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Lenz's Law

- We 'derived' Faraday's Law for a special case: a metal bar was dragged through a perpendicular magnetic field. The balance between electric and magnetic forces led to a potential difference ($\mathcal{E}$) between the ends of the bar. Completing the 'loop' (such that we have both a circuit and a closed surface), we saw that the magnetic flux

$$\Phi_B = \bar{B} \cdot \bar{A} = BA\cos\theta$$

changes due to the change in area of that closed surface. Faraday's law was then expressed as:

$$\mathcal{E} = -\frac{d}{dt}\Phi_m \qquad (\underline{\text{NOTE}}: \Phi_m = \Phi_B)$$

- However, $\frac{d\Phi_m}{dt} \neq 0$ for other reasons as well (aside from just the area changing)

1) $B = B(t)$ — magnetic field strength changes

2) $\theta = \theta(t)$ — orientation of loop ($\bar{A}$) changes w/ respect to $\bar{B}$

→ any means by which the magnetic flux changes w/ time (i.e. dynamically) is sufficient to create an electromotive force $\mathcal{E}$

- Lenz was a Russian physicist (1804-1865) who studied electromagnetic induction after Faraday and came up w/ the 'law' named in his honor:

Lenz's Law: Given a current loop permeated a magnetic field ($\bar{B}$), assume that the flux Φ_m is changing for some reason (e.g. $B = B(t)$, changing area of loop). Then a current (I_{ind}) will be induced and also create an associated magnetic field ($\bar{B}_{ind}$) with direction that **opposes** changes in Φ_B. Put another way, the induced current is such that Φ_m due to $\bar{B} + \bar{B}_{ind}$ 'tries' to stay constant

- if $\frac{d}{dt}\Phi_m > 0$, then $\bar{B}_{ind}$ opposes $\bar{B}$ (i.e. sign difference)
- if $\frac{d}{dt}\Phi_m < 0$, then $\bar{B}_{ind}$ supports $\bar{B}$ (i.e. same sign)

□ A few salient points can be raised here:

- Lenz's law explains the minus sign in Faraday's Law (i.e. $\mathcal{E} = -\, d\Phi_B/dt$) : induced magnetic fields never boost time-varying magnetic fields (that would violate **conservation of energy**)

  ⇝ think of our example from 3/1 w/ the moving bar : the induced current was such that it created a force that opposed the mechanical change being made by sliding the bar

- It's like the $\bar{B}$ has some inertia in that it resists change

  ⇝ when we deal w/ circuits again, we'll see that this electrical-mechanical analogy is spot-on (i.e. that 'inductance' is directly analogous to the momentum of a moving mass)

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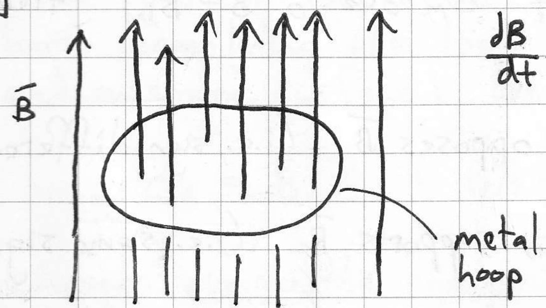
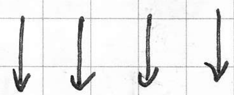
- Note that we discuss induced currents in the loop, but that is consistent w/ Faraday's law in that the $\mathcal{E}$ ($=\Delta V$) generated is what produces I_{ind} and that $B_{ind} \sim I_{ind}$

$\boxed{ex}$

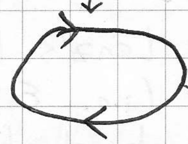


$\frac{dB}{dt} > 0$ (i.e. field is getting stronger, equivalent to field lines getting denser)

$\bar{B}_{ind}$ opposes $\bar{B}(t)$

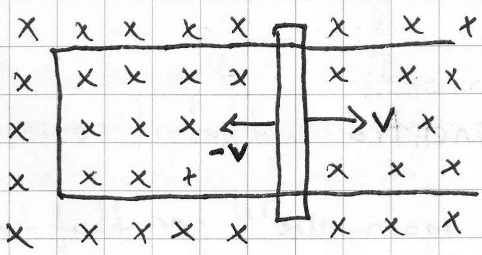


since $\bar{B}_{ind}$ points downwards, the induced current must be clock-wise (when looking down from above)



NOTE: what matters is the flux Φ_m through the area surrounded by the loop (A); what happens outside the loop (in terms of $\bar{B}$) won't matter $\therefore$

$\boxed{ex}$



Come back to our moving bar (e.g. Giordano fig. 21.6)

- if $v > 0$, then $\frac{d\Phi_m}{dt} > 0$ and $\bar{B}_{ind}$ must come out of the pg. to oppose the change
$\rightarrow$ I_{ind} goes counterclockwise

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- if $v<0$, then $\frac{d\Phi_m}{dt} < 0$ (since the area is getting smaller)
  so $\bar{B}_{ind}$ must go into the page to resist the change.
  $\rightarrow I_{ind}$ goes clockwise

$\boxed{\text{ex}}$ Drop a strong magnet down a copper tube (Google it to see some neat videos!)

$\boxed{\text{see also 'eddy current brake'}}$

Q: Why does the magnet fall so slowly? what is opposing gravity?

A: There is a drag force (thereby leading to a relatively low terminal velocity) due to a current induced in the tube

- Consider a segment of the tube (i.e. a ring) <u>below</u> the magnet
- As the magnet approaches the ring (w/ some velocity v), there is a ~~[illegible]~~ change in the magnetic flux of the ring

$$\frac{d\Phi_m}{dt} > 0 \quad \text{(flux increasing due to magnet falling towards ring)}$$

- A current is induced in the ring so to create a magnetic field that opposes this change in flux (i.e. $\bar{B}_{ind}$ points upwards). This field creates a force in the direction opposite of gravity (essentially a drag force) that acts on the magnet
- Similar logic holds for a ring <u>above</u> the magnet (just the sign is flipped because $d\Phi_m/dt < 0$ there!)

<u>NOTE</u>: For thicker (higher-quality) copper tubes w/ same inner diameter, the magnet falls more slowly. This is because the same $\mathcal{E}$ is induced, but less resistance $\rightarrow$ higher I_{ind}

$\boxed{\text{Q}}$ what is the appropriate orientation of the ring? Vertical? Cross-sectional?

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ex Audio cassette tapes

- another practical example of magnetic induction
- the 'tape' is a long sheet of magnetizable material
- the tape player (or recorder as the case may be) has a 'tape head' that can run current through a loop
- as the tape is run across the head, it causes variations in the tape head's response due to variations in the magnetic strength encoded onto the tape
- these 'variations' are essentially the audio signal (and can then be fed to a speaker to create the audible sound)

- Signals are encoded onto the tape by changing the magnetization at a given location.
  - position along the length of the tape correlates to time
  - strength of magnetization at a given tape location correlates to sound pressure magnitude (and thereby can be used to drive a speaker
  - running the tape over the tape head uses the principle of magnetic induction to transfer that auditory information