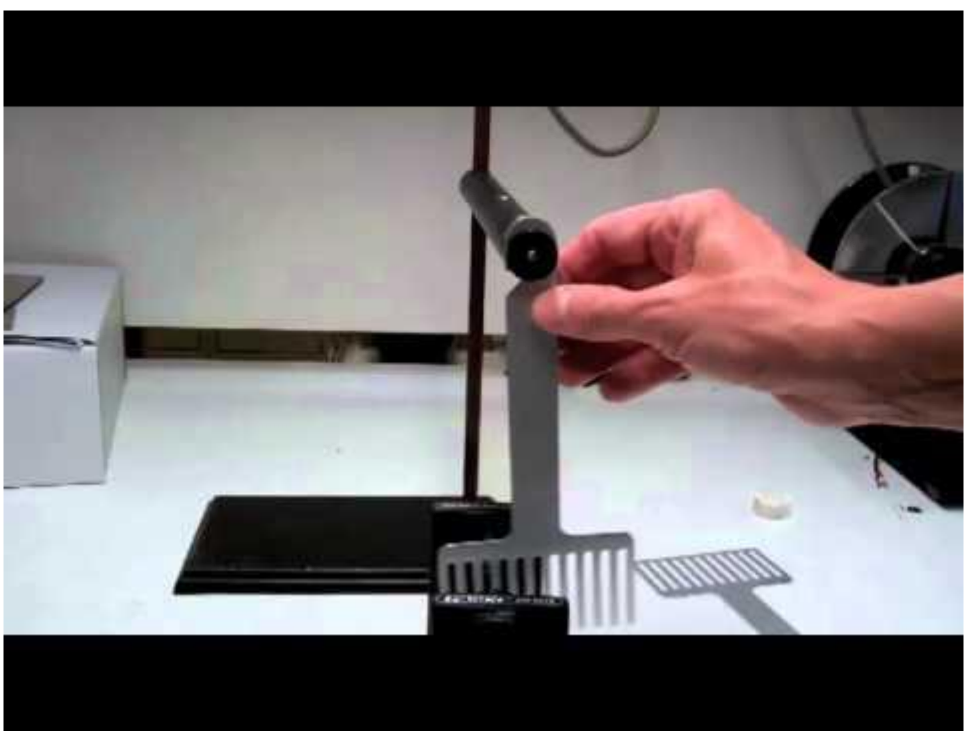
But In the solid plate, the induced eddy currents are not broken up by the solid plate, and the solid plate stop through the magnetic field.

This is why the slotted plate, with the much smaller induced eddy currents, is only slowed slightly as it passes through the gap between the magnets (although the slowing will stop it eventually). Eddy currents are often undesirable, forcing equipment designers to minimize them by segmenting or laminating electrical devices that must operate in an environment of changing magnetic fields. However, eddy currents can also be useful and are employed in certain practical applications, such as the brakes of train cars.

التيارات الدوامية



- مرور قطعة معدنية خلال مجال مخناطيسي فإنه يتولد فيها تيارات كهربائية دوامية و إذا استمرت بالاهتزاز (مثل البندول) فإن الاهتزاز يقل تدريجياً إلى أن يتوقف . لأن التيارات الدوامية تشتت الطاقة على شكل حرارة بسبب المقاومة .
- التيارات الدوامية في البندول (1) أكبر و بالتالي يتوقف بسرعة .
- البندول (2) يحتاج وقتاً أكبر لأن التيارات الدوامية في كل جزء أقل .
- غالباً التيارات الدوامية غير مرغوب فيها و خاصة في المحركات و المحولات الكهربائية . لذلك يكون القلب الحديدي على شكل شرائح رقيقة معزولة بالورنيش لتقليل التيارات الدوامية .
- هناك بعض الحالات تكون فيها التيارات الدوامية مفيدة في حالة مكابح عربات القطار .



https://www.youtube.com/watch?v=MglUIiBy2lQ

Metal Detector Passing through metal detectors, especially at airports, is an unavoidable part of life these days. A metal detector works by using electromagnetic induction, often called ***pulse induction***.

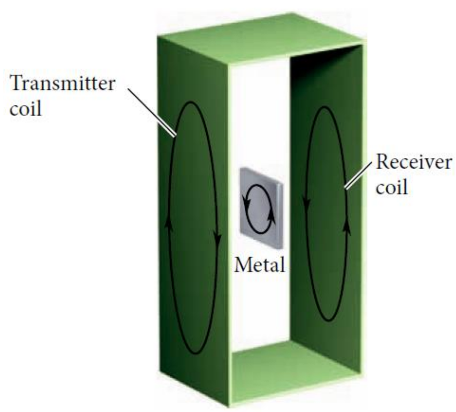
A metal detector has a transmitter coil and a receiver coil. An alternating current is applied to the transmitter coil, which then produces an alternating magnetic field. As the magnetic field of the transmitter coil increases and decreases, it induces a current in the receiving coil that tends to counteract the change in the magnetic flux produced by the transmitter coil.

The induced current in the receiver coil is measured when nothing but air is between the coils.

If a conductor in the form of a metal object passes between transmitter and receiver coils, a current will be induced in the metal object in the form of eddy currents.

These eddy currents will act to counter the increase and decrease in the changing magnetic field produced by the transmitter coil, which in turn induces a current in the receiver coil that tends to counter the increase in current in the metal.

The measured current in the receiver coil will be less when any metal object is present between the two coils. A schematic diagram of an airport metal detector is shown in Figure 9.12.



A transmitter coil and a receiver coil are located on opposite sides of an entry door. The person or object to be scanned passes through the door between the two coils. Suppose that the current in the transmitter coil is flowing in the direction shown and increasing. A current will

Thus, the overall effect of the metal plate in the metal detector is to decrease the observed current in the receiver coil. The metal object does not have to be a flat plate; any piece of metal, provided it is large enough, will have currents induced in it that can be detected by measuring the induced current in the receiver coil.

Metal detectors are also used **to control traffic lights.** In this application, a rectangular wire loop, which serves as both transmitter and receiver coil, is embedded in the road surface. A pulse of current is passed through the loop, which induces eddy currents in any metal near the loop. The current in the loop is measured after the current pulse is completed. When a car moves onto the road surface above the loop, eddy currents induced in the metal of the car cause a different current to be measured between pulses, which then triggers the traffic light to switch to green

Induced Potential Difference on a Wire Moving in a Magnetic Field

1- Watch this video to understand the idea

https://www.youtube.com/watch?v=GR44Ajut3hU

$$F_B = evB = F_E = eE.$$

$$E = vB.$$

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

$$\Delta V_{\text{ind}} = v\ell B.$$

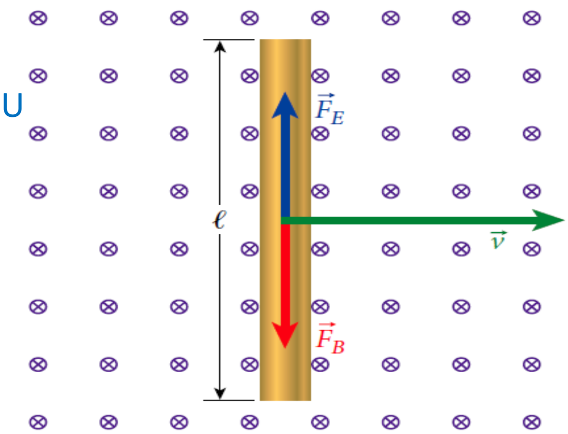
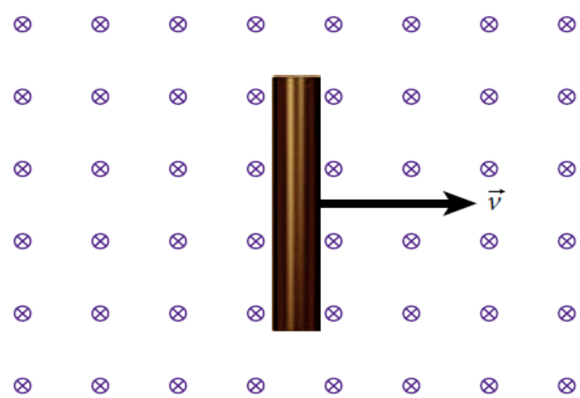


FIGURE 29.13 A moving conductor in a constant magnetic field. The magnetic and electric forces on the conduction electrons are shown.

29.4 In-Class Exercise

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?

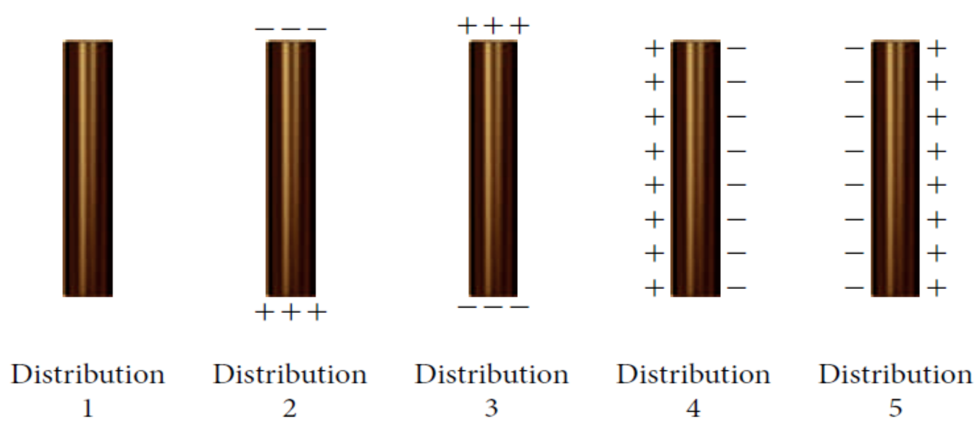
a) distribution 1

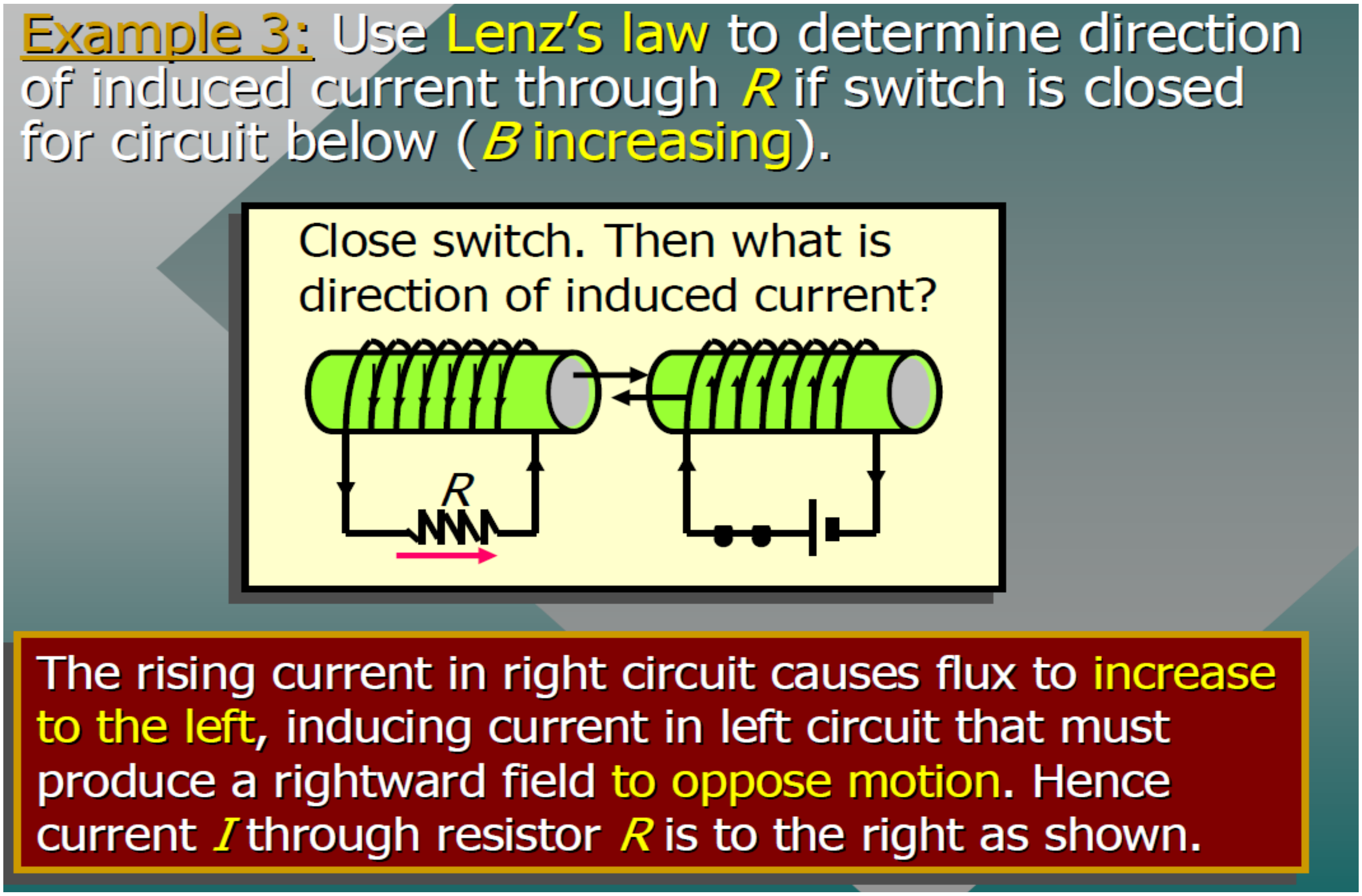
b) distribution 2

c) distribution 3

d) distribution 4

e) distribution 5



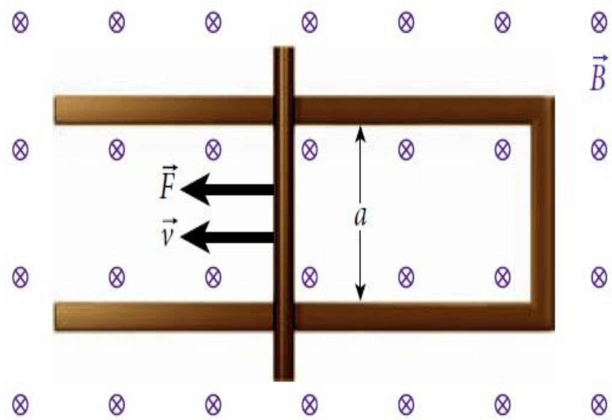


EXAMPLE 9.3 Satellite tethered to a Space Shuttle.

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 $B = 5.1\text{x}10^{-5}$ 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 .9.4 **Pulled Conducting rod.**

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



29.5 In-Class Exercise

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

a) 0.821 V

b) 2.95 V

c) 10.4 V

d) 30.1 V

e) 225 V

Book questions from 35- 41 P253

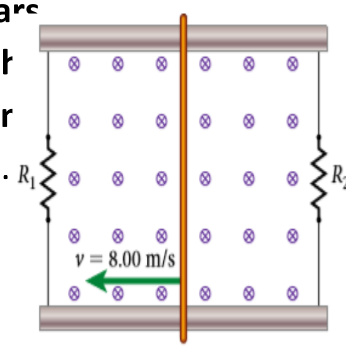
Exercises

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 in level flight at a speed of 913 km/h. Assume that the downward component of the Earth's magnetic field is B = 5.00×10^{-5} T.

A. 0.821 V
B. 2.95 V
C. 10.4 V
D. 225 V

9.62 A wire of length l= 10.0 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 to induce a potential difference of 2.00 V across it?

7.75 A conducting rod of length 50.0 cm slides over two parallel metal bars placed in a magnetic field with a magnitude of 1000. G, as shown in the figure. The ends of the rods are connected by two resistors, R1 = 100Ω and R2 = 200 Ω the conducting rod moves with a constant speed of 8.00 m/s.



A. What are the currents flowing through the two resistors?

B. What power is delivered to the resistors?

C. What force is needed to keep the rod moving with constant velocity?

from 35-39 P253

29.4 Generators and Motors

Eletric Motor: converts Electric energy to Mechanical energy

* **المحرك الكهربائي** : جهاز يحول الطاقة الكهربائية إلى طاقة حركية .

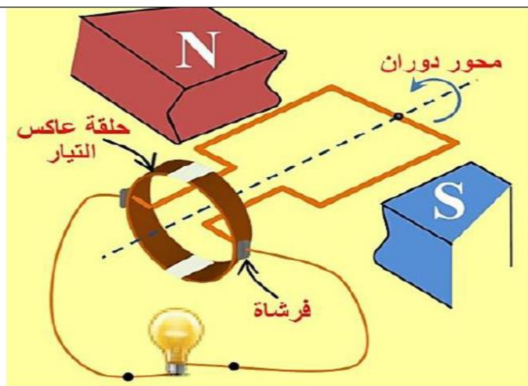
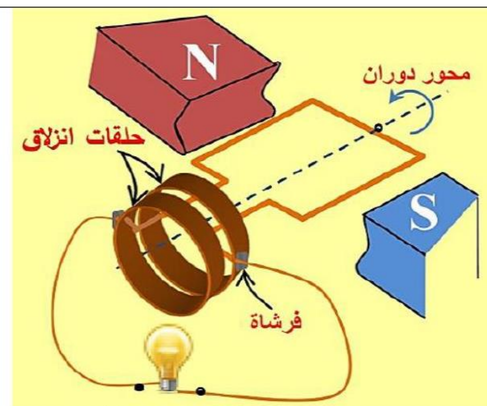
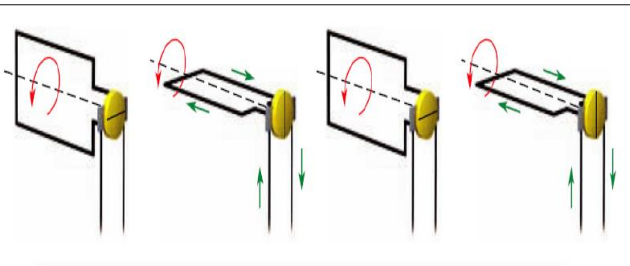
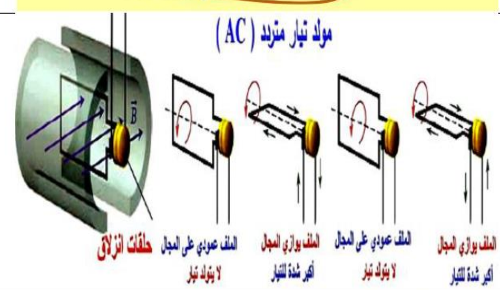
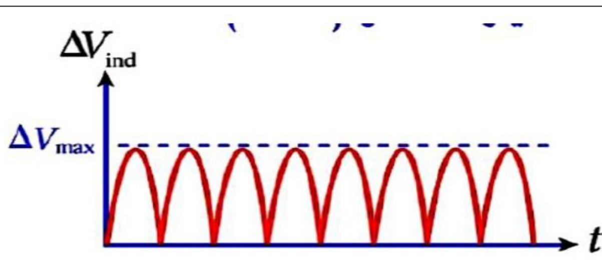
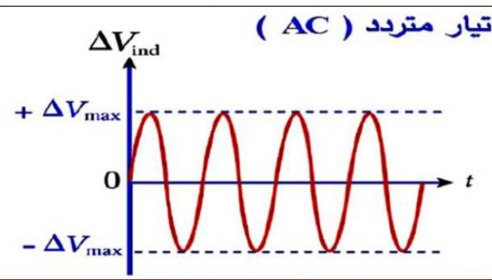
Electric Generator: Converts Mechanical energy to Electric energy

* **المولد الكهربائي** : جهاز يحول الطاقة الحركية إلى طاقة كهربائية .

في المولدات يتم تحريك الملف بعدة طرق منها :

* قوة دفع بخار الماء عن طريق حرق الوقود الاحفوري أو المفاعلات النووية
* قوة دفع الرياح
* قوة دفع الياه الساقطة (السدود و الشلالات)

https://youtu.be/fJ50PhfDXNQ

D C generator	A C generator	
تتغير شدة التيار كل لحظة لكن الاتجاه ثابت	تتغير شدة التيار كل لحظة و اتجاهه كل نصف دورة من دورات المولد و كذلك فرق الجهد	التعريف
Continuous pulse current	Induced voltage difference is a sinusoidal function	الوصف
		constructure
		Induced current
		Graph curve
$\Delta V_{ind} = NAB\omega \sin\theta$ $\Delta V_{max} = NAB\omega$	$\Delta V_{ind} = NAB\omega \sin\omega t$ $\Delta V_{ind} = \Delta V_{max} \sin\omega t$	Law

$$\omega = 2\pi f = \frac{2\pi}{T}$$

Regenerative braking Hybrid cars are propelled by a combination of gasoline power and electrical power. One attractive feature of a hybrid vehicle is that it is capable of **regenerative braking.**

When the brakes are used to slow or stop a nonhybrid vehicle, the kinetic energy of the vehicle **is turned** into heat in the brake pads.

In a hybrid car, the brakes are connected to the electric motor, which functions as a generator, charging the car's battery. Thus, the kinetic energy of the car is partially recovered during braking, and this energy can later be used to propel the car, contributing to its efficiency and greatly increasing its gas mileage in stop-and-go driving.

– المولدات عملياً أكثر تعقيداً . فبدل من المغناطيسات الدائمة تستخدم مغناطيسات كهربائية لتوليد مجال مغناطيسي .

الكبح بالتوليد المعاكس: السيارات الهجينة (تعمل على البترول و الكهرباء)

– في السيارات التي تعمل على البترول تتحول الطاقة الحركية في المكابح إلى طاقة حرارية .

– في السيارة الهجينة تتحول الطاقة الحركية من خلال محرك كهربائي إلى طاقة كهربائية (حيث يعمل المحرك كمولد للتيار) يقوم بشحن البطارية حيث يمكن إعادة استخدامها في تحريك السيارة .

9.4 Self-test Opportunity 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. Decide whether each of the following statements **is true or false.**

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 magnitude, B, is doubled.

d) The average induced potential difference doubles if the area, A, is doubled.

Q19) 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 ɸ(t) = BA cos (2Пft). If (B = 1.00 T and A = 1.00 m^2,)

what must the value of f be for the maximum induced potential difference to be 110. V?

17.5 Hz.

Q20) A motor has a single loop inside a magnetic field of magnitude (B= 0.87 T). If the area of the loop is (A= 300. cm^2),

find the maximum angular speed possible for this motor when connected to a source of emf providing 170 V.

$\omega = 6500$ Hz

Q21) Your friend decides to produce electrical power by turning a coil of (1.00 × 105 circular) loops of wire around an axis parallel to a diameter in the Earth's magnetic field, which has a local magnitude of (B= 0.300 G). The loops have a radius of (r= 25.0 cm.)

a) If your friend turns the coil at a frequency of (f= 150.0 Hz), what peak current will flow in a resistor, (R = 1500. Ω), connected to the coil?

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?

(a) $i_{ind,peak} = 0.370$ A

(b) $i_{avg} = 0.262$ A, $P_{avg} = 103$ W

regenerative braking

Hybrid cars are propelled by a combination of gasoline power and electrical power. One attractive feature of a hybrid vehicle is that it is capable of regenerative braking. When the brakes are used to slow or stop a nonhybrid vehicle, the kinetic energy of the vehicle is turned into heat in the brake pads. This heat dissipates into the environment, and energy is lost. In a hybrid car, the brakes are connected to the electric motor , which functions as a generator, charging the car's battery. Thus, the kinetic energy of the car is partially recovered during braking, and this energy can later be used to propel the car, contributing to its efficiency and greatly increasing its gas mileage in stop-and-go driving.

FIGURE 29.19 Automobile hybrid engine, cut open to show the regenerative brake system, shown in close-up view in the inset.

29.5 Induced Electric Field

Consider a positive charge q moving in a circular path with radius r in an electric field, • E. The work done on the charge is equal to the integral of the scalar product of the force and the differential displacement vector.

$$W = \oint \vec{F} \cdot d\vec{s} = q \oint \vec{E} \cdot d\vec{s}.$$

$$\oint \vec{F} \cdot d\vec{s} = \oint q\vec{E} \cdot d\vec{s} = \oint q \cos 0^\circ E ds = qE \oint ds = qE(2\pi r).$$

Since the work done by a constant electric field is $\Delta V_{ind} q$, we get

$$\Delta V_{ind} = \oint \vec{E} \cdot d\vec{s}.$$

Now we can express the induced potential difference in a different way

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}.$$

29.6 Inductance of a Solenoid

Consider a long solenoid with N turns carrying a current, i. This current creates a magnetic field in the center of the solenoid, resulting in a magnetic flux, ϕB. The same magnetic flux goes through each of the N windings of the solenoid.

$$N\Phi_B = Li,$$

L, called the inductance

The unit of inductance is the henry (H)

The flux linkage for this solenoid is

$$N\Phi_B = (n\ell)(BA),$$

$$L = \frac{\mu_o N^2 A}{\ell} = \mu_o n^2 A \ell$$

- You can see from equation that the inductance of a solenoid depends only on the geometry (length(l), area(A), and number of turns (N) of the device.
- Any solenoid has an inductance, and when a solenoid is used in an electric circuit, it is called an inductor, simply because its inductance is its most important property as far as the current flow is concerned

29.7 Self-Inductance and Mutual Induction

self-induction **"The changing current in the first coil also induces a potential difference in that coil, and thus the magnetic field from that coil also changes."**

According to Faraday's Law of Induction the self-induced potential difference for any inductor is given by

$$\Delta V_{ind,L} = -\frac{d(N\Phi_B)}{dt} = -\frac{d(Li)}{dt} = -L\frac{di}{dt},$$

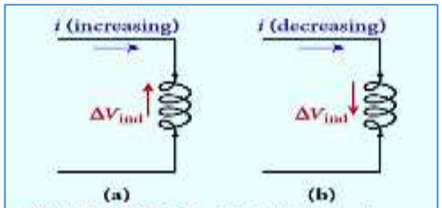


FIGURE 29.20 (a) Self-induced potential difference in an inductor when the current is increasing. (b) Self-induced potential difference in an inductor when the current is decreasing.

The negative sign in equation provides the clue that the induced potential difference always opposes any change in current

- **Figure 29.20a shows current flowing through an inductor and increasing with time. Thus, the self-induced potential difference will oppose the increase in current.**
- **In Figure 29.20b, the current flowing through an inductor is decreasing with time. Thus, a self-induced potential difference will oppose the decrease in current.**
- **We have assumed that these inductors are ideal inductors; that is, they have no resistance**

$$V_{ind,L} = -N\frac{d\Phi_B}{dt} = -L\frac{di}{dt}$$

$$d\Phi = \Phi_f - \Phi_i$$
$$di = i_f - i_i$$

mutual induction **Changing the current in the first coil also induces a potential difference in the second coil.**

Now let's consider two adjacent coils with their central axes aligned (Figure 29.21). Coil 1 has N1 turns, and coil 2 has N2 turns. The current in coil 1 produces a magnetic field, B1. The flux linkage in coil 2 resulting from the magnetic field in coil 1 is $N_2\phi_{1\to2}$. The mutual inductance, $M_{1\to2}$, of coil 2 due to coil 1 is defined as

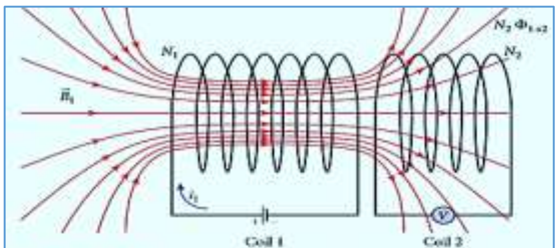


FIGURE 29.21 Coil 1 has current i_1. Coil 2 has a voltmeter capable of measuring small, induced potential differences.

$$\Delta V_{ind,2} = -M\frac{di_1}{dt} = -N_2\frac{d\Phi_{1\to2}}{dt}$$

$$\Delta V_{ind,1} = -M\frac{di_2}{dt} = -N_1\frac{d\Phi_{2\to1}}{dt}$$

$$M = \frac{NBA}{i} = \frac{N(\mu_0 ni)(\pi r_1^2)}{i} = N\pi\mu_0 nr_1^2.$$

We see that the potential difference induced in one coil is proportional to the change of current in the other coil

where M is the mutual inductance between the two coils. The SI unit of mutual inductance is the henry.

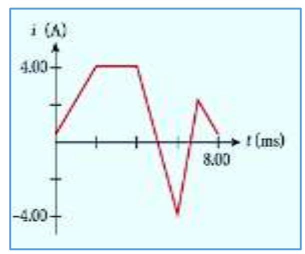
Q22) a solenoid with length (l= 20cm), it has (N= 1000 laps) with radius (r= 10cm), flowing an electrical current of (i= 4A) through it.

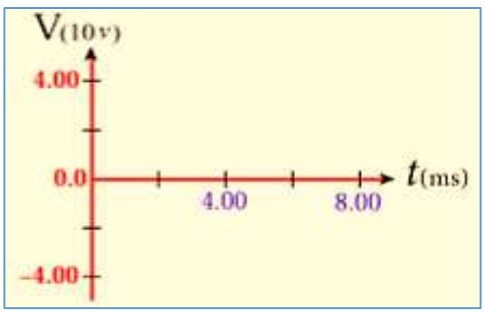
1- **calculate the solenoid inductance(L)?**
2- **What is the induced potential difference in the solenoid if the current change its direction during t = 0.2 s?**

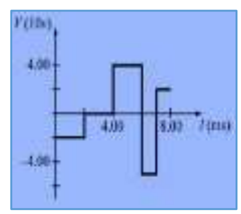
L= 0.2 H

ΔV = 7.9 V

Q23) The figure shows the current through a (L=10.0-mH) inductor over a time interval of (Δt= 8.00 ms) . Draw a graph showing the self-induced potential difference, $\Delta V_{ind,\,L}$, L, for the inductor over the same interval

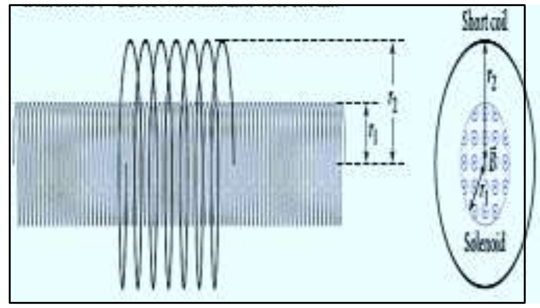






Q24) A long solenoid with circular cross section of radius (r_1 = 2.80 cm) and (n = 290 turns/cm) is inside and coaxial with a short coil with circular cross section of radius (r_2 = 4.90 cm) and (N = 31 turns), The current in the solenoid is increased at a constant rate from zero to (i = 2.20 A) over a time interval of (Δt= 48.0 ms) .

What is the potential difference induced in the short coil while the current is changing?



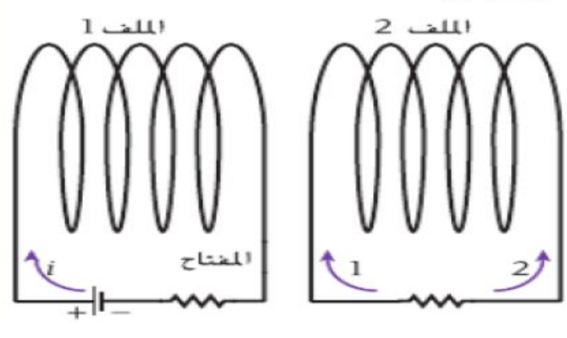
$\Delta V_{ind} = -0.128$ V.

9.6 in-Class exercise Suppose the current in the short coil in Solved Problem 9.1 is increased steadily from zero to *i* = 2.80 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

مراجعة المفاهيم 9.6

يوضح الشكل ملفين متطابقين. يمر تيار *i* في الملف 1 في الاتجاه الموضح. عند فتح المفتاح في دارة الملف 1. ماذا يحدث في الملف 2؟



a) يُستحث تيار في الملف 2 يتدفق في الاتجاه 1.

b) يُستحث تيار في الملف 2 يتدفق في الاتجاه 2.

c) لا يُستحث تيار في الملف 2.

29.9 Energy and Energy Density of a Magnetic Field

We can think of an inductor as a device that can store energy in a magnetic field

$$P = V_{\text{emf}} i = \left(L \frac{di}{dt} \right) i.$$

Now let's consider an ideal solenoid with length ℓ, cross-sectional area A, and n turns per unit length, carrying current i. The energy stored in the magnetic field of the solenoid using is

$$U_B = \tfrac{1}{2} L i^2 = \tfrac{1}{2} \mu_0 n^2 \ell A i^2.$$

The magnetic field occupies the volume enclosed by the solenoid, which is given by ℓA. Thus, the energy density, u_B, of the magnetic field of the solenoid is

$$u_B = \frac{\tfrac{1}{2} \mu_0 n^2 \ell A i^2}{\ell A} = \tfrac{1}{2} \mu_0 n^2 i^2.$$

Since $B = \mu_0 n i$ for a solenoid, the energy density of the magnetic field of a solenoid can be expressed as

$$u_B = \frac{1}{2\mu_0} B^2.$$

Q25) Consider a long solenoid with a circular cross section of radius ($r = 8.10$ cm) and ($n = 2.0\times 10^4$ turns/m). The solenoid has length ($l = 0.540$ m) and is carrying a current of magnitude ($i = 4.04 \times 10^{-3}$ A.

How much energy is stored in the magnetic field of the solenoid?

$4.55 \cdot 10^{-5}$ J

Q26) Having just learned that there is energy associated with magnetic fields, an inventor sets out to tap the energy associated with the Earth's magnetic field.

What volume of space near Earth's surface contains 1 J of energy, assuming the strength of the magnetic field to be ($B= 5.0 \times 10^{-5}$ T)?

$1.01 \cdot 10^3\ m^3$.

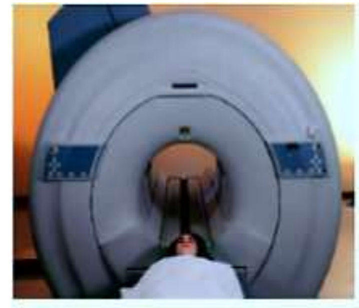
This volume is equivalent to a 10 m by 10 m by 10 m cube. This is a fraction of the size of a house.

Q27) Consider a clinical MRI (magnetic resonance imaging) superconducting magnet has a diameter of (d= 1.00 m) , length of(⌊= 1.50 m) , and a uniform magnetic field of(b= 3.00 T).

Determine

(a) the energy density of the magnetic field and

(b) the total energy in the solenoid.



$3.58 \cdot 10^6$ J/m^3.

$4.22 \cdot 10^6$ J

Q28) A magnetar (magnetic neutron star) has a magnetic field near its surface of magnitude (B=4.0 × 10^{10} T) .

Calculate the energy density of this magnetic field.

$6.366 \cdot 10^{26}$ J/m^3

29.10 Applications to Information Technology

Computers and many consumer electronics devices use magnetization and induction to store and retrieve information. Examples are computer hard drives, videotapes, audiotapes, and the magnetic strips on credit cards. During the last decade, the use of storage media based on other technologies, such as the optical storage of information on CDs and DVDs and the flash memory cards in digital cameras, has increased; however, magnetic storage devices are still a technological mainstay and the basis of a multibillion dollar industry

Computer hard Drive

One device that stores information using magnetization and induction is the computer hard drive. The hard drive stores information in the form of bits, the binary code consisting of zeros and ones. Eight bits make a byte, which can represent a number or an alphanumeric character. A modern hard drive can hold up to 2 terabyte (1012 bytes) of information. A hard drive consists of one or more rotating platters with a ferromagnetic coating accessed by a movable read/write head, as shown in Figure 29.29.

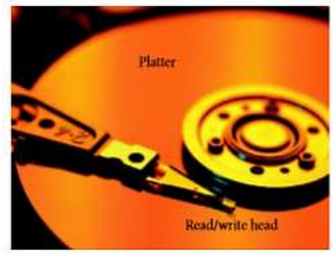


FIGURE 29.29 The read/write head and spinning platter inside a computer hard drive.

The read/write head can be positioned to access any one of many tracks on the rotating platter. The operation of a read/write head in a conventional hard drive is illustrated in Figure 29.30a. As the coated platter moves below the read/write head, a pulse of current in one direction magnetizes the surface of the platter to represent a binary one, or a pulse of current in the opposite direction magnetizes the surface representing a binary zero. In Figure 29.30a, a binary one is represented by a red arrow pointing to the right, and a binary zero is represented by a green arrow pointing to the left. In read mode, when the magnetized areas of the platter pass beneath the read sensor, a positive or negative current is induced, and the electronics of the hard drive can tell if the information is a zero or a one. The method used to encode and read back data shown in Figure 29.30 is called longitudinal encoding because the magnetic fields of the magnetized areas of the platter are parallel or antiparallel to the motion of the platter. The data storage capacity of hard drives has been increased by making the magnetized areas smaller and by adding more platters and read/write heads

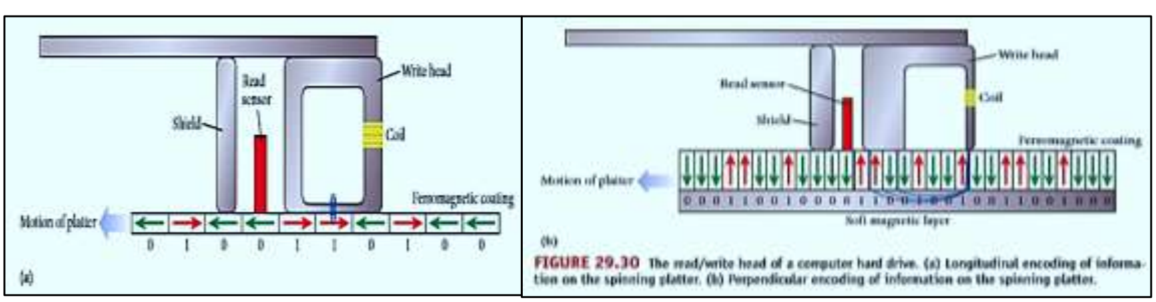


FIGURE 29.30 The read/write head of a computer hard drive. (a) Longitudinal encoding of information on the spinning platter. (b) Perpendicular encoding of information on the spinning platter.