Electromagnetic Theory

CREDIT HOURS FIRST LEVEL(PHYSICS /PHYSICS AND COMPUTER SCIENCE PROGRAM)

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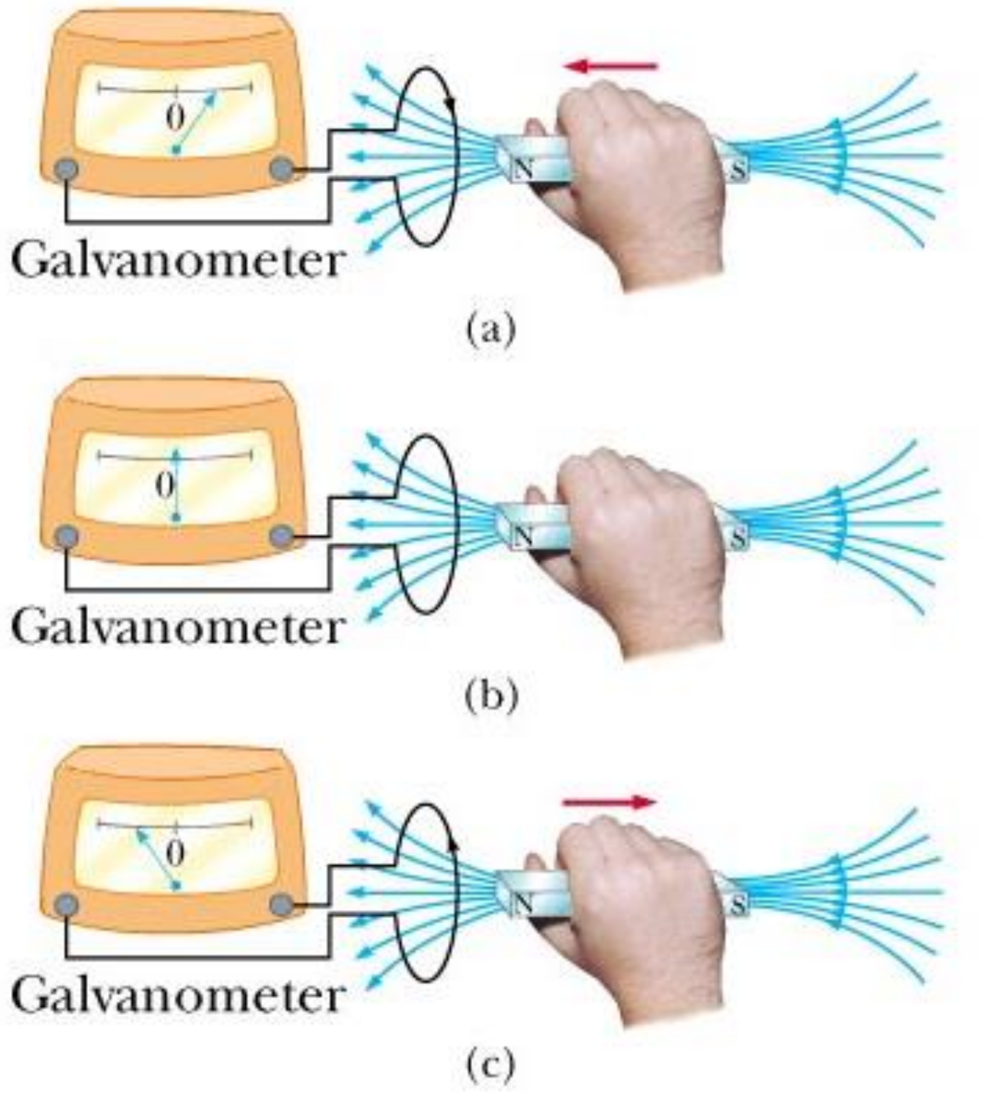
Chapter7: Faraday's Law and Inductance of Magnetic Fields

- Faraday's Law of induction.
- Motional emf.
- Induced emf and electric fields.
- Maxwell Equations.

Faraday's Law of induction.

Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil. No matter how the change is produced, the voltage will be generated. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field, rotating the coil relative to the magnet, etc.

Faraday's law is a fundamental relationship which comes from Maxwell's equations. It serves as a succinct summary of the ways a voltage (or emf) may be generated by a changing magnetic environment. The induced emf in a coil is equal to the negative of the rate of change of magnetic flux times the number of turns in the coil. It involves the interaction of charge with magnetic field.



Faraday's experiment : Induction from a magnet moving through a coil

The key experiment which lead Michael Faraday to determine Faraday's law was quite simple. It can be quite easily replicated with little more than household materials. Faraday used a cardboard tube with insulated wire wrapped around it to form a coil. A voltmeter was connected across the coil and the induced EMF read as a magnet was passed through the coil. The setup is shown in Figure below:

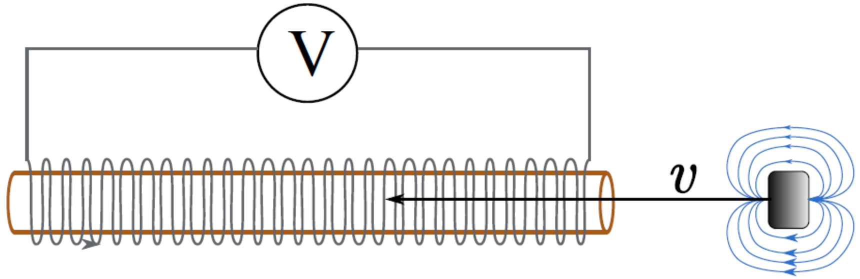


Figure: *Faraday's experiment: a magnet is passed through a coil.*

The observations were as follows:

1.Magnet at rest in or near the coil: No voltage observed.

2.Magnet moving toward the coil: Some voltage measured, rising to a peak as the magnet nears the center of the coil.

3.Magnet passes through the middle of the coil: Measured voltage rapidly changes sign.

4.Magnet passes out and away from the coil: Voltage measured in the opposite direction to the earlier case of the magnet moving into the coil.

How is the electromagnetic induction described?

What is electromagnetic induction?

Electromagnetic induction is the process by which a current can be *induced* to flow due to a changing magnetic field.

There are two key laws that describe electromagnetic induction:

1.Faraday's law, due to 19th century physicist Michael Faraday. This relates the rate of change of magnetic flux through a loop to the magnitude of the *electro-motive force* ξ induced in the loop. The relationship is $\xi = \frac{d\Phi}{dt}$

The electromotive force or *EMF* refers to the potential difference across the *unloaded* loop (i.e. when the resistance in the circuit is high). In practice it is often sufficient to think of EMF as voltage since both voltage and EMF are measured using the same unit, the volt.

2. Lenz's law is a consequence of conservation of energy applied to electromagnetic induction. It was formulated by Heinrich Lenz in 1833. While Faraday's law tells us the magnitude of the EMF produced, Lenz's law tells us the direction that current will flow. It states that the direction is always such that it will **oppose the change in flux which produced it**. This means that any magnetic field produced by an induced current will be in the **opposite** direction to the change in the original field.

Lenz's law is typically incorporated into Faraday's law with a minus sign, the inclusion of which allows the same coordinate system to be used for both the flux and EMF. The result is sometimes called the Faraday-Lenz law, $\xi = -\frac{d\Phi}{dt}$

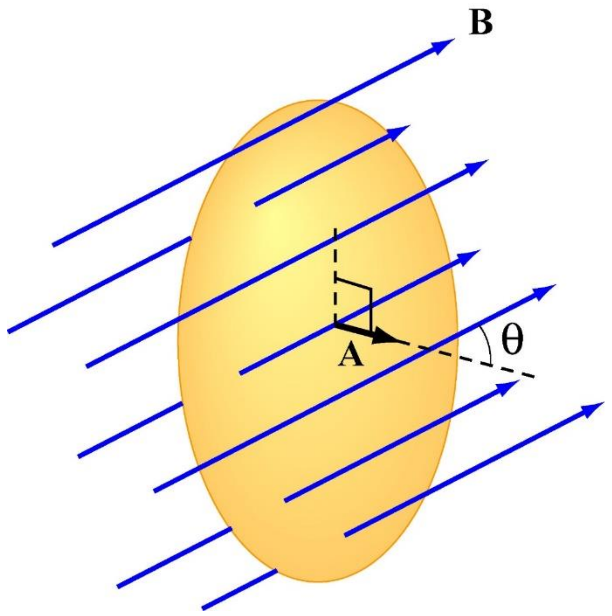
In practice we often deal with magnetic induction in multiple coils of wire each of which contribute the same EMF. For this reason an additional term N representing the number of turns is often included, *i.e.* $\xi = -N\frac{d\Phi}{dt}$

The magnetic flux through a loop.

Suppose that a loop enclosing an area A lies in a uniform magnetic field B as in figure.

Then the magnetic flux through this loop is equal to Φ =BA cos θ.

$$\xi = -\frac{d\Phi}{dt} = -\frac{d(B\ A\cos\theta)}{dt}$$



From the pervious expression, we see that an EMF can be induced in the circuit in several ways:

1- The magnitude of B can change with time.

2- The area enclosed by the loop can change with time.

3- The angle θ between B and the normal to the loop can change with time.

4- Any combination of the above can occur.

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

A changing magnetic flux *induces* an EMF, a curling E field

Analogous to Electric Flux (Gauss' Law)

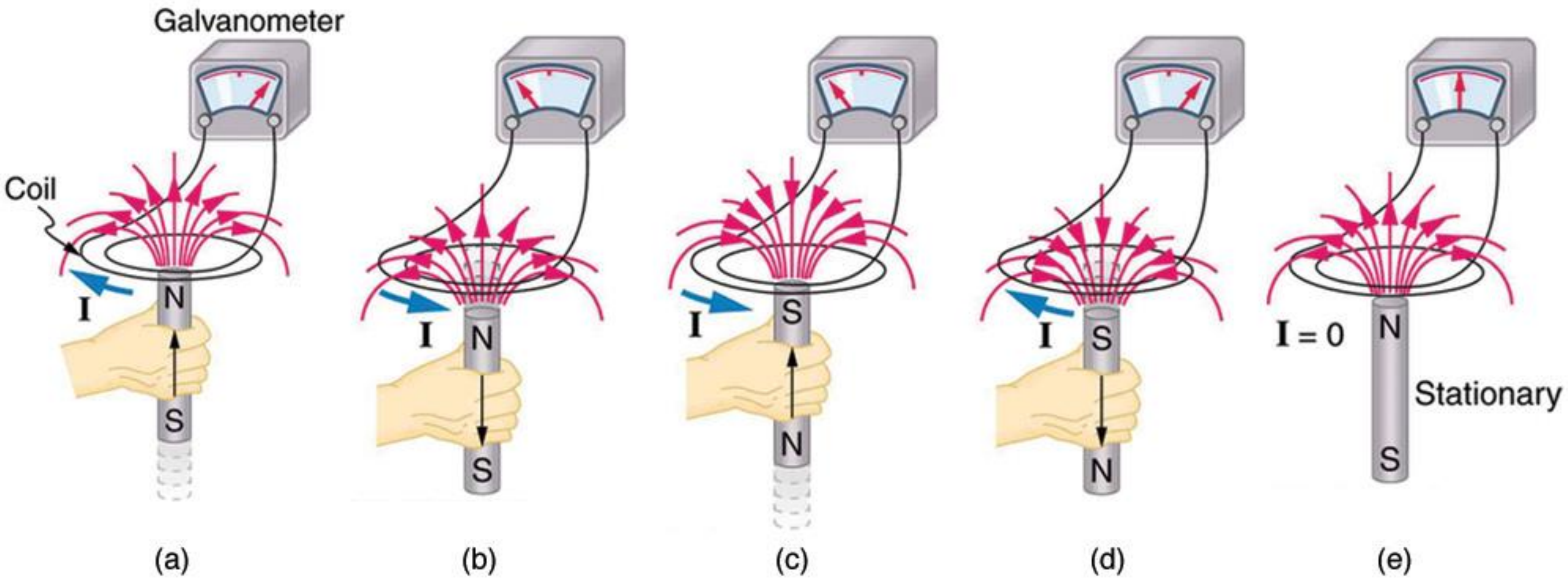
(1) Uniform **B**

$$\Phi_B = B_\perp A = BA\cos\theta = \vec{\mathbf{B}} \cdot \vec{\mathbf{A}}$$

(2) Non-Uniform **B**

$$\mathbf{\Phi}_B = \iint_S \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}}$$

An experiment easily performed and often done in physics labs is illustrated in Figure down. An emf is induced in the coil when a bar magnet is pushed in and out of it. Emfs of opposite signs are produced by motion in opposite directions, and the emfs are also reversed by reversing poles. The same results are produced if the coil is moved rather than the magnet—it is the relative motion that is important. The faster the motion, the greater the emf, and there is no emf when the magnet is stationary relative to the coil.



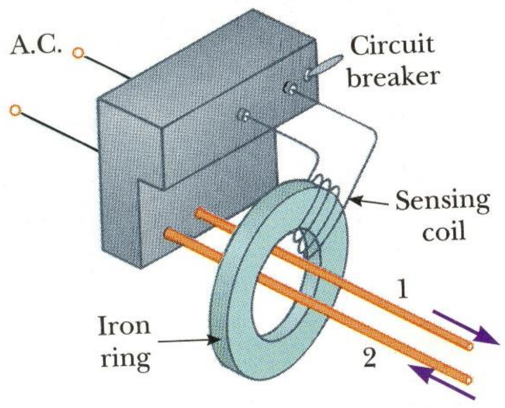
Movement of a magnet relative to a coil produces emfs as shown. The same emfs are produced if the coil is moved relative to the magnet. The greater the speed, the greater the magnitude of the emf, and the emf is zero when there is no motion.

Some Applications of Faraday's Law:

Electric Guitar

Induction Stovetops

Metal Detector

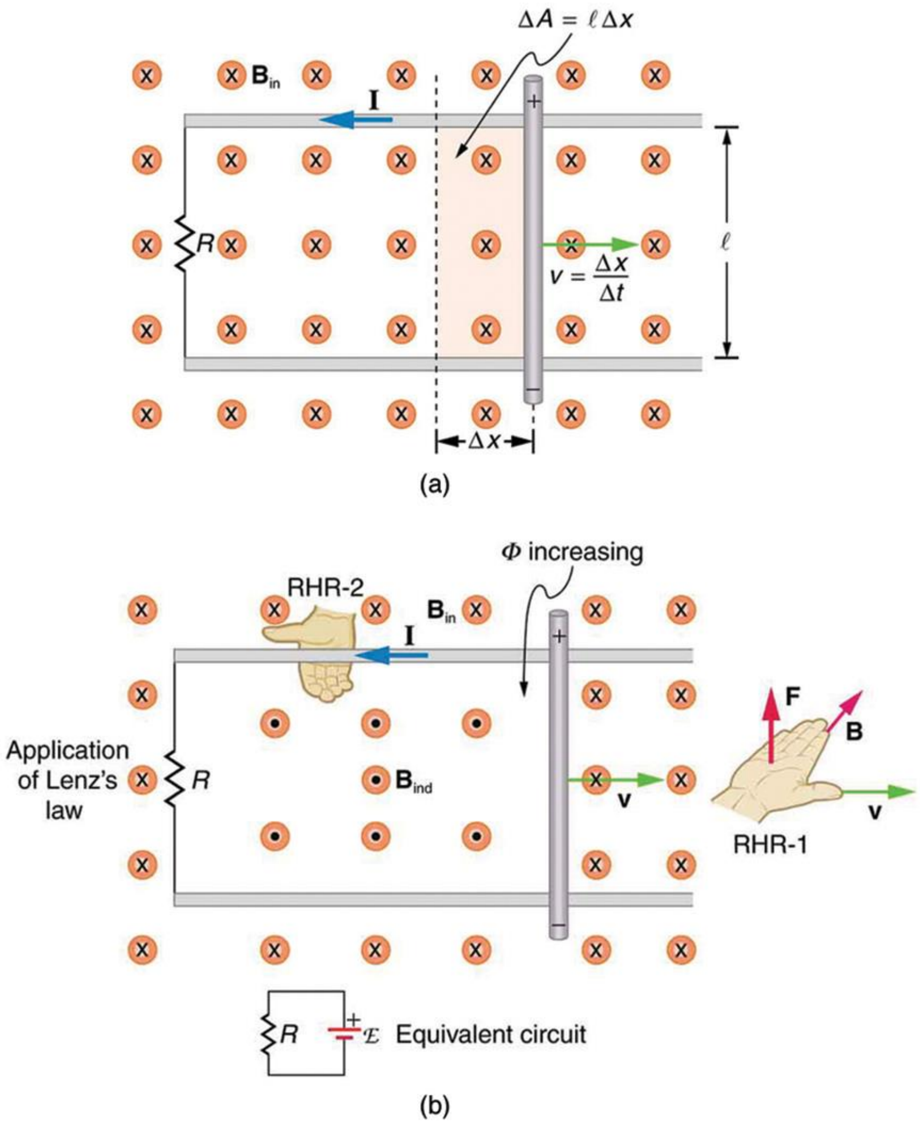


Ground Fault Interrupters (GFI)

Motional EMF

any change in magnetic flux induces an emf opposing that change—a process known as induction. Motion is one of the major causes of induction. For example, a magnet moved toward a coil induces an emf, and a coil moved toward a magnet produces a similar emf. In this section, we concentrate on motion in a magnetic field that is stationary relative to the Earth, producing what is loosely called ***motional emf***. One situation where motional emf occurs is known as the Hall effect and has already been examined. Charges moving in a magnetic field experience the magnetic force $F = qvB \sin \theta$, which moves opposite charges in opposite directions and produces an emf $= \Delta V = E\ell = B\ell v$. We saw that the Hall effect has applications, including measurements of B and v. We will now see that the Hall effect is one aspect of the broader phenomenon of induction, and we will find that motional emf can be used as a power source. Consider the situation shown in Figure below(a,b). A rod is moved at a speed v along a pair of conducting rails separated by a distance ℓ in a uniform magnetic field B. The rails are stationary relative to B and are connected to a stationary resistor R. The resistor could be anything from a light bulb to a voltmeter. Consider the area enclosed by the moving rod, rails, and resistor. B is perpendicular to this area, and the area is increasing as the rod moves. Thus the magnetic flux enclosed by the rails, rod, and resistor is increasing. When flux changes, an emf is induced according to Faraday's law of induction.

Figure . (a) A motional emf = $B\ell v$ is induced between the rails when this rod moves to the right in the uniform magnetic field. The magnetic field B is into the page, perpendicular to the moving rod and rails and, hence, to the area enclosed by them. (b) Lenz's law gives the directions of the induced field and current, and the polarity of the induced emf. Since the flux is increasing, the induced field is in the opposite direction, or out of the page. RHR-2 gives the current direction shown, and the polarity of the rod will drive such a current. RHR-1 also indicates the same polarity for the rod. (Note that the script E symbol used in the equivalent circuit at the bottom of part (b) represents emf.)

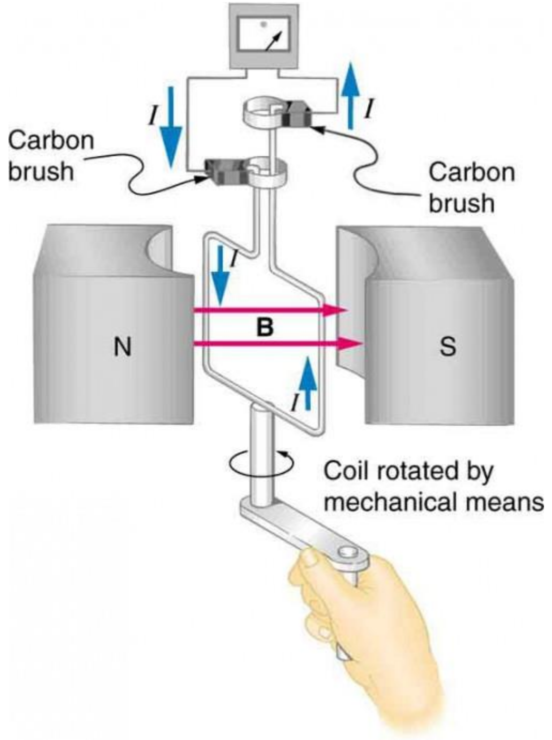


Motional emf also occurs if the magnetic field moves and the rod (or other object) is stationary relative to the Earth (or some observer). We have seen an example of this in the situation where a moving magnet induces an emf in a stationary coil. It is the relative motion that is important. What is emerging in these observations is a connection between magnetic and electric fields. A moving magnetic field produces an electric field through its induced emf. We already have seen that a moving electric field produces a magnetic field—moving charge implies moving electric field and moving charge produces a magnetic field.

Motional emfs in the Earth's weak magnetic field are not ordinarily very large, or we would notice voltage along metal rods, such as a screwdriver, during ordinary motions. For example, a simple calculation of the motional emf of a 1 m rod moving at 3.0 m/s perpendicular to the Earth's field gives emf = $B\ell v = (5.0 \times 10^{-5}\ \text{T})(1.0\ \text{m})(3.0\ \text{m/s}) = 150\ \mu\text{V}$. This small value is consistent with experience.

The method of inducing an emf used in most electric generators is shown in Figure 3. A coil is rotated in a magnetic field, producing an alternating current emf, which depends on rotation rate and other factors that will be explored in later sections. Note that the generator is remarkably similar in construction to a motor (another symmetry).

Rotation of a coil in a magnetic field produces an emf. This is the basic construction of a generator, where work done to turn the coil is converted to electric energy. Note the generator is very similar in construction to a motor.

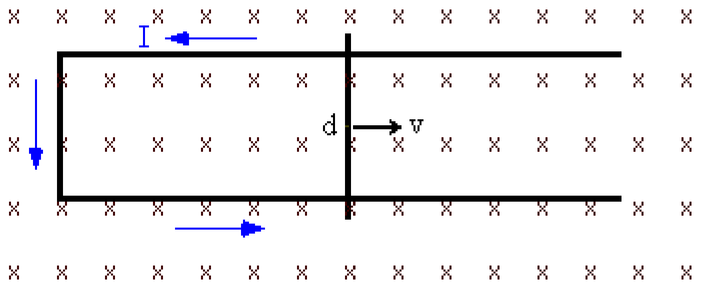


What's the difference between motional emf and induced emf?

``Induced emf'' is the more general term. By Faraday's Law, you get an induced emf whenever there's a changing magnetic flux through a loop. If the changing emf is due to some kind motion of a conductor in a magnetic field, you would call it a ``motional emf''. For example, if a loop moves into or out of a region of field, or rotates, or a bar rolls along a rail, you'd get a ``motional'' induced emf. But if the changing magnetic flux were due to, say, an increasing current in a wire, you wouldn't call it a ``motional'' emf.

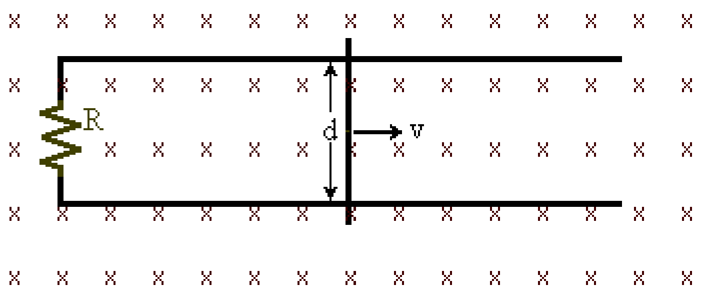
If we place the wire on a conducting rail, a current will start to flow in the circuit formed by the rail and the wire.

The emf driving the current is equal to vB times the length d of the section of wire connecting the rails. (The work done per unit charge is vBd, when a charge moves from one end of the moving wire to the other end.) The current flowing in the circuit will be I = vBd/R, where R is the resistance of the circuit.
In the above "filamentary" circuit (consisting only of wires or rods) the motional emf = B*d*v.
The magnetic flux through the circuit at time t is Φ_B = B*A = B*L*d, where L is the length of the circuit at time t.
The rod moves with speed v.



The rate at which the flux changes is $\Delta\Phi_B/\Delta t$ = B*d*ΔL/Δt = B*d*v, since the only thing changing is the length of the circuit, and ΔL/Δt = v.
We can therefore write
$\Delta\Phi_B/\Delta t$ (filamentary circuit with moving parts, constant B) = motional emf.
Motional emf is not induced emf. The flux of the magnetic field though a fixed area does not change. Instead, an external force does work moving wires that are part of a circuit in a constant magnetic field. But for **filamentary circuits** we can write down one mathematical equation that expresses both Faraday's law and motional emf.
$\Delta\Phi_B/\Delta t$ (any flux changes through filamentary circuit) = emf.
In this equation emf stands for motional and induced emf.

Problem:
In the figure on the right, assume that R = 6 Ω, d = 1.2 m, and a uniform 2.5 T magnetic field is directed into the page. At what speed should the bar be moved to produce 0.5 A in the resistor?



Solution:
Reasoning:•
The rate at which the flux changes is $d\Phi_B/dt$ = B*d*dL/dt = B*d*v, since the only thing changing is the length of the circuit, and ΔL/Δt = v.
The current flowing in the circuit will be I = vBd/R.
Details of the calculation:•
I = vBd/R. Therefore v = IR/(Bd) = 0.5 A*6 Ω/(2.5 T*1.2 m) = 1 m/s.

Maxwell's Equations

Maxwell's Equations are a set of 4 complicated equations that describe the world of electromagnetics. These equations describe how electric and magnetic fields propagate, interact, and how they are influenced by objects.

James Clerk Maxwell [1831-1879] was an Einstein/Newton-level genius who took a set of known experimental laws (Faraday's Law, Ampere's Law) and unified them into a symmetric coherent set of Equations known as Maxwell's Equations. Maxwell was one of the first to determine the speed of propagation of electromagnetic (EM) waves was the same as the speed of light - and hence to conclude that EM waves and visible light were really the same thing.

Maxwell's Equations are critical in understanding Antennas and Electromagnetics. They are formidable to look at - so complicated that most electrical engineers and physicists don't even really know what they mean. Shrouded in complex math (which is likely so "intellectual" people can feel superior in discussing them), true understanding of these equations is hard to come by.

MAXWELL’S EQUATIONS

1.Electric field lines originate on positive charges and terminate on negative charges. The electric field is defined as the force per unit charge on a test charge, and the strength of the force is related to the electric constant ε_0, also known as the permittivity of free space. From Maxwell’s first equation we obtain a special form of Coulomb’s law known as Gauss’s law for electricity.

2.Magnetic field lines are continuous, having no beginning or end. No magnetic monopoles are known to exist. The strength of the magnetic force is related to the magnetic constant μ_0, also known as the permeability of free space. This second of Maxwell’s equations is known as Gauss’s law for magnetism.

3.A changing magnetic field induces an electromotive force (emf) and, hence, an electric field. The direction of the emf opposes the change. This third of Maxwell’s equations is Faraday’s law of induction, and includes Lenz’s law.

4.Magnetic fields are generated by moving charges or by changing electric fields. This fourth of Maxwell’s equations encompasses Ampere’s law and adds another source of magnetism—changing electric fields.

Name	Integral form
Gauss's law	$\oiint_{\partial V} \mathbf{E} \cdot \mathrm{d}\mathbf{A} = \frac{Q(V)}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\oint_{\partial S} \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$

معلومات التواصل

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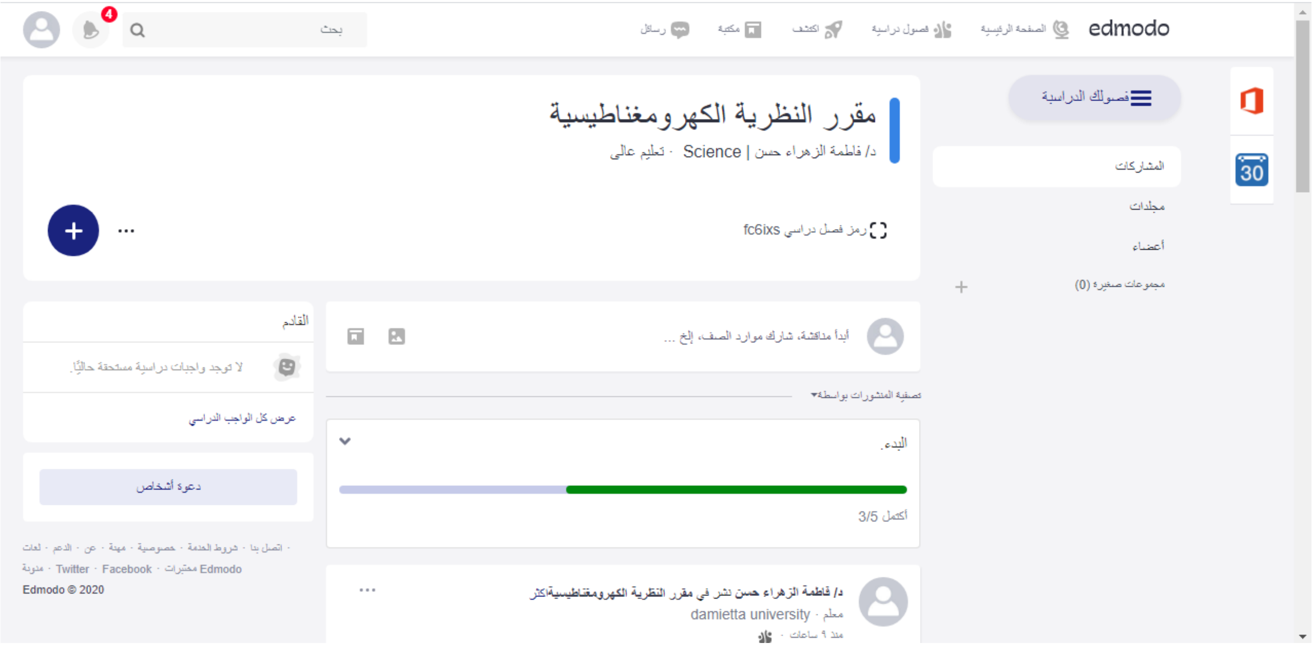

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