

Module 3 : MAGNETIC FIELD

Lecture 18 : Electromagnetic Induction

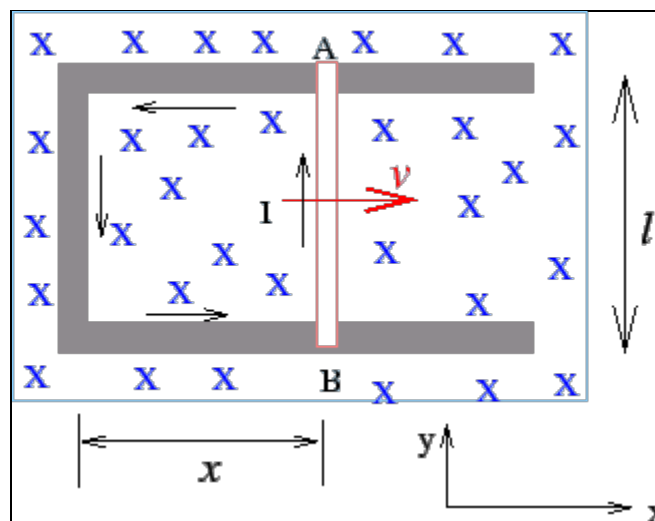
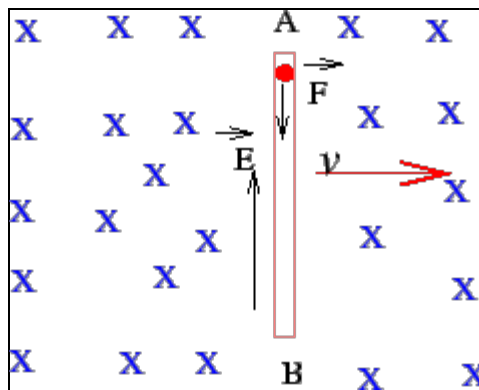
Objectives

In this lecture you will learn the following

- Study in detail the principle of electromagnetic induction.
- Understand the significance of Lenz's law.
- Solve problems involving motional emf.

Motional Emf :

Consider a straight conductor AB moving along the positive x-direction with a uniform speed v . The region is in a uniform magnetic field pointing into the plane of the page, i.e. in $-z$ direction.



The fixed positive ions in the conductor are immobile. However, the negatively charged electrons experience a Lorentz force $-|e|\vec{v} \times \vec{B} = -|e|vB\hat{j}$, i.e. a force along the $-y$ direction. This pushes the electrons from the end A to the end B, making the former positive with respect to the latter. Thus an induced electric field is established in the

conductor along the positive y direction. The acceleration of electrons would stop when the electric field is built to a

strength which is strong enough to annul the magnetic force. This electric field $\vec{E} = \vec{v} \times \vec{B}$ is the origin of what is

known as *motional emf*. The motion of charges finally stops due to the resistance of the conductor

If the conductor slides along a stationary U- shaped conductor, the electrons find a path and a current is established in the circuit. The moving conductor thereby becomes a seat of the motional emf. We may calculate the emf either by considering the work that an external agency has to do to keep the sliding conductor move with a uniform velocity or by direct application of Faraday's law.

If the induced current is I , a force IlB acts on the wire in the negative x direction. In order to maintain the uniform velocity, an external agent has to exert an equal and opposite force on the sliding conductor. Since the distance moved in time dt is vdt , the work done by the external agency is

$$dW = IlB \cdot vdt = Blv(dq)$$

where $dq = Idt$ is the amount of charge moved by the seat of emf along the direction of the current. The emf is an electric potential difference.

Thus, the emf is equivalently the work done in moving a unit charge. Thus,

$$\mathcal{E} = \frac{dW}{dq} = Blv$$

This emf corresponds to the potential difference between the ends A and B.

An alternate derivation of the above is to consider the flux linked with closed circuit. Taking the origin at the extreme left end of the circuit, the area of the circuit in the magnetic field is lx where x is the distance of the sliding rod from the fixed end. The flux linked with the circuit is, therefore, $\Phi = Blx$. The rate at which flux changes is therefore given by

$$\mathcal{E} = \frac{d\Phi}{dt} = Bl \frac{dx}{dt} = Blv$$

If \vec{B} is not perpendicular to the plane of the circuit, we will need to take the perpendicular component of \vec{B} in the above formula.

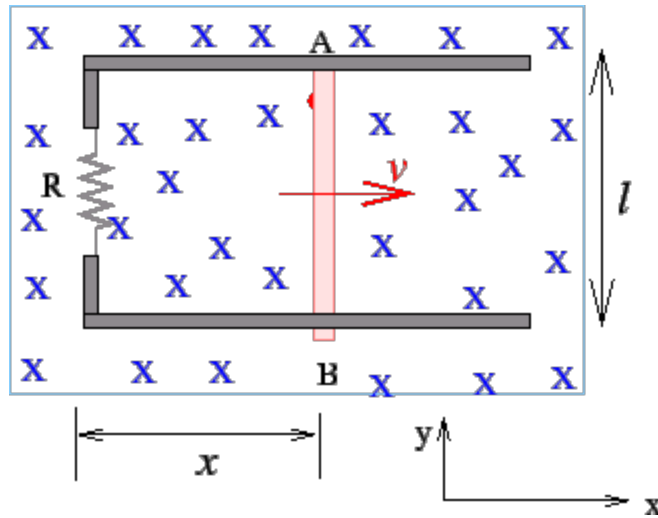
Note that, in the illustration above, the magnetic flux linked with the circuit is increasing with time in the negative z direction. The direction of the induced current is, therefore, such that the magnetic field due to the current is along the positive z -direction, which will oppose increase of flux. Hence the current, as seen from above, is in the anticlockwise direction.

Example 18

In the above circuit if the part of the fixed rails parallel to the sliding conductor has a resistance R and the rest of the circuit may be considered resistanceless, obtain an expression for the velocity of the conductor at time t , assuming that it starts with an initial velocity v_0 at $t = 0$. Explain the change in the kinetic energy of the sliding rod.

Solution :

Since the emf is $\mathcal{E} = Blv$, the current flowing through the sliding conductor is $I = Blv/R$.



The force acting on the sliding conductor is $\vec{F} = I\vec{L} \times \vec{B} = -\frac{B^2 l^2 v}{R} \hat{i}$

The force is a retarding one, slowing down the conductor in accordance with Lenz's law.

(This is the amount of force an external agency must apply on the sliding conductor in the positive x-direction to keep the rod moving with a constant speed.) Thus the equation of motion of the conductor is

$$m \frac{dv}{dt} = -\frac{B^2 l^2 v}{R}$$

The equation may be solved by separating the variables and integrating from time $t = 0$ to t . We get

$$\int_{v_0}^v \frac{dv}{v} = - \int_0^t \frac{B^2 l^2}{mR} dt$$

which gives

$$\ln \frac{v}{v_0} = -\frac{B^2 l^2}{mR} t$$

i.e.

$$v = v_0 \exp \left(-\frac{B^2 l^2}{mR} t \right)$$

We can calculate the power dissipated in the circuit in this time by using $dW/dt = I^2 R = B^2 l^2 v^2 / R$, so that

$$\begin{aligned} W &= \frac{B^2 l^2}{R} \int_0^t v^2 dt \\ &= \frac{B^2 l^2}{R} v_0^2 \int_0^t e^{-2\frac{B^2 l^2}{mR} t} dt \\ &= (mv_0^2/2) \left[1 - e^{-2\frac{B^2 l^2}{mR} t} \right] \end{aligned}$$

which is precisely the change in the kinetic energy of the conductor

$$(mv_0^2/2) - (mv^2/2)$$

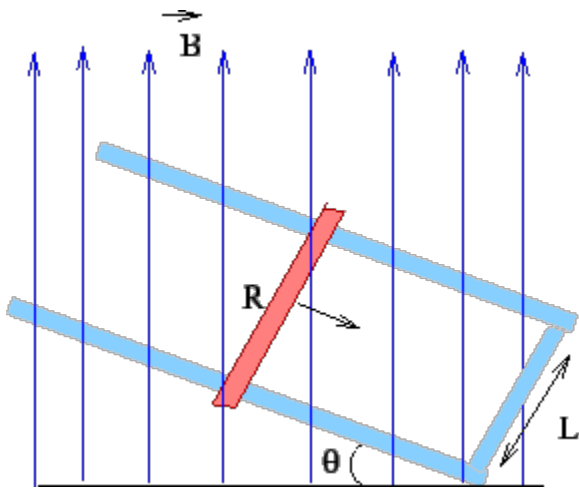
Exercise 1

A pair of parallel conducting rails are inclined at an angle θ to the horizontal. The rails are connected to each other at the ground by a conducting strip. A conductor of resistance R , oriented parallel to the strip can slide down the incline along the rails. The resistances of the rails and the strip are negligible.

A uniform magnetic field \vec{B} exists in the vertical direction. The slider is released at some height. Show that the slider attains a terminal speed given by

$$v = \frac{mgR \sin \theta}{B^2 L^2 \cos^2 \theta}$$

where L is the distance between the rails.



Exercise 2

In the above problem, show that after attaining the terminal velocity, the change in the potential energy of the slider is equal to the Joule heat produced in the slider.

Hint for Solution :

In the preceding exercise, show that the current is given by $BLv \cos \theta / R$. The rate of Joule heat is $I^2 R$. The

amount of heat produced in time t is $I^2 R t$. In time t , the slider moves through a distance vt . The change in the potential energy is $mgvt \sin \theta$.

Example 19

A conductor AB is moving with a speed v parallel to a long straight wire carrying a current I . What is the potential difference between the ends A and B ?

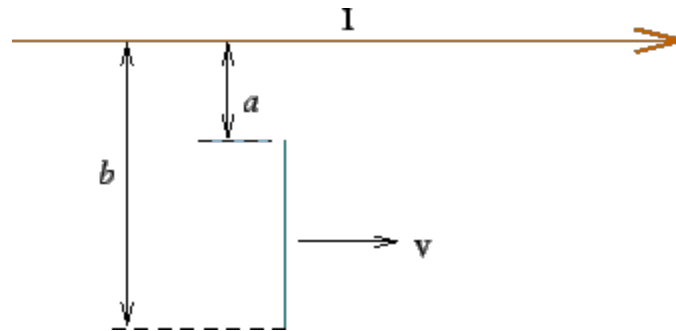
Solution :

From the discussion above, the electric field acting at any point on the moving conductor is Lorentz force per unit charge, i.e., $\vec{v} \times \vec{B}$. Since the field is not constant along AB, the emf is obtained by integrating the electric field along AB.

The field at an element of width dx at a distance x from the wire is . Since \vec{v} and \vec{B} are perpendicular,

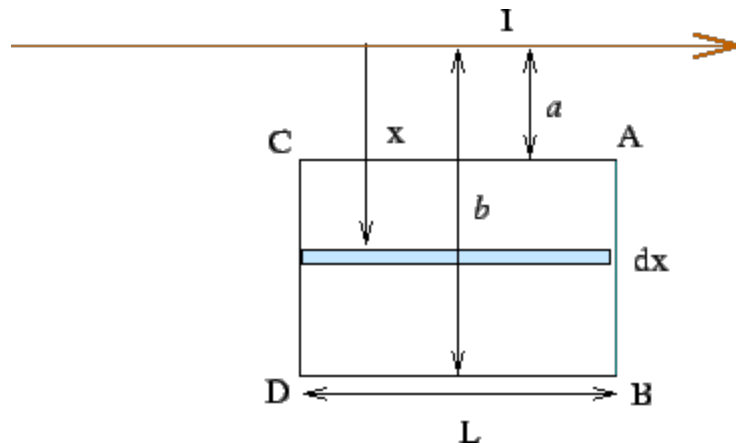
$$\mu_0 I / 2\pi x$$

$$\begin{aligned}\mathcal{E} &= \int_a^b \frac{\mu_0 I v}{2\pi} \frac{dx}{x} \\ &= \frac{\mu_0 I v}{2\pi} \ln(a/b)\end{aligned}$$



One can obtain the same expression by a direct application of Faraday's law. It is not necessary to have a physical circuit to calculate the potential difference. One can imagine the conductor AB to be a rod sliding along a rail. As the rod moves, the area of the closed region ACDB increases. We consider an area element of width dx at a distance x from the wire. Since \vec{B} and the area vector are parallel, $d\Phi = \frac{\mu_0 I}{2\pi} L \frac{dx}{x}$

Integrating, $\Phi = \frac{\mu_0 I}{2\pi} L \ln(b/a)$



Thus

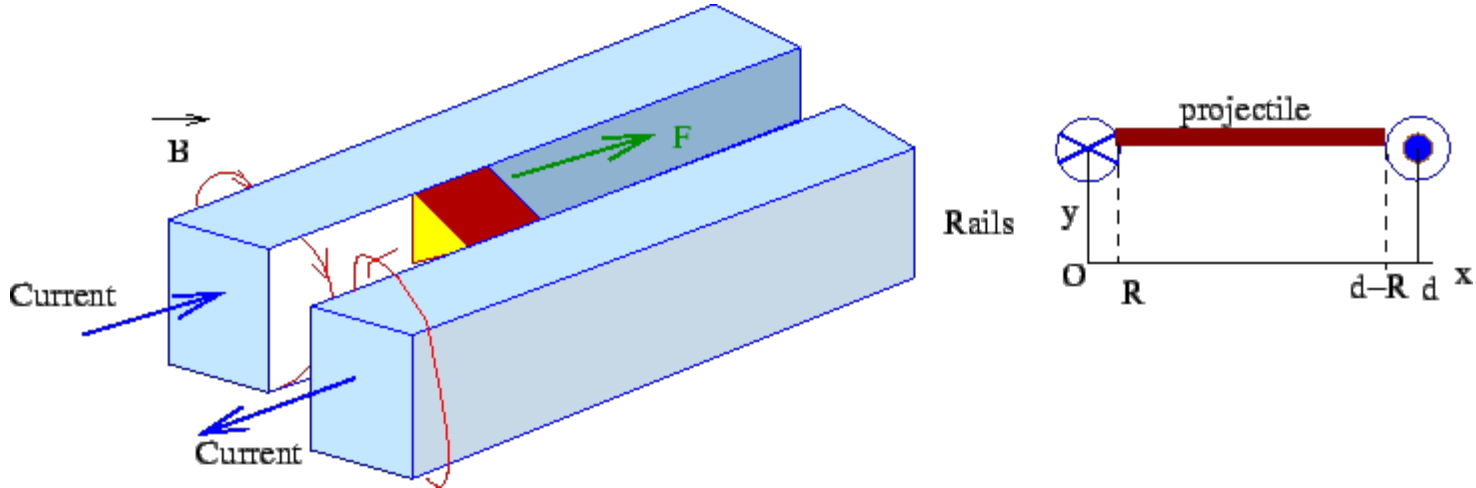
$$\begin{aligned}\mathcal{E} = -\frac{d\Phi}{dt} &= \frac{\mu_0 I}{2\pi} \ln(a/b) \frac{dL}{dt} \\ &= \frac{\mu_0 I}{2\pi} v \ln(a/b)\end{aligned}$$

since the rate of increase of the length of the rectangle is $dL/dt = v$.

Example 20

A rail gun is essentially a linear electromagnetic accelerator which uses Lorentz force to propel an armature (connected to a projectile) between two parallel rails carrying high current. The current enters through one of the rails and returns through the other rail. The current in the rails produce magnetic field in the region between the rails. The armature is subject to a force parallel to the rails.

The separation between the rails is small compared to the length of the rails so that the magnetic field due to the rails may be approximated as due to infinitely long wires carrying current. However, because the armature provides a path for the current, there is no current in the rails beyond the armature. The magnetic field is, therefore, equal to that due to semi-infinite wire (i.e. reduced by a factor of 2 from that of an infinite wire).



In the figure shown, the radii of cross section of the rails are R each and the separation between them is d . The fields due to both the wires are in the $-y$ direction, so that the force $I d\vec{l} \times \vec{B}$ acts along the $-z$ direction, parallel

to the rails. The field at a distance x from the origin shown is $\vec{B} = -\frac{\mu_0 I}{4\pi} \left[\frac{1}{x} + \frac{1}{d-x} \right]$

The force on the armature is obtained by integrating the force on the element dx of the armature

$$\begin{aligned} d\vec{F} &= I d\vec{l} \times \vec{B} \\ &= I^2 \frac{\mu_0 I}{4\pi} dx \left[\frac{1}{x} + \frac{1}{d-x} \right] \hat{i} \times (-\hat{j}) \\ &= -I^2 \frac{\mu_0 I}{4\pi} \hat{k} dx \left[\frac{1}{x} + \frac{1}{d-x} \right] \end{aligned}$$

$$\begin{aligned} \vec{F} &= -I^2 \frac{\mu_0 I}{4\pi} \hat{k} \int_R^{d-R} \left[\frac{1}{x} + \frac{1}{d-x} \right] dx \\ &= -I^2 \frac{\mu_0}{2\pi} \hat{k} [\ln(d-R) - \ln(R)] \end{aligned}$$

A typical rail gun design to achieve high acceleration of a projectile, a pulse current in excess of 100 kAmp is used. With a rail separation of $d = 5\text{cm}$ and $R = 1\text{cm}$, we have $F = 2772\text{m/s}^2$. For a projectile mass of 20 gms. the acceleration produced is in excess of $14,000g$!

Example 21

A rectangular conducting loop of length a and width b , having a resistance R falls under gravity with its smaller side remaining vertical during the fall. A non-uniform magnetic field exists, directed horizontally and perpendicular to the

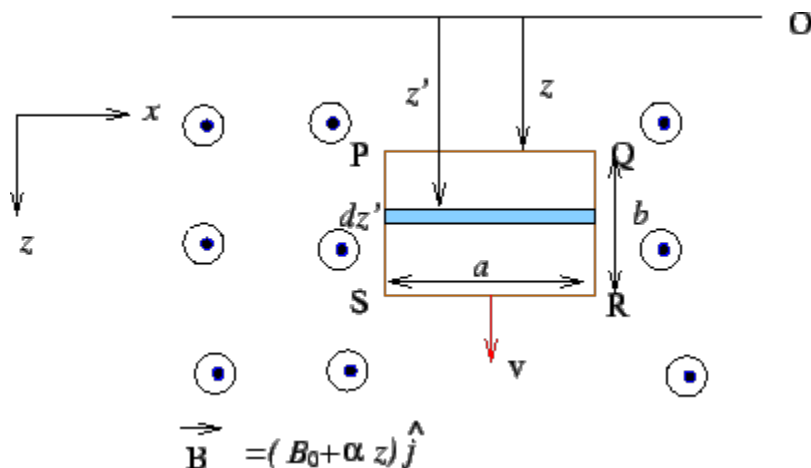
plane of the loop. The magnitude of the magnetic field increases linearly with distance $B(z) = B_0 + \alpha z$, where z is the distance of the top of the loop from the position from which the loop falls. Obtain an expression for the velocity of the loop with distance of fall and find the terminal velocity.

Solution :

Let the axes be as shown, with the y-axis out of the plane of the paper. The induced current in the loop is clockwise so as to oppose the flux increase as the loop falls. The velocity of the loop is $v = dz/dt$.

The flux through a strip of width dz' at position z' is $(B_0 + \alpha z')adz'$. The net flux through the loop is

$$\begin{aligned}\Phi &= \int_z^{z+b} (B_0 + \alpha z')adz' \\ &= B_0 ab + \frac{\alpha a}{2}(2zb + b^2)\end{aligned}$$



The induced emf is $\mathcal{E} = \frac{d\Phi}{dt} = \alpha ab \frac{dz}{dt} = \alpha abv$

The induced current is $I = \alpha abv/R$. When the loop falls, the sides of the loop are subject to magnetic forces $I\vec{l} \times \vec{B}$.

The forces on the sides QR and SP cancel. The magnetic force on the sides PQ and RS are

$$\begin{aligned}\vec{F}_m &= IaB(z)\hat{k} - IaB(z+b)\hat{k} \\ &= Ia(B_0 + \alpha z)\hat{k} - Ia[B_0 + \alpha(z+b)]\hat{k} \\ &= -Iab\alpha\hat{k} \\ &= -(\alpha ab)^2 \frac{v}{R} \hat{k}\end{aligned}$$

The equation of the motion of the loop having a mass m is $m \frac{dv}{dt} = mg - \frac{(\alpha ab)^2}{R} v$

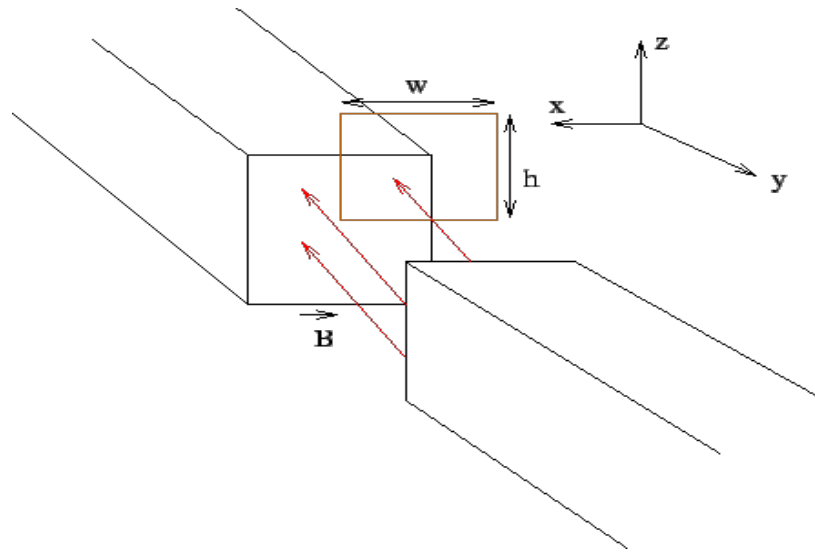
which has a solution

$$v = \frac{mgR}{(\alpha ab)^2} \left[1 - \exp\left(-\frac{(\alpha ab)^2}{R}t\right) \right]$$

The terminal velocity is $v_{\infty} = mgR/(\alpha ab)^2$, which can also be directly obtained by equating F_m with mg .

Exercise 3

A rectangular loop of width w and height h falls under gravity into a region of constant magnetic field B . The loop has a mass m and resistance R . The magnetic field, which remains perpendicular to the plane of the loop, is constant within the pole pieces and is zero outside.



(a) Find the current in the loop when the speed of the loop is v and (i) it is partly inside and partly outside the field region (ii) it is wholly inside the field.

(b) Find the force acting on the loop in both the cases above.

(c) Determine the terminal velocity of the loop.

Assume that the pole pieces are much deeper than the height h .

(Answer : (a) (i) Bwv/R counter-clockwise (ii) zero. (b) B^2w^2v/R acts only on the lower edge. (c) terminal

speed in case (i) is $v_0 = mgR/B^2w^2$. Once wholly inside, the speed increases with time as $v = v_0 + gt$.)

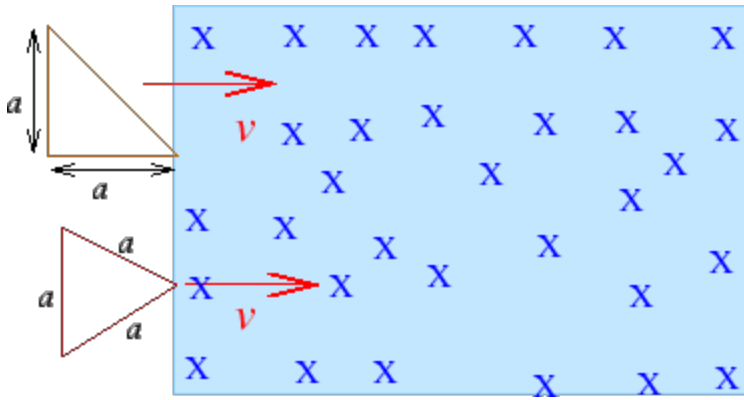
Exercise 4

A triangular current loop in the shape of a right isosceles triangle of base $a = 1\text{m}$ enters a region of constant magnetic field with a uniform speed $v = 2\text{m/s}$. At $t = 0$ a corner of the base is at the edge of the field region (top of the figure). Find the emf at time (i) $t = 0.3\text{s}$ and (ii) $t = 1\text{s}$.

(Ans. (i) 0.6 volts (ii) zero.)

Exercise 5

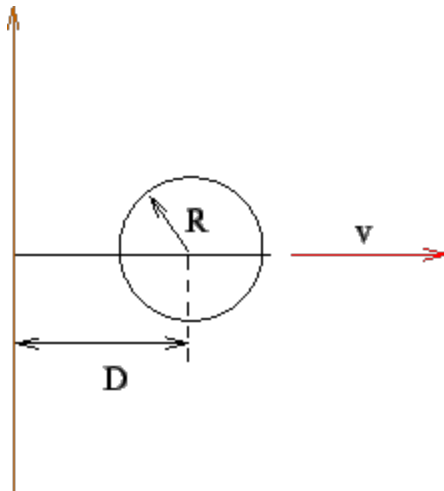
Repeat the above exercise for an equilateral triangle with side $a = 1\text{m}$.



(Answer : 0.7 volts)

Exercise 6

(Mathematically difficult problem) : A circular loop of radius R lies in the same plane as a long straight conductor carrying a current I . The centre of the loop is at a distance D from the wire ($D > R$). The loop moves perpendicular to the wire with a uniform speed v . Calculate the motional emf developed.



(Hint : Consider the field at an element of area $r dr d\theta$. The distance of the element from the wire is $D + r \cos \theta$.

Calculate the flux by integrating from $r = 0$ to R and from $\theta = 0$ to 2π . Use :

$$\int_0^{2\pi} \frac{d\theta}{D + r \cos \theta} = \frac{2\pi}{\sqrt{D^2 - r^2}}$$

(Answer $\mu_0 I v (D / \sqrt{D^2 - R^2} - 1)$)

Recap

In this lecture you have learnt the following

- Changing magnetic flux gives rise to an emf. Faraday's law relates the emf to the rate of change of flux.
- Flux change may arise due to time dependent magnetic field or due to a change in the area through which the flux

is changing.

- The direction of emf is such that it opposes the change in magnetic flux. The direction of the induced current is given by Lenz's law.
- Motional emf is the emf induced in a conductor which is moving in a magnetic field. The source of motional emf is the Lorentz force acting on the charge carriers.