PHYS 270 – SUPPL. #4

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Chapter 34. Electromagnetic Induction

Electromagnetic induction is the scientific principle that underlies many modern technologies, from the generation of electricity to communications and data storage.

Induction

- E-fields generate B fields (E field in a conductor drives current that creates B)
- Can B fields generate E- fields?
- Yes if the B fields vary in time -Faraday

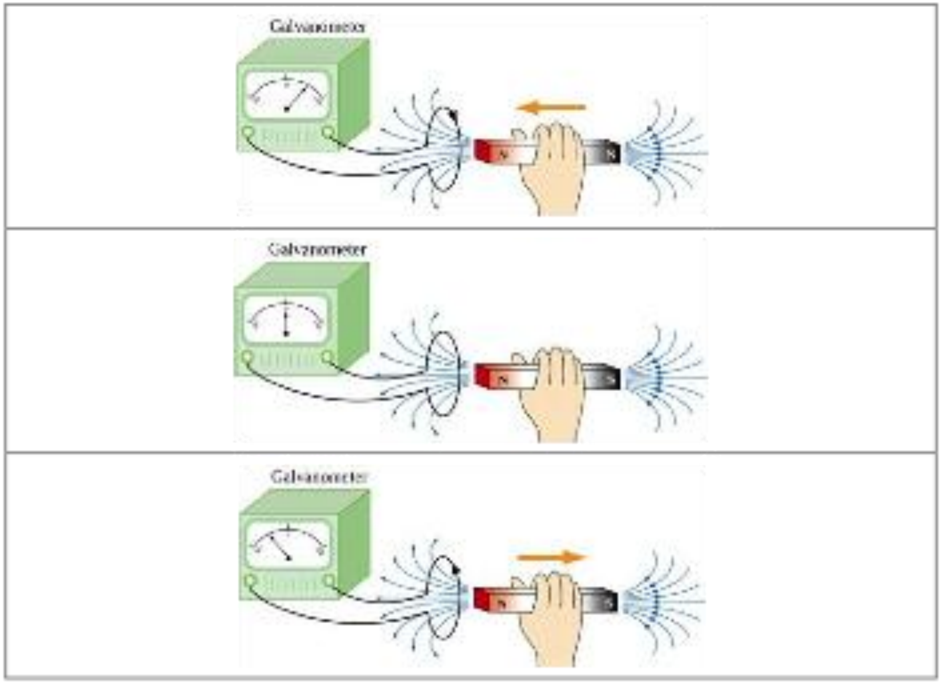


Figure 10.1.1 Electromagnetic induction

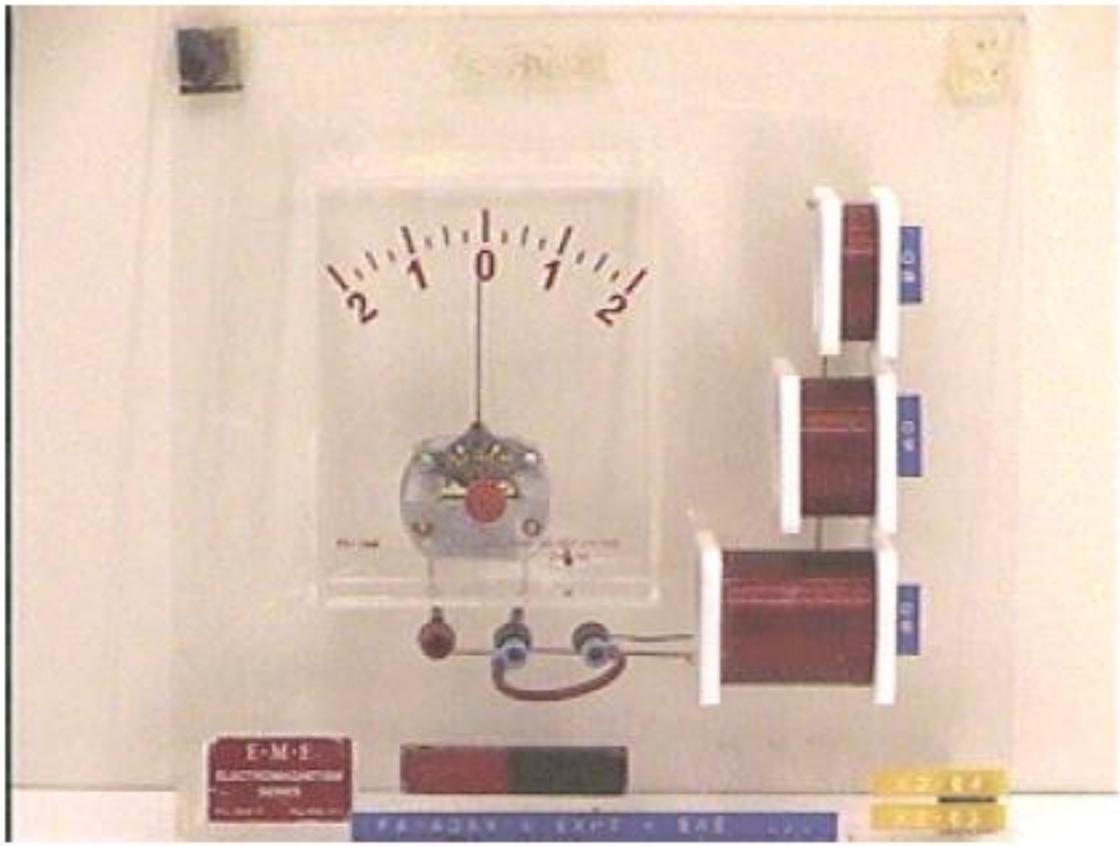
- Current flows only if B through the loop is changing
- Faster movement more current
- Current direction changes when either motion or magnet polarity is reversed
- Current linear function of number of turns

Coil behaves as connected to a battery source. EMF

$$EMF \rightarrow \varepsilon = -N \frac{d\Phi_m}{dt}$$

K2-04 Experiment

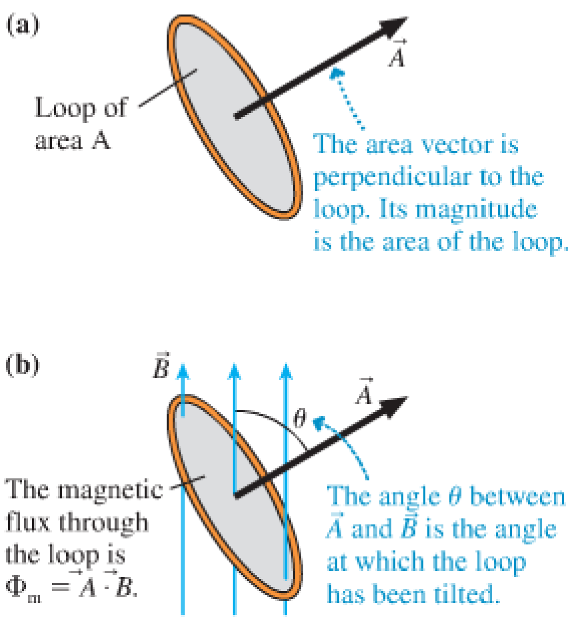
K2-04: FARADAY'S EXPERIMENT - EME SET - 20, 40, 80 TURN COILS

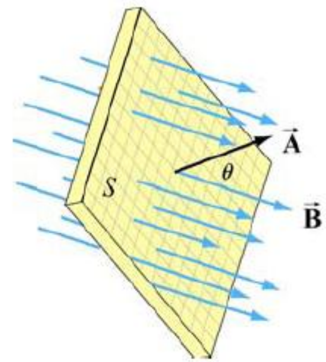


MAGNETIC FLUX CONVENTIONS

UNIFORM B

FIGURE 34.14 Magnetic flux can be defined in terms of an area vector .





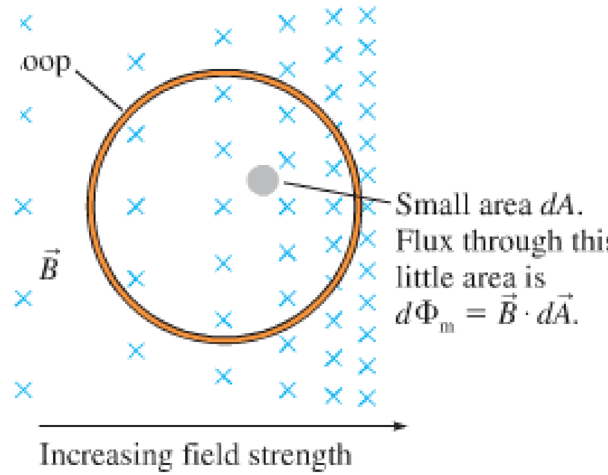
$$\Phi = AB\cos\theta$$

$$\Phi = \vec{A} \bullet \vec{B}$$

Units: T-m^2 =Wb (Weber)

NON-UNIFORM B

IGURE 34.16 A loop in a nonuniform ıagnetic field.

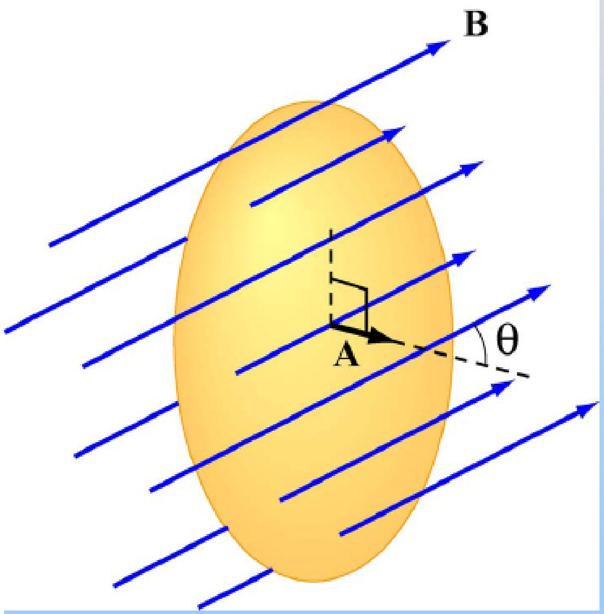


$$d\Phi = \vec{B} \bullet d\vec{A}$$

$$\Phi = \oint \vec{B} \bullet d\vec{A}$$

Magnetic Flux Thru Wire Loop

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**

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

Faraday's Law of Induction

$$\mathcal{E} = -N \frac{d\Phi_B}{dt}$$

A changing magnetic flux *induces* an EMF

What is EMF?

$$\mathcal{E} = \int \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}}$$

Looks like potential. It's a "driving force" for current

N number of loops in a coil

What about the minus sign ?

$$\varepsilon = -\frac{d}{dt}(BA\cos\theta) = -\left(\frac{dB}{dt}\right)A\cos\theta - B\left(\frac{dA}{dt}\right)\cos\theta + BA\sin\theta\left(\frac{d\theta}{dt}\right) \qquad (10.1.5)$$

How can induce a emf:

1. Change magnitude of B
2. Change area A
3. Change angle θ

Thus, we see that an emf may be induced in the following ways:

(i) by varying the magnitude of $\vec{\mathbf{B}}$ with time (illustrated in Figure 10.1.3.)

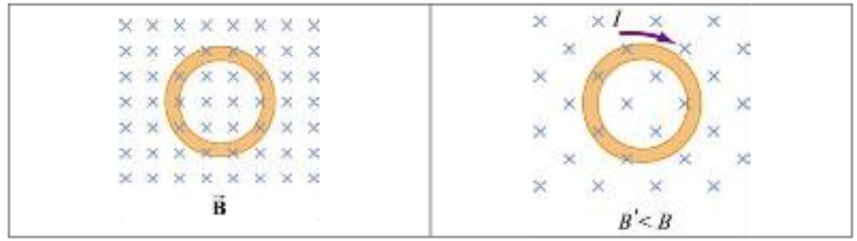


Figure 10.1.3 Inducing emf by varying the magnetic field strength

(ii) by varying the magnitude of $\vec{\mathbf{A}}$, i.e., the area enclosed by the loop with time (illustrated in Figure 10.1.4.)

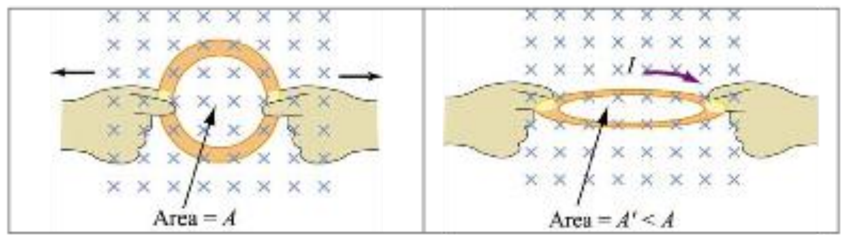


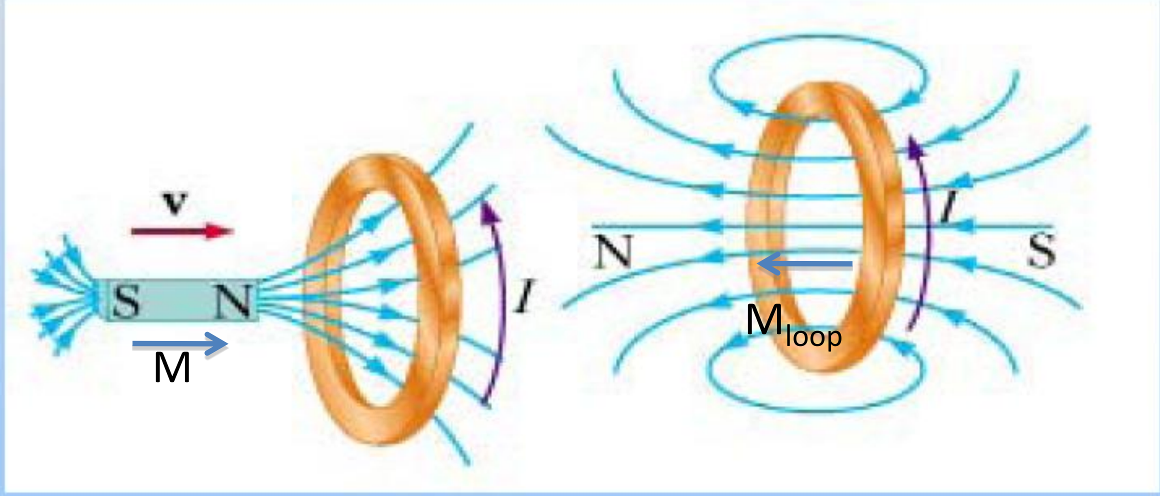
Figure 10.1.4 Inducing emf by changing the area of the loop

(iii) varying the angle between $\vec{\mathbf{B}}$ and the area vector $\vec{\mathbf{A}}$ with time (illustrated in Figure 10.1.5.)

Figure 10.1.5 Inducing emf by varying the angle between $\vec{\mathbf{B}}$ and $\vec{\mathbf{A}}$.

Minus Sign? Lenz's Law

Induced EMF is in direction that ***opposes*** the change in flux that caused it



To illustrate how Lenz's law works, let's consider a conducting loop placed in a magnetic field. We follow the procedure below:

1. Define a positive direction for the area vector $\vec{\mathbf{A}}$.

2. Assuming that $\vec{\mathbf{B}}$ is uniform, take the dot product of $\vec{\mathbf{B}}$ and $\vec{\mathbf{A}}$. This allows for the determination of the sign of the magnetic flux Φ_B.

3. Obtain the rate of flux change $d\Phi_B / dt$ by differentiation. There are three possibilities:

$$\frac{d\Phi_B}{dt}: \begin{cases} >0 & \Rightarrow \text{ induced emf } \varepsilon < 0 \\ <0 & \Rightarrow \text{ induced emf } \varepsilon > 0 \\ =0 & \Rightarrow \text{ induced emf } \varepsilon = 0 \end{cases}$$

4. Determine the direction of the induced current using the right-hand rule. With your thumb pointing in the direction of $\vec{\mathbf{A}}$, curl the fingers around the closed loop. The induced current flows in the same direction as the way your fingers curl if $\varepsilon > 0$, and the opposite direction if $\varepsilon < 0$, as shown in Figure 10.1.6.

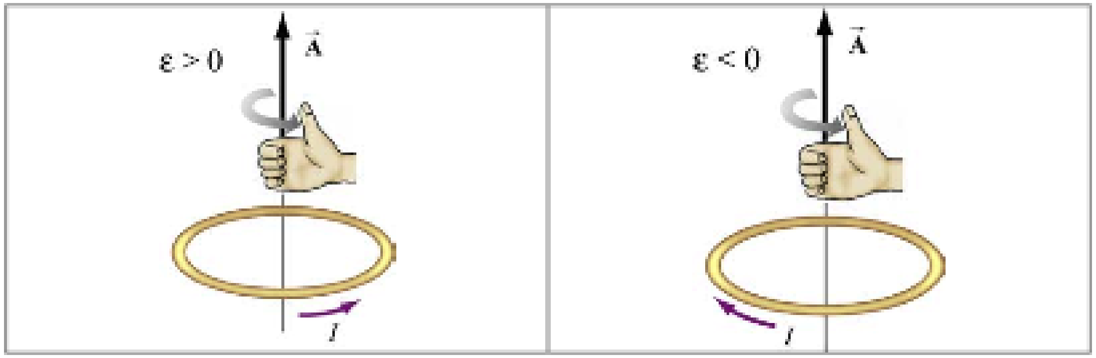
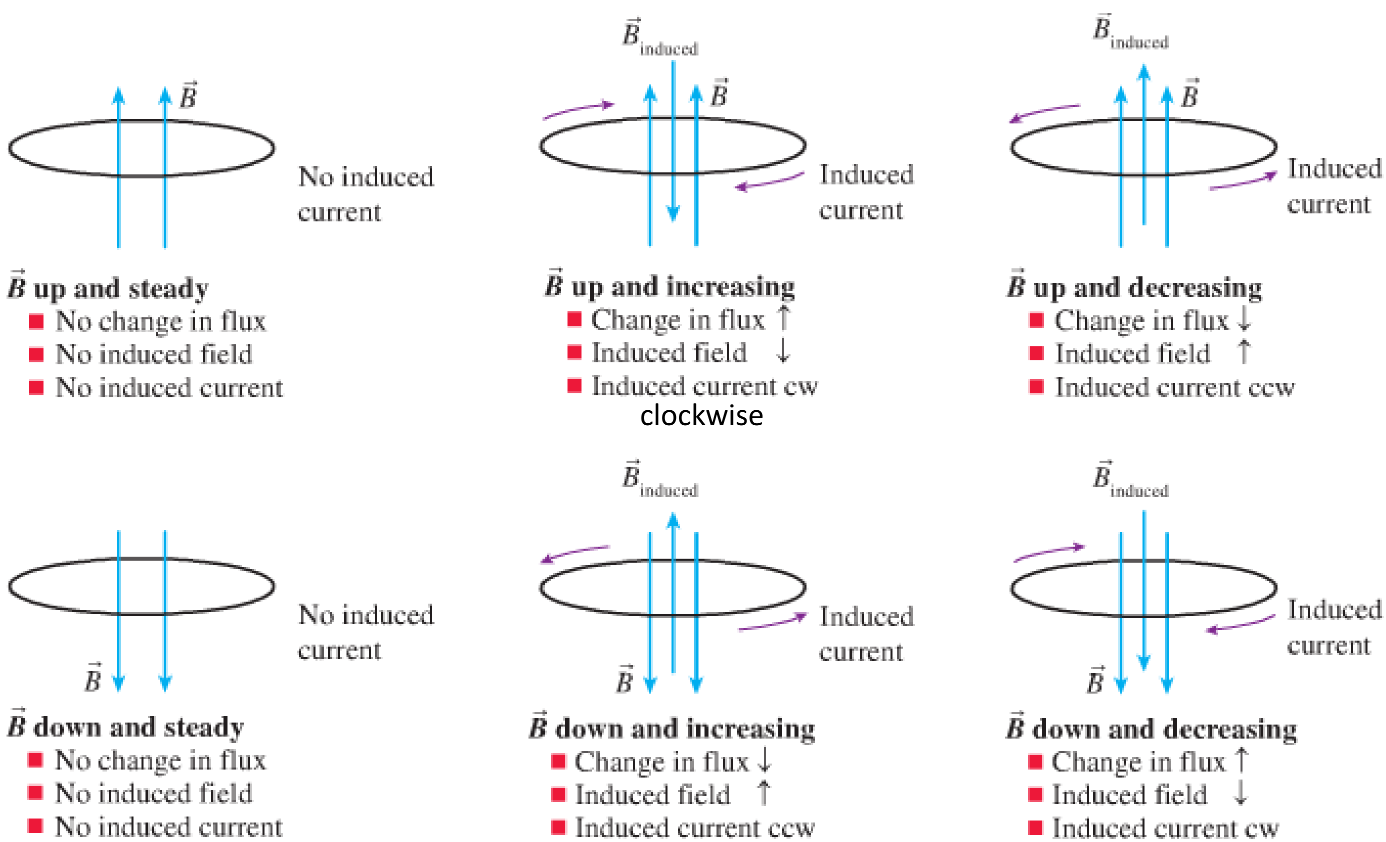


Figure 10.1.6 Determination of the direction of induced current by the right-hand rule

LENZ's LAW APPLICATION

FIGURE 34.22 The induced current for six different situations.



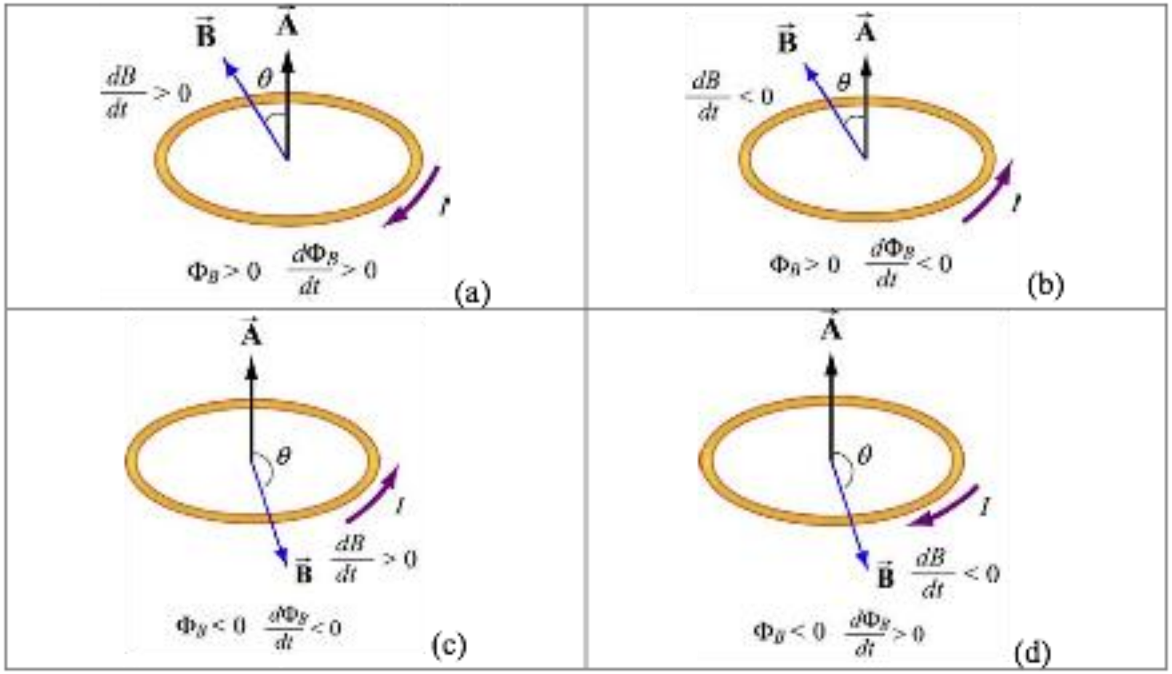


Figure 10.1.7 Direction of the induced current using Lenz's law

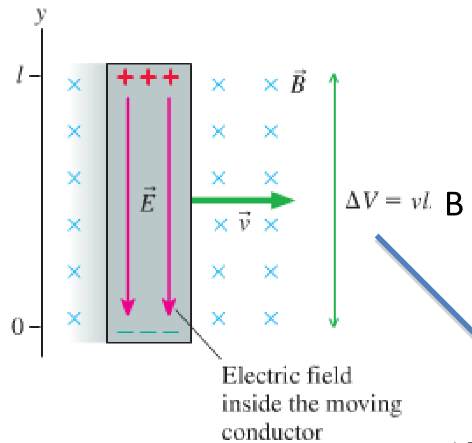
The above situations can be summarized with the following sign convention:

Φ_B	$d\Phi_B/dt$	ε	I
+	+	−	−
	−	+	+
−	+	−	−
	−	+	+

The positive and negative signs of I correspond to a counterclockwise and clockwise currents, respectively.

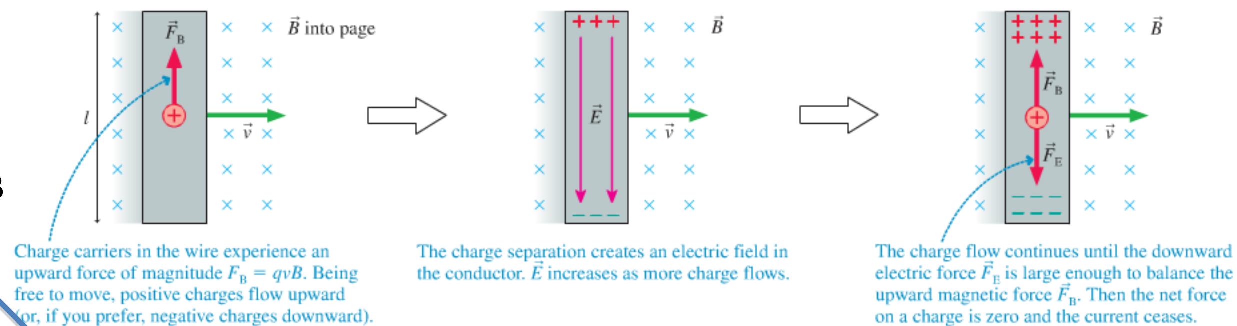
HOW TO CREATE E-FIELDS

(a) Magnetic forces separate the charges and cause a potential difference between the ends. This is a motional emf.



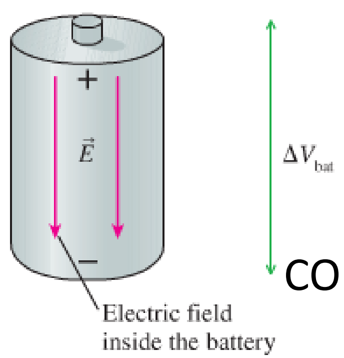
NON-COULOMBIC OR INDUCTIVE

FIGURE 34.2 The magnetic force on the charge carriers in a moving conductor creates an electric field inside the conductor.



$$\Delta V = V_{top} - V_{bottom} = -\int_0^l E_y\,ds = -\int_0^l -(vB)\,ds = vBl$$

(b) Chemical reactions separate the charges and cause a potential difference between the ends. This is a chemical emf.



COULOMBIC

$$F_E = qE$$

$$F_B = qvB$$

$$E = vB$$

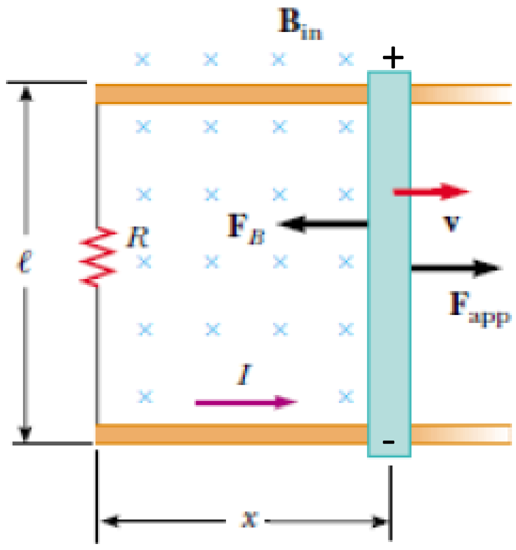
$$EMF, \varepsilon = vlB$$

Motional emf

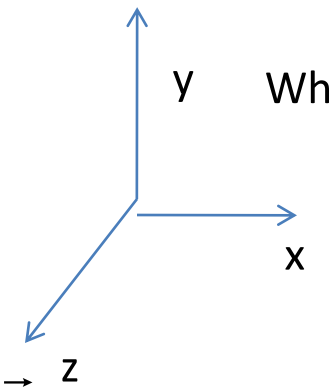
The motional emf of a conductor of length *l* moving with velocity *v* perpendicular to a magnetic field *B* is

$$\mathcal{E} = vlB$$

HOW TO CREATE CURRENTS



(a)



Who provides the energy?

What happens if I give the wire a push?

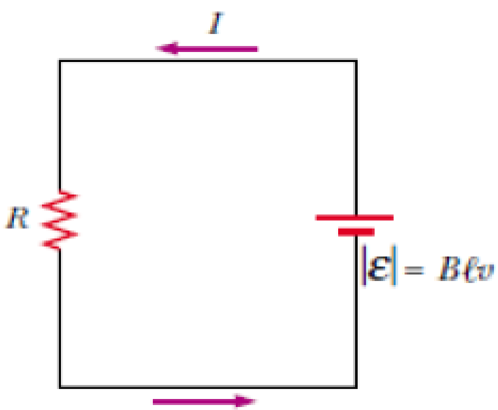
$$I = \varepsilon / R = vlB / R$$

$$\vec{F}_B = I(l\hat{e}_y) \times (-B\hat{e}_z) = -IlB\hat{e}_x = -\hat{e}_x\left(\frac{B^2 l^2 v}{R}\right)$$

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

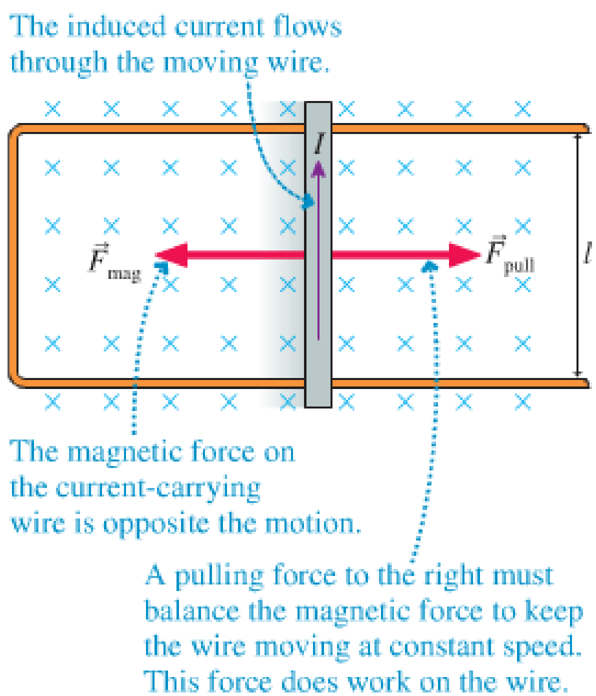
$$dv / v = -\frac{B^2 l^2 v}{mR} dt = -dt / \tau$$

$$v(t) = v(t=0)\exp(-t/\tau)$$



ENERGY – POWER ISSUES

FIGURE 34.6 A pulling force is needed to move the wire to the right.



$$dW = \vec{F} \bullet d\vec{s}$$

$$P = dW/dt = \vec{F} \bullet (d\vec{s}/dt) = \vec{F} \bullet \vec{v}$$

To maintain constant $\vec{v}$ need to apply a force

$$\vec{F}_{pull} = e_x IlB = e_x (vlB/R)lB$$

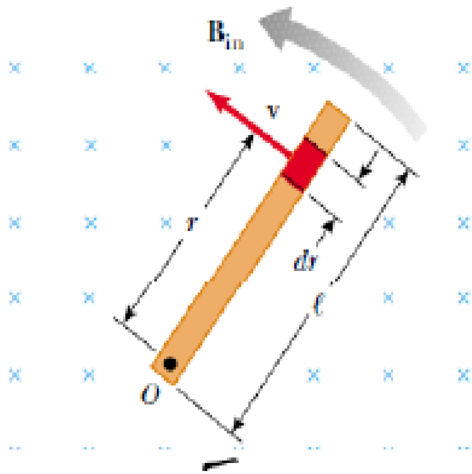
$$P_{inp} = \frac{(vlB)^2}{R}$$

$$P_{diss} = I^2 R = \frac{(vlB)^2}{R}$$

Energy Conservation

A simple generator transforms mechanical power to electrical power

Rotating conducting bar in magnetic field



A conducting bar of length ℓ rotates with a constant angular speed ω about a pivot at one end. A uniform magnetic field **B** is directed perpendicular to the plane of rotation, as shown in Figure 31.11. Find the motional emf induced between the ends of the bar.

Let dq be charge within element dr

In equilibrium:

$$F_E = F_B \rightarrow dqdE = dqvB$$

dE parallel to the bar and across dE

$$\mathrm{v} = \omega \mathrm{r} \rightarrow \mathrm{dE} = \omega \mathrm{rB}$$

$$\text{For uniform E - field} \rightarrow |\Delta \mathrm{V}| = \mathrm{Ed}$$

$$\mathrm{dV} = \mathrm{dEdr} = \omega \mathrm{Brdr}$$

$$\Delta \mathrm{V} = \omega \mathrm{B} \int_0^{l} \mathrm{rdr} = \frac{l^2}{2}\omega B$$

Hydroelectric Power

FIGURE 34.4 Pictorial representation of a metal bar rotating in a magnetic field.

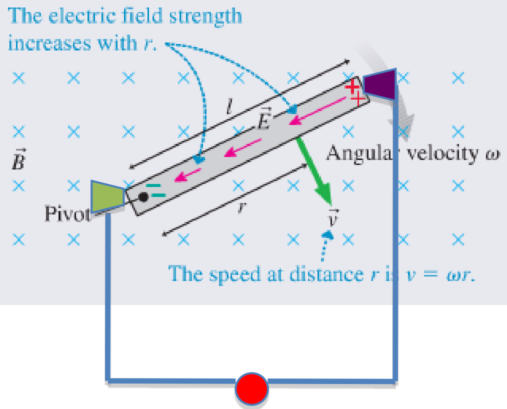


FIGURE 34.6 A pulling force is needed to move the wire to the right.

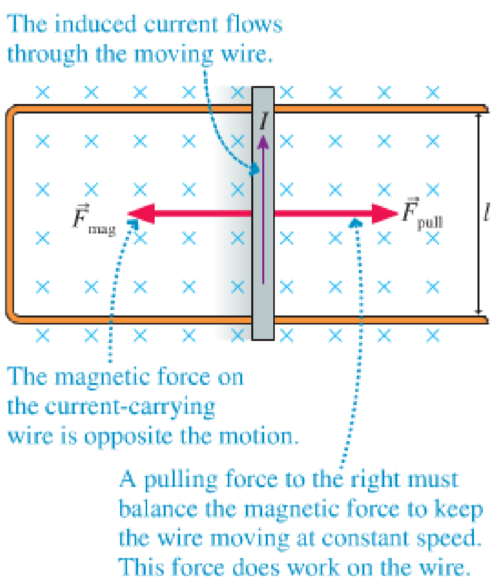
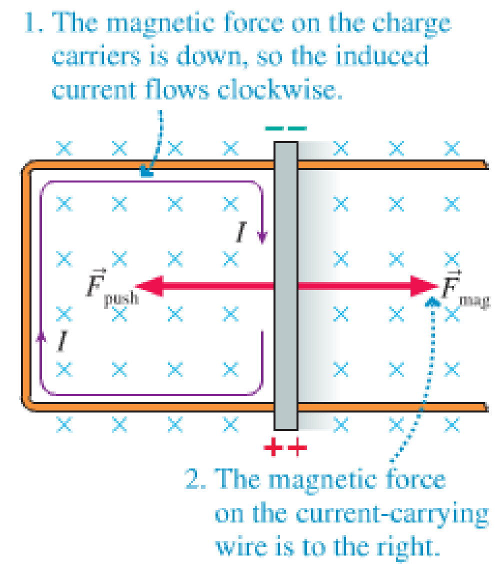
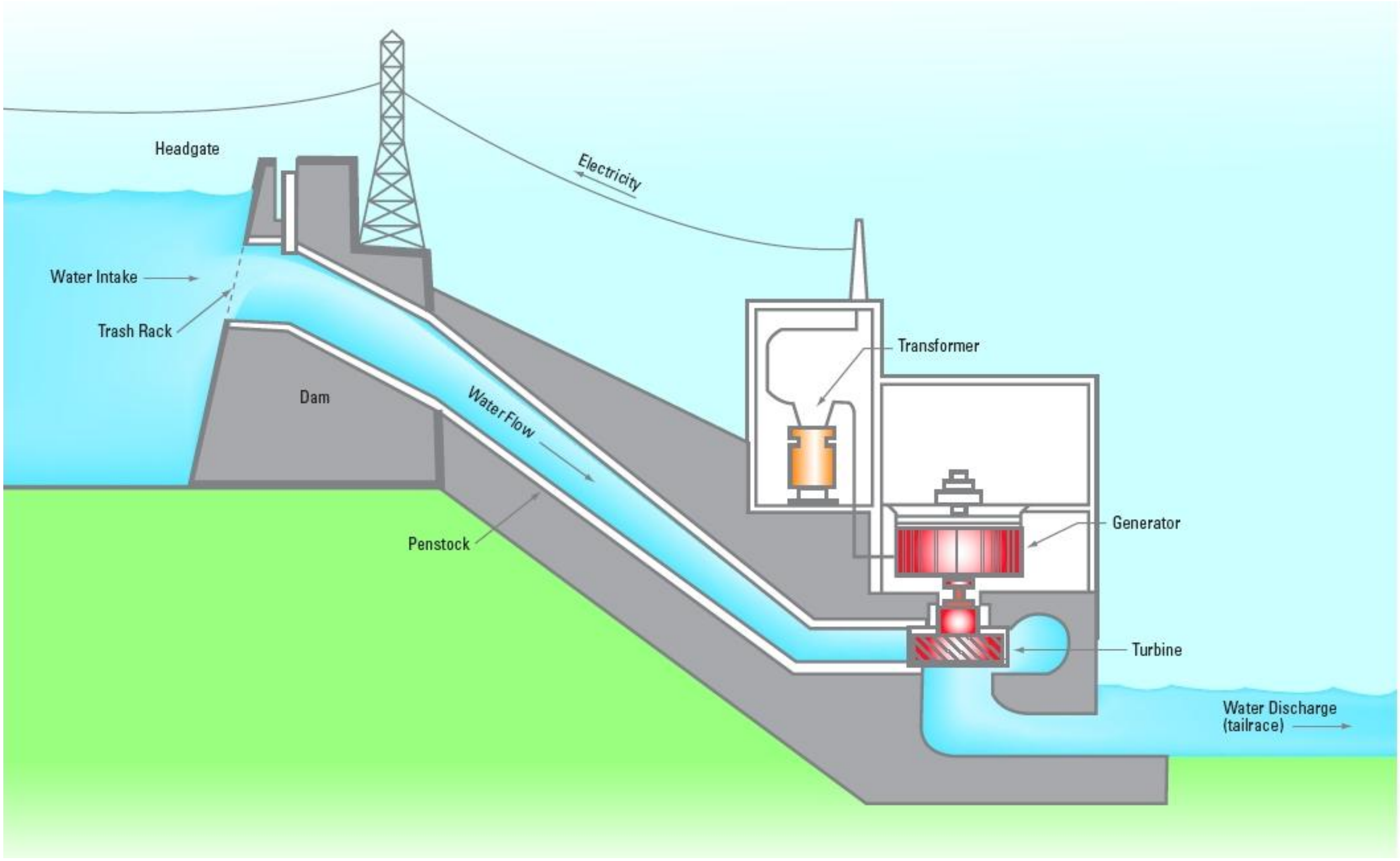


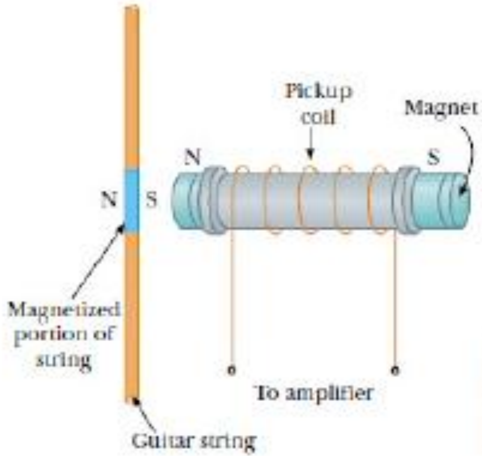
FIGURE 34.7 A pushing force is needed to move the wire to the left.

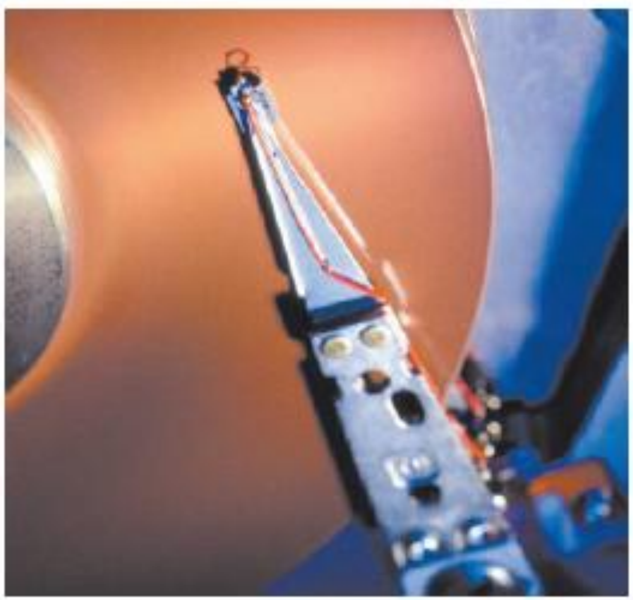


Hydro-Electric Station



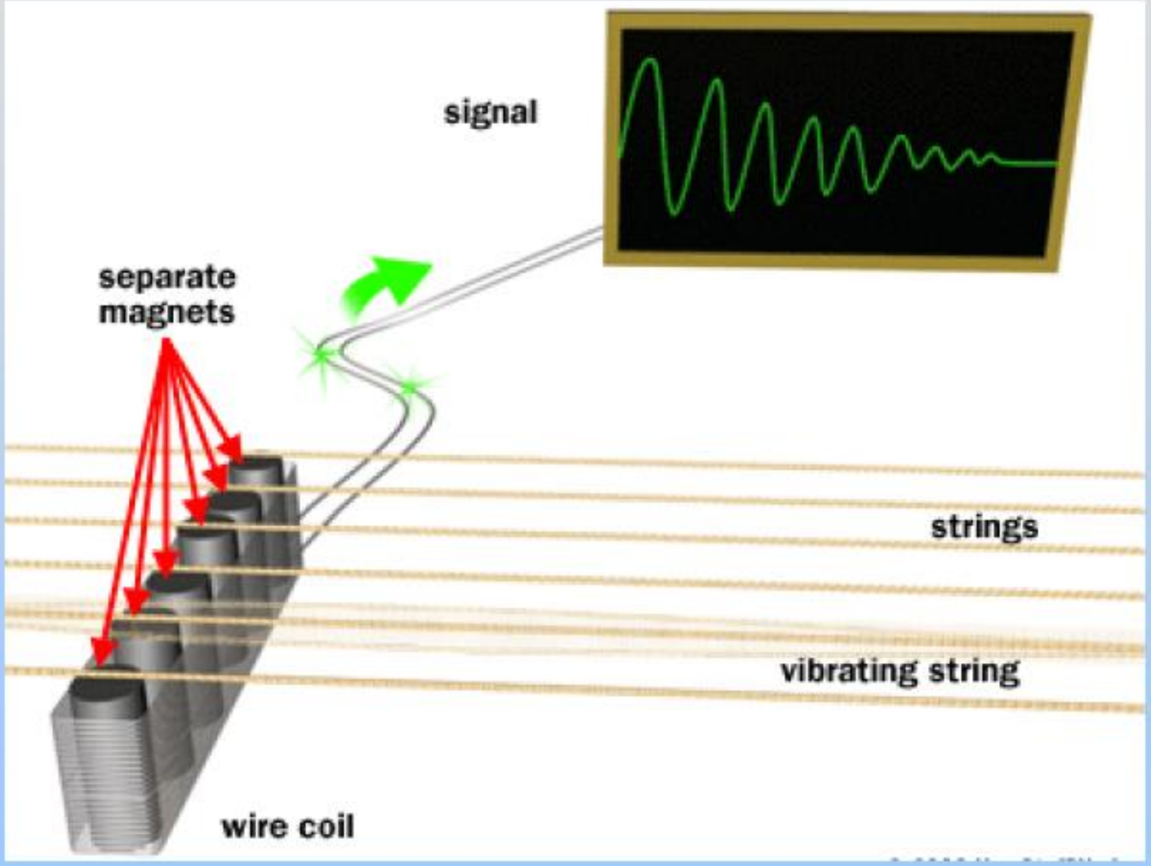
Watch movie at www.opg.com/power/hydro/howitworks.asp





Magnetic data storage encodes information in a pattern of alternating magnetic fields. When these fields move past a small *pick-up coil,* the changing magnetic field creates an induced current in the coil. This current is amplified into a sequence of voltage pulses that represent the 0s and 1s of digital data.

Electric Guitar



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TETHERED SATELLITE SYSTEM

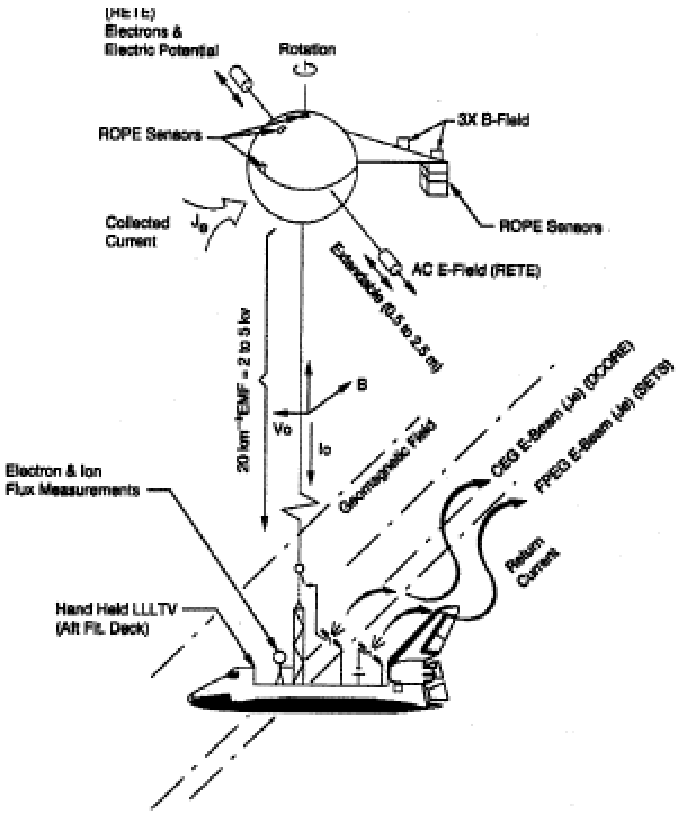

Figure 1.6 TSS Functional Schematic

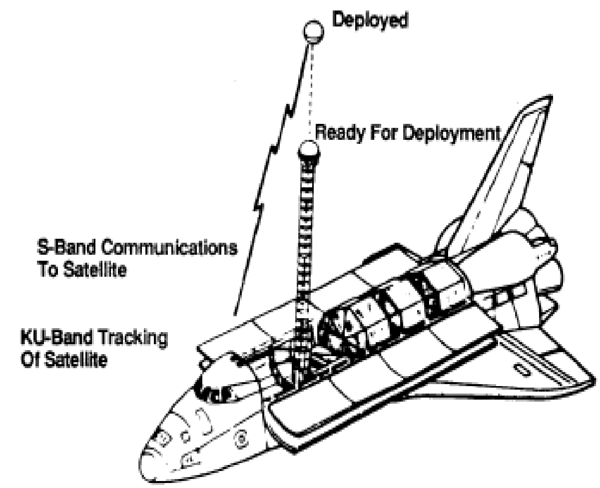

Figure 1.1 TSS-1 Satellite and Tether Attached to 12 Meter Extendible Boom

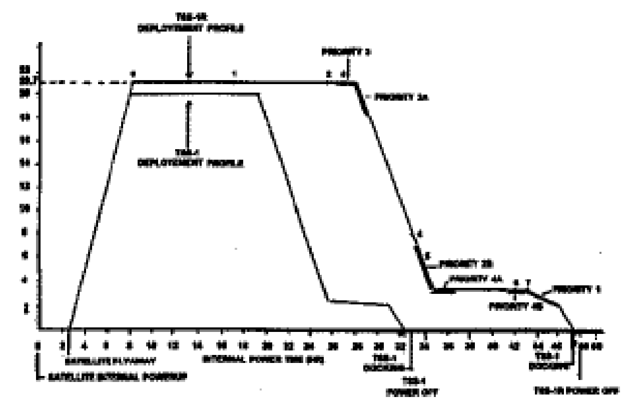

Figure 1.3 TSS1 and TSS1R Timelines

EMF=vlB= (8 km/sec) (20 km)(.3 x10^{-4} T)=4.8 kV

R= 4.8 kV/1A=4800 Ohm

P=I(EMF)=4.8 kW