# Faraday's Law

Faraday's Law is one of 4 basic equations of the theory of electromagnetism, called Maxwell's Equations. We have said before that charges makes electric fields. This is the truth, but not the whole truth. Michael Faraday (British physicist, c.1850) showed that there is a second way to make an electric field: a *changing* magnetic field makes an electric field.

Faraday's Law (in words): An induced emf ($\mathcal{E}$) is created by changing magnetic field.

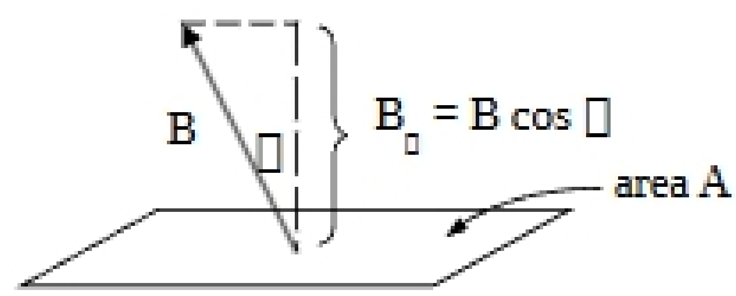
Definition: emf , $\mathcal{E}$ = a voltage difference ($\Delta V = E\, d$ ) capable of doing useful work, generating power. Think of emf as a battery voltage. Batteries have an emf, but resistors do not, even though a resistor R can have a voltage difference across it ($\Delta V = I\, R$ )

Definition: **magnetic flux** through a loop of area A = $\Phi_B = B A \cos\theta = B_\perp A$

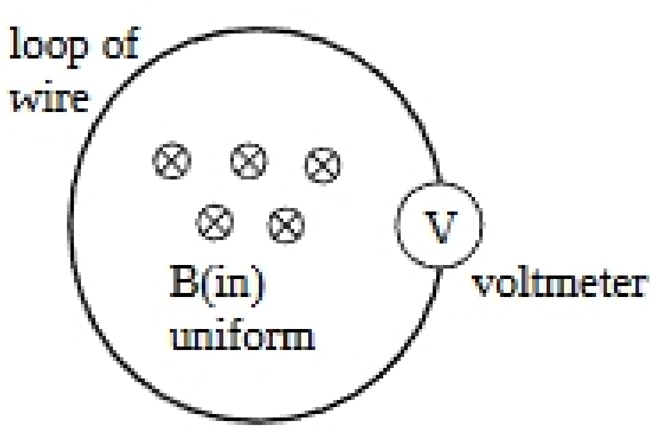
$B_\perp$ is component of **B** perpendicular to the area A.

If B-field is perpendicular to the area A, then $\Phi = B\, A$.

Units $[\Phi] = \mathrm{T{\cdot}m^2}$ = weber (Wb)



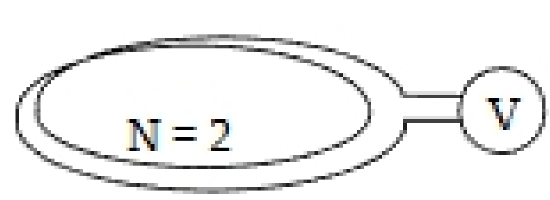

Faraday's Law (in symbols): $\mathcal{E}_{(1\ \text{loop})} = -\dfrac{\Delta\Phi}{\Delta t}$




If **B** = constant $\Rightarrow$ voltage = $\mathcal{E}$ = 0

If **B** is changing with time $\Rightarrow$ $|\mathcal{E}| = \left|\dfrac{\Delta\Phi}{\Delta t}\right| \neq 0$.

If have several loops, $\mathcal{E}_{(N\ \text{loop})} = -N\dfrac{\Delta\Phi}{\Delta t}$



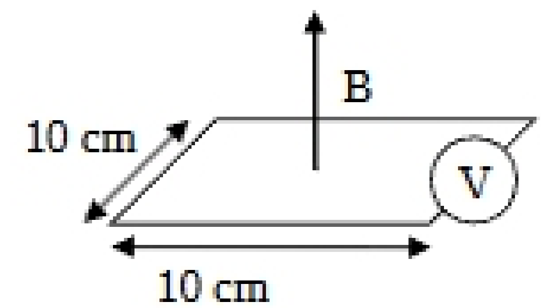
We can change the magnetic flux Φ in several ways:

1) change B (turn the magnetic field up or down)

2) change A (by altering shape of the loop)

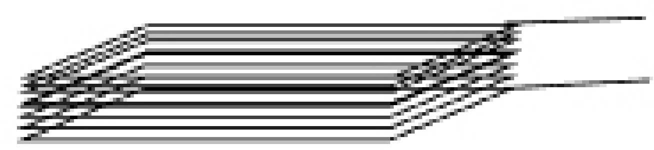
3) change the angle θ between the B-field and the plane of the loop (by rotating the loop, say)

Example of Faraday's Law: We have a square wire loop of area A = 10 cm × 10 cm, perpendicular to a magnetic field B which is *increasing* at a rate $\frac{DB}{Dt} = +0.1\,T/s$. What is the magnitude of the emf E induced in the loop?




Answer: $|E| = \frac{DF}{Dt} = \frac{D(BA)}{Dt} = A\frac{DB}{Dt} = (0.01m^2)(0.1T/s) = 10^{-3}\,V = 1mV$

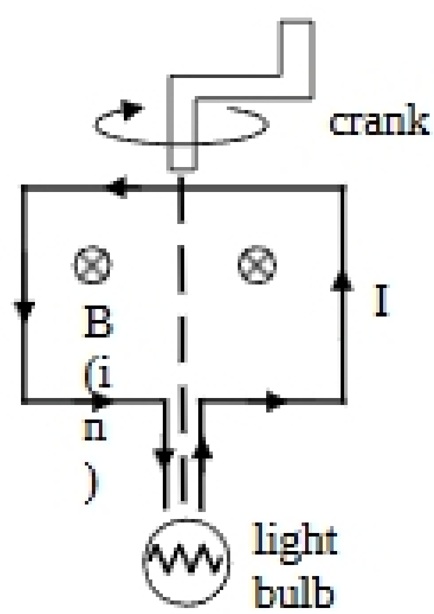
What is the emf if N = 1000 loops?



$$|E| = N\frac{D(BA)}{Dt} = 1000 \times 10^{-3}\,V = 1V$$

**Electrical Generators**

Convert mechanical energy (KE) into electrical energy (just the opposite of motors). A wire loop in a constant B-field (produced by a magnet) is turned by a crank. The changing magnetic flux in the loop produced an emf which drives a current.

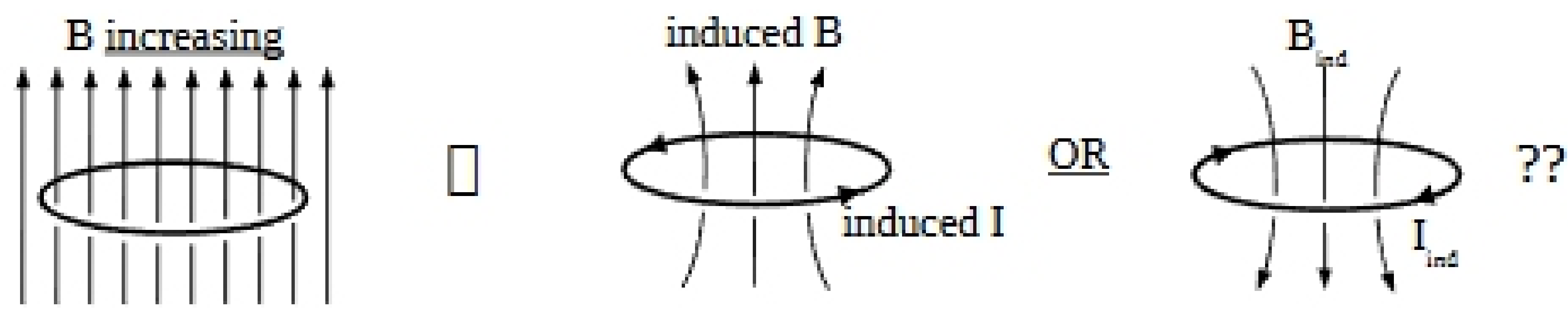



## Lenz's Law

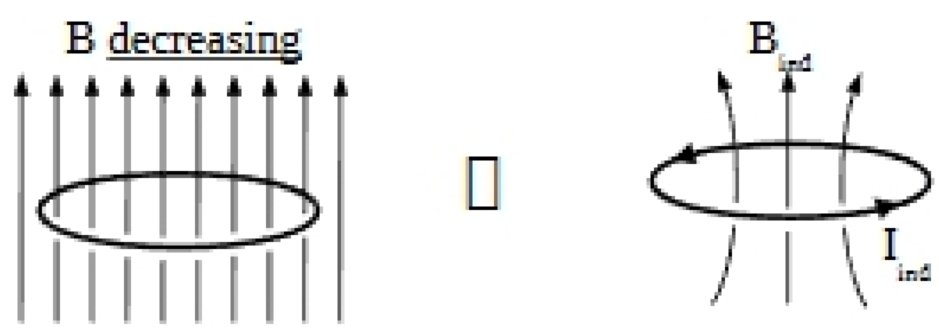
The minus sign in Faraday's law is a reminder of …

**Lenz's Law:** the induced emf E induces a current that flows in the direction which creates an induced B-field that *opposes the change* in flux.

Example: a loop of wire in an external B-field which is increasing like so



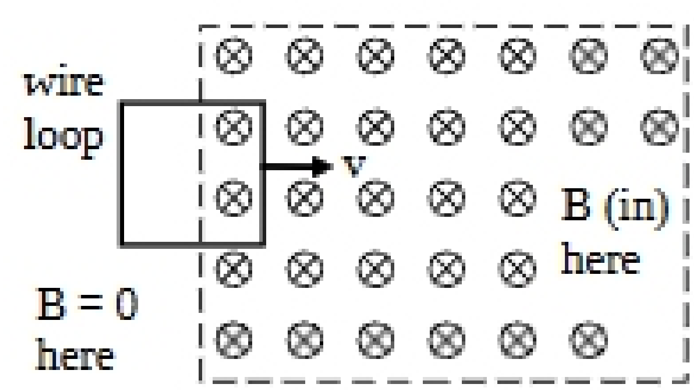

Answer: $B_{induced}$ downward opposes the increase in original B.



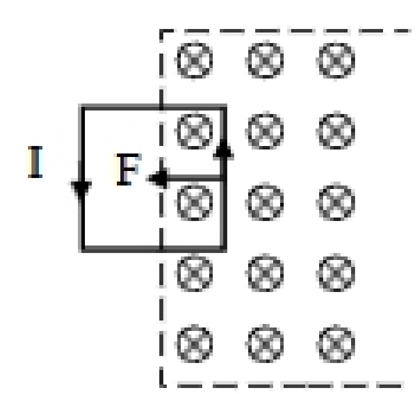

Here, induced B is upward to oppose the decrease in the original B.

Lenz's Law says "Change is bad! Fight the change! Maintain the status quo."

**Example of use of Lenz's Law** A square loop of wire moving to the right enters a region where there is a uniform B-field (in). What is the direction of the current through the wire: CW or CCW? Answer: CCW




The flux is increasing as the loop enters the field. In order to fight the increase, the induced B-field must be out-of-the-page. A induced CCW current will produce a B-field pointing out.




Does the magnetic field exert a net force on the loop as it enters the field? Answer: Yes. The upward current on the right side of the loop will feel a force to the left (from $F_{wire}$ = ILB and R.H.R.). Notice that the direction of the force on the wire loop will slow its motion.

There is a subtlety in this problem that we have glossed over. To get the direction of the force on the right-hand side of the wire, we assumed that the direction of the (imaginary positive) moving charges in the wire is upward, along the direction of the current, and not to the right, along the