Physics 115
General Physics II

Session 30

Induction
Induced currents

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Lecture Schedule

12-May	Mon	23	DC Circuits & Meters	21.5-21.8
13-May	Tues	24	DC Circuits	21.5-21.8
15-May	Thurs	25	RC circuits	21.6-21.7
16-May	Fri	26	Circuits - Neurons	
19-May	Mon	27	Magnetism	22.1
20-May	Tues	28	Magnetic Force	22.2-22.5
22-May	Thurs	29	Magnetic Fields	22.6-22.7
22-May	Fri	30	Induced EMF, Applications	23.1-23.3
26-May	***holiday***		NO CLASS	
27-May	Tues	31	Energy, RL circuits	23.4-23.8
29-May	Thurs	32	Transformer	23.9-23.10
30-May	**Fri**		**EXAM 3 - Chapters 21,22,23**	
2-Jun	Mon	33	AC circuits	24.1-24.3
3-Jun	Tues	34	AC circuits	24.4-24.5
5-Jun	Thurs	35	Resonance, Applications	24.6
6-Jun	Fri	36	Last class - review	
June 9	**FINAL EXAM**		**2:30-4:20 p.m.**	**Comprehensive**
	Mon		**Monday, June 9, 2014**	

Today

Announcements

- Monday = holiday: no class!
- Exam 3 is next Friday 5/30
  - Same format and procedures as previous exams
    - If you took exams with section B at 2:30, do so again
  - Covers material discussed in class from Chs. 21, 22, and parts of 23 covered by end of class on Tuesday;
    - we will skip section 22-8, magnetism in matter
  - Practice questions will posted next Tuesday evening, we will review them in class Thursday

Last time

Direction of $I_{INDUCED}$: Lenz's Law

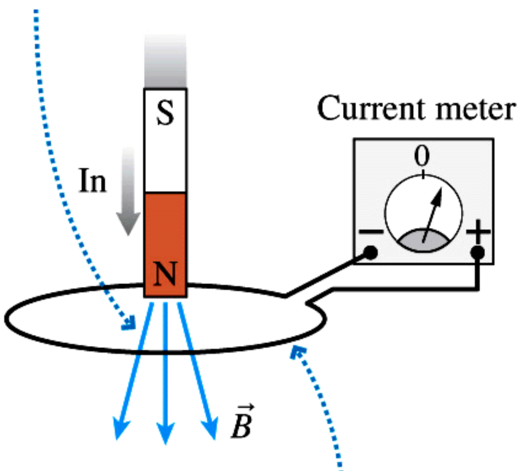
Faraday: Induced current in a closed conducting loop only if the magnetic flux through the loop is ***changing****, and emf is proportional to the* ***rate of change****.*

Lenz's Law (1834):
The direction of the induced current is such that its magnetic field opposes the change in flux.

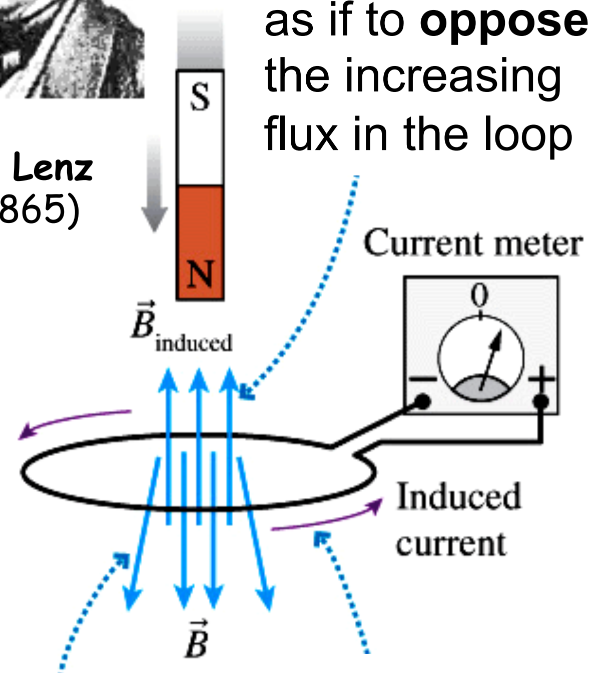
Heinrich Lenz
(1804-1865)

Induced I in the loop must make a B field that points **upward,** as if to **oppose** the increasing flux in the loop

Example: push N-seeking end of a bar magnet into a loop of wire:

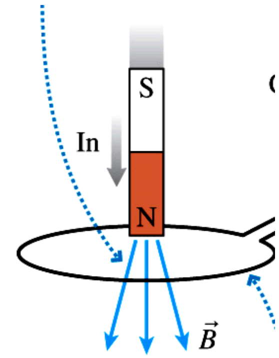


B flux through the loop points **downward** and is **increasing**



To make a B field that points **upward** the induced current must be counter-clockwise (by RHR)

- Circular coil has d=5 cm, 40 turns, R=10 ohms
- B through coil *increases* from 0.02 to 0.04 T in 1 sec
  - What is induced EMF?



$$\Phi_{INITIAL} = BA = B(\pi r^2) = (0.02T)\cdot 3.14\cdot(0.05m/2)^2 = 1.57\times10^{-4}$$

$$\Phi_{FINAL} = 2\Phi_{INITIAL}$$

$$\mathcal{E} = -N\frac{\Phi_{FINAL}-\Phi_{INITIAL}}{\Delta t} = -40\left(\frac{1.57\times10^{-4}Wb}{1\text{s}}\right) = -6.28\times10^{-3}\left[\frac{Wb}{s}\right]$$

$$Notice: \left[\frac{Wb}{s}\right] = \left[\frac{T\cdot m^2}{s}\right] = \left[\frac{(N/A\cdot m)\cdot m^2}{s}\right] = \left[\frac{N\cdot m}{A\cdot s}\right] = \left[\frac{J}{C}\right] = V$$

  - What is induced current in coil?

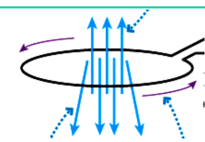
$$|\mathcal{E}| = 6.28\times10^{-3}V \quad (6.3\,mV)$$

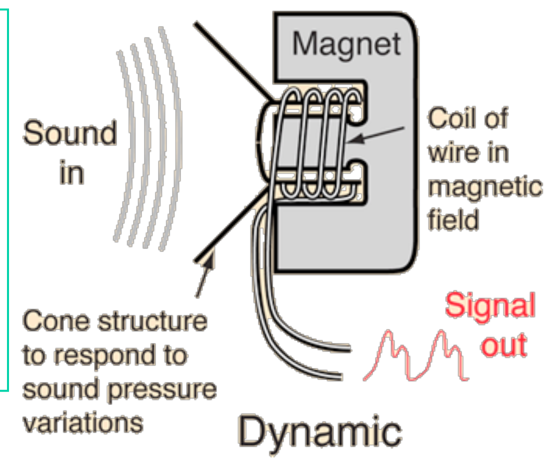
$$I = \frac{\mathcal{E}}{R} = \frac{6.28\times10^{-3}V}{10\,\Omega} = 0.63\,mA$$

  - Which way does current flow?

Flux down is increasing, so
I must make flux pointing up→CCW

Microphone:
Sound wave makes coil attached to diaphragm vibrate near magnet, electrical signal is produced



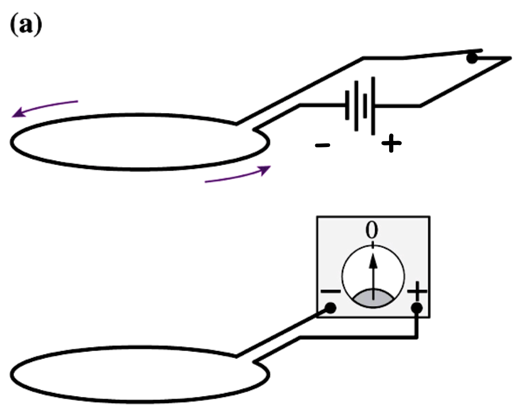


Lenz's Law with loop as source of B

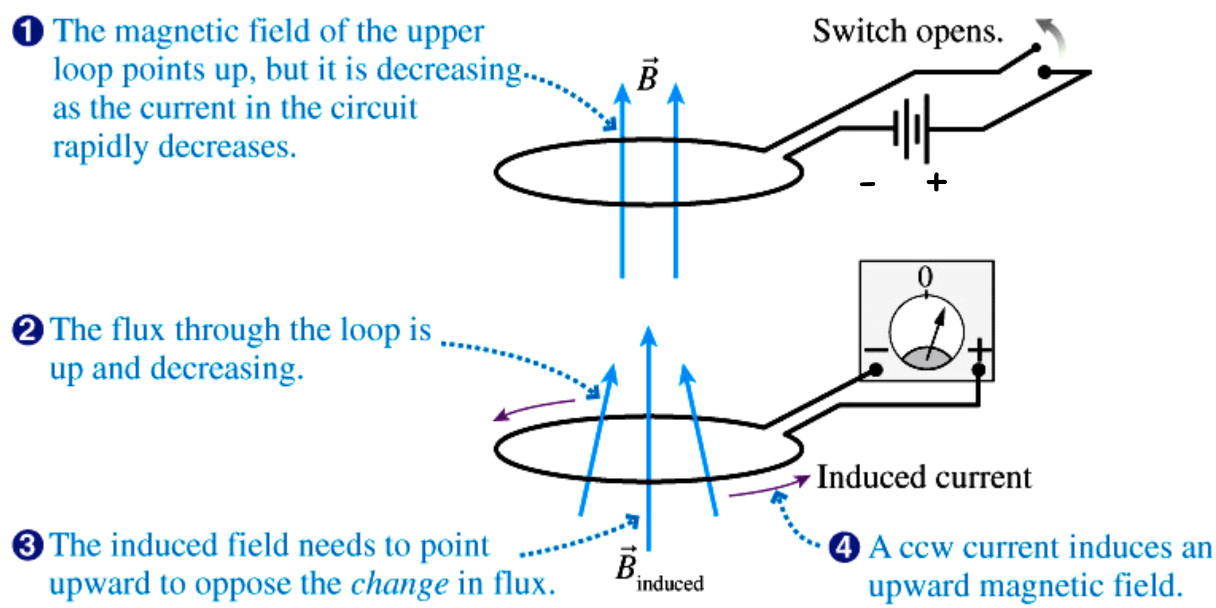
The switch in the upper loop's circuit has been closed for a long time. (loop = normal conductor, with R > 0)

Q: Which way does B flux through lower loop point ?

What happens in the **lower** loop when the switch is opened?



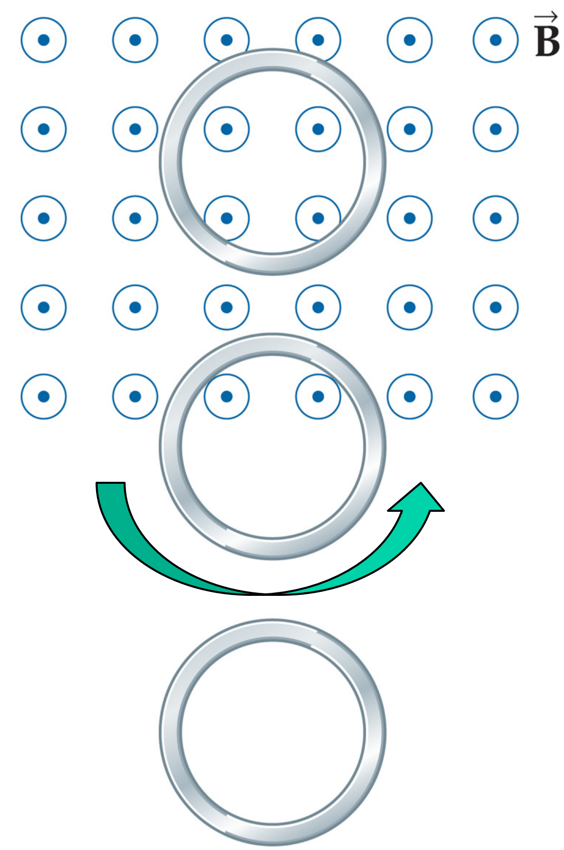
Which way does the change in B flux through lower loop point ?



Change in flux due to motion of loop

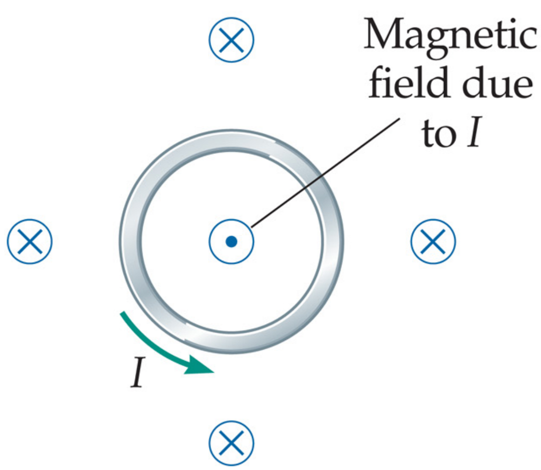
- Conducting loop falls out of a uniform B field zone
  1. In uniform B: flux = BA = constant
     - So induced emf and I = 0
  2. Partly inside uniform B: flux changing
     - Induced I
     - Direction: opposes change
  3. Outside: B=0 = constant
     - No change: I = 0

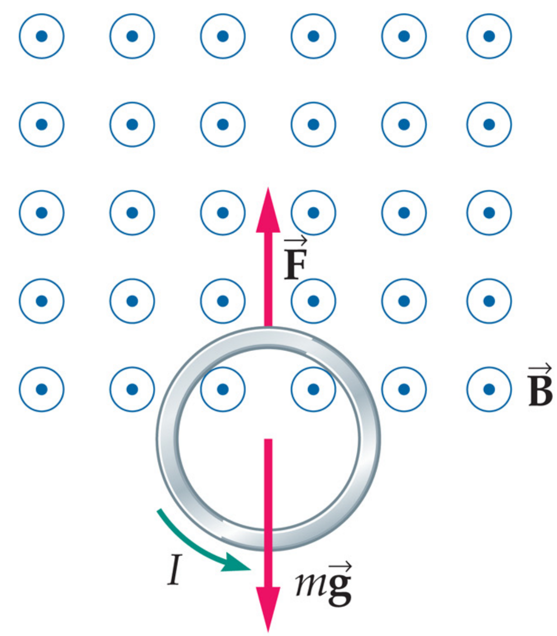
Direction of I during step 2:
B points out of screen
Φ = BA is **decreasing**
(decreasing A with B>0)
B *inside* loop due to induced
I must **add to** external B
RHR: I must be **CCW**



B Force on the falling loop due to induction

- Notice: while in changing B-field region, the loop carries induced I, so it behaves like a bar magnet
  - If I is CCW, induced field inside loop points out of screen (and weaker "return" field outside the loop points into screen)
  - Part of loop inside B experiences an attractive (upward) force
    - To see this: apply RHR to I direction at top of loop
  - Part of loop outside has F=0
  - **Net** force on loop = upward
    - Acts to oppose motion of loop





Induced I in a loop with changing area

Conducting wire slides with speed v along a U-shaped conducting rail.

The induced emf **E** creates a current I around the loop.

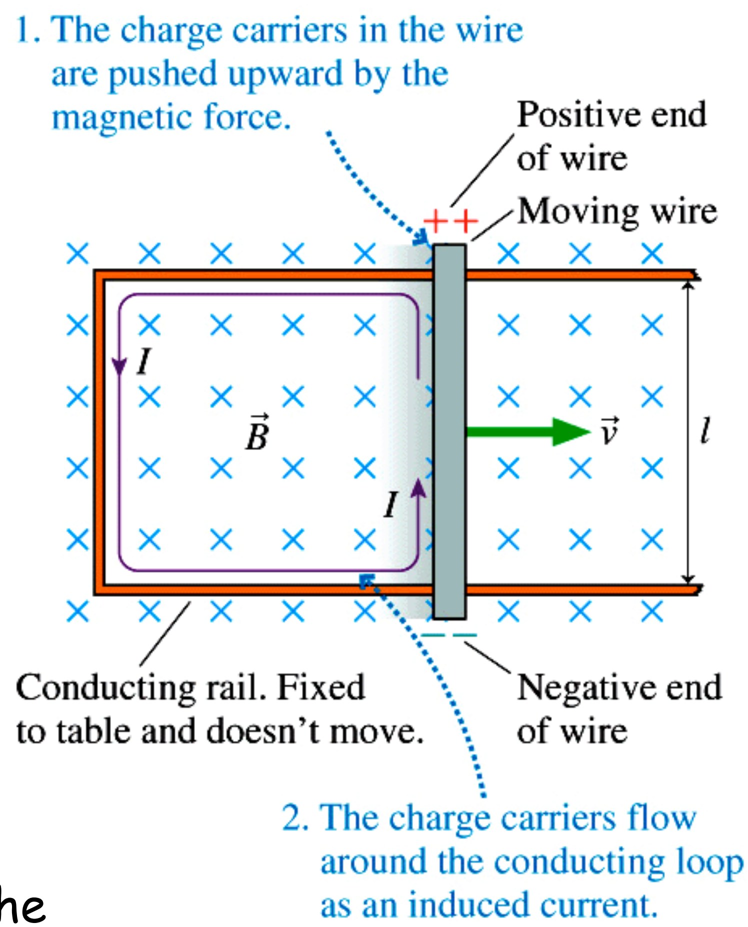
$$\mathcal{E} = -\frac{\Delta\Phi}{\Delta t} = -\frac{\Delta(BA)}{\Delta t}$$

$$= -B\frac{\Delta A}{\Delta t} = -Bl\frac{\Delta w}{\Delta t} = -Blv$$

$$I = \frac{E}{R} = \frac{vlB}{R}$$

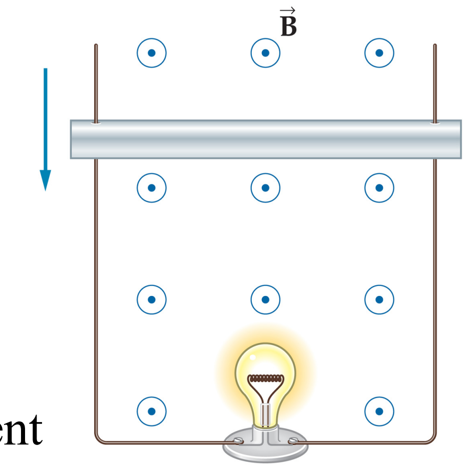
R is the net resistance of slider and rails

BTW: notice R will increase as we go to the right, or decrease as we go to the left… (unless R of bar is >> R of rails)



Motional EMF: Examples

1. Slider has length 10 cm, v=2m/s, B =0.3 T, and $R_{bulb=}$5 Ω
   - What is current? Which direction?



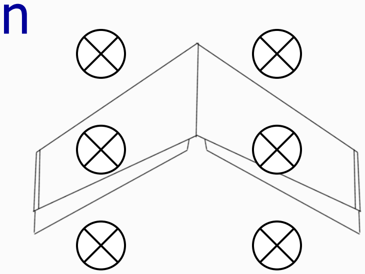
$$\frac{\Delta\Phi}{\Delta t}=\frac{B\Delta A}{\Delta t}=\frac{B\left(l\Delta x\right)}{\Delta t}=BlV=0.3T\left(0.1m\right)\frac{2m}{s}=0.06\frac{Wb}{s}$$

$$so \quad \boxed{\mathcal{E}=-BlV}=-0.06V;\quad I=\frac{\mathcal{E}}{R}=-\left(\frac{0.06}{5}\right)=12mA$$

Upward flux is being *reduced* so B points down → CCW current

- Airplane wing is 30 m long. Plane flies North at 250 m/s, where **B**$_{earth}$ = 4.7 x10^{-5} T North and 6 x10^{-5} T down
  - What is ΔV across the wing?

  (B's N component applies no force, only downward)



No loop → I=0, but B still creates EMF across wing:

Same analysis as moving rod (imagine a loop with break in wire)

$$\mathcal{E}=-\frac{\Delta\Phi}{\Delta t}=\frac{B\left(l\Delta x\right)}{\Delta t}=Blv=\left(6\ x10^{-5}\ T\right)\left(30m\right)250m/s=0.45V$$

Forces and Induction

We assumed that the sliding conductor moves with a constant speed *v*.

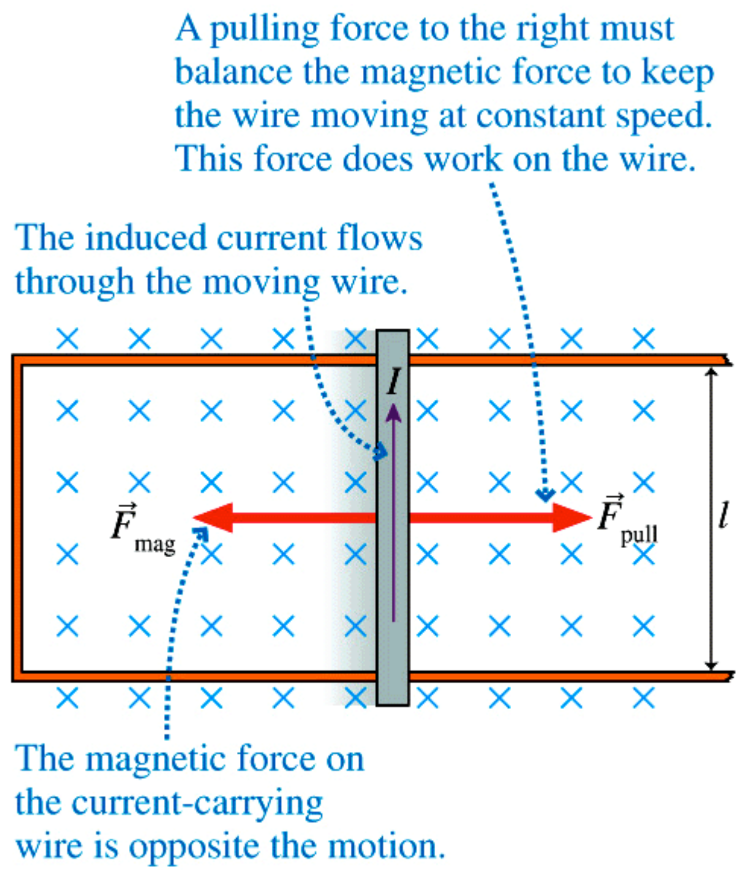
But a current carrying wire in a B field experiences a force F_{mag}

For directions of I and B shown here, the force on it must point to the left by RHR

Constant v requires net F = 0

So we must supply a counter-force F_{pull} to make speed constant.

$$-F_{pull} = F_{mag} = I\,l\,B = \left(\frac{vlB}{R}\right) lB = \frac{v l^2 B^2}{R}$$



Energy, work and power for slider

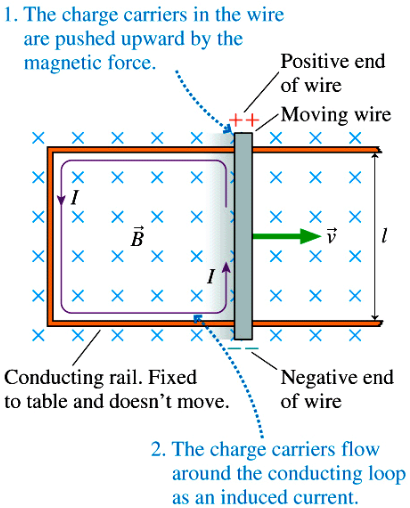
If we apply F to the slider, we are doing work on the slider: W= F d
(Notice: Whether the wire moves to the right or left, a force opposing the motion is created, so we always have to do work on it. If we stop working, v=0, induced I→0, and opposing F stops also!)
Mechanical power we must supply → P = W/t = F (d /t) = Fv

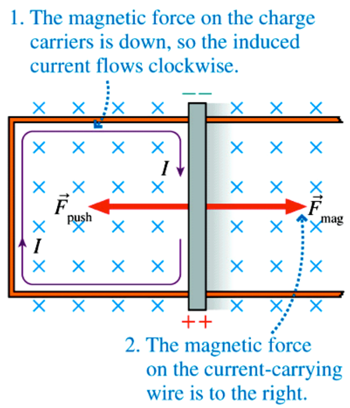
$$P_{\text{pull}} = F_{\text{pull}} v = \frac{v^2 l^2 B^2}{R}$$

Compare to the electrical power dissipated by the resistance in the rails + slider:

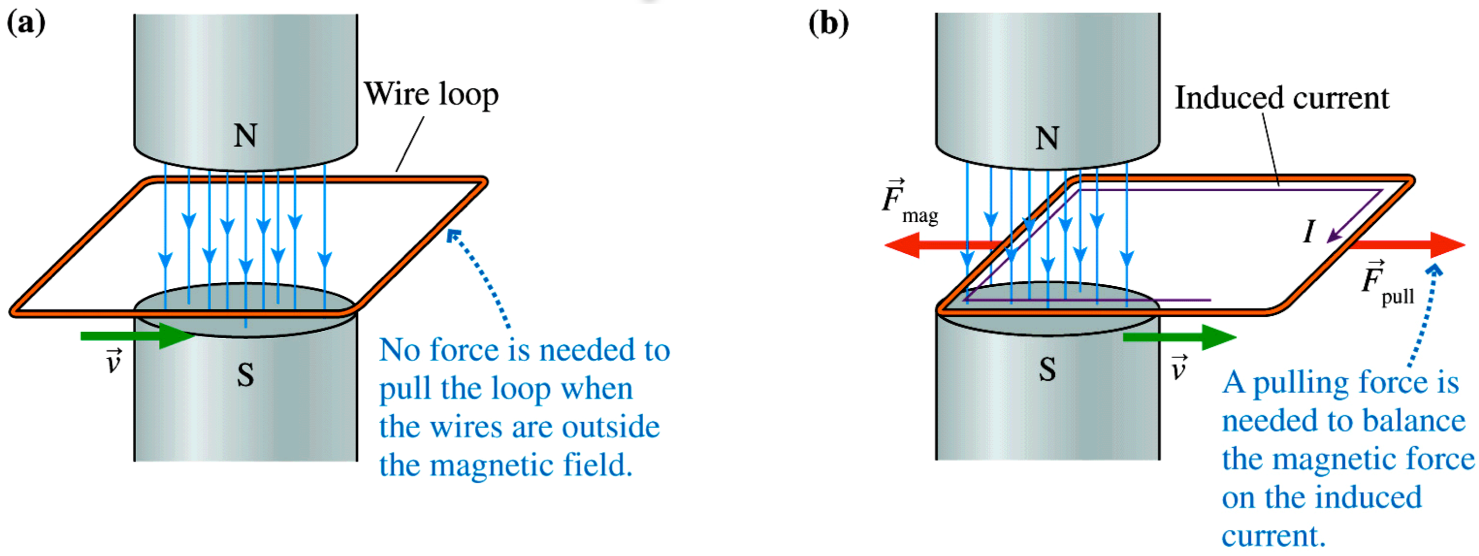
$$P_{\text{dissipated}} = I^2 R = \left(\frac{vlB}{R}\right)^2 R = \frac{v^2 l^2 B^2}{R}$$

So work done moving the conductor = energy dissipated in the resistance.
Energy is conserved.
The slider is a machine for converting mechanical work into heat!





Eddy Currents*



Move a square copper loop between the poles of a magnet:

- No current / forces while no conductor is in the field area (a).
- When one side of the loop enters the field (b), a current will be induced and a magnetic force will be exerted on the conductor.
- An external force will be required to pull the loop out of the magnetic field, even though copper is not a magnetic material.

However, if we cut the loop, there will be no circuit, so no current flows, so no B force.

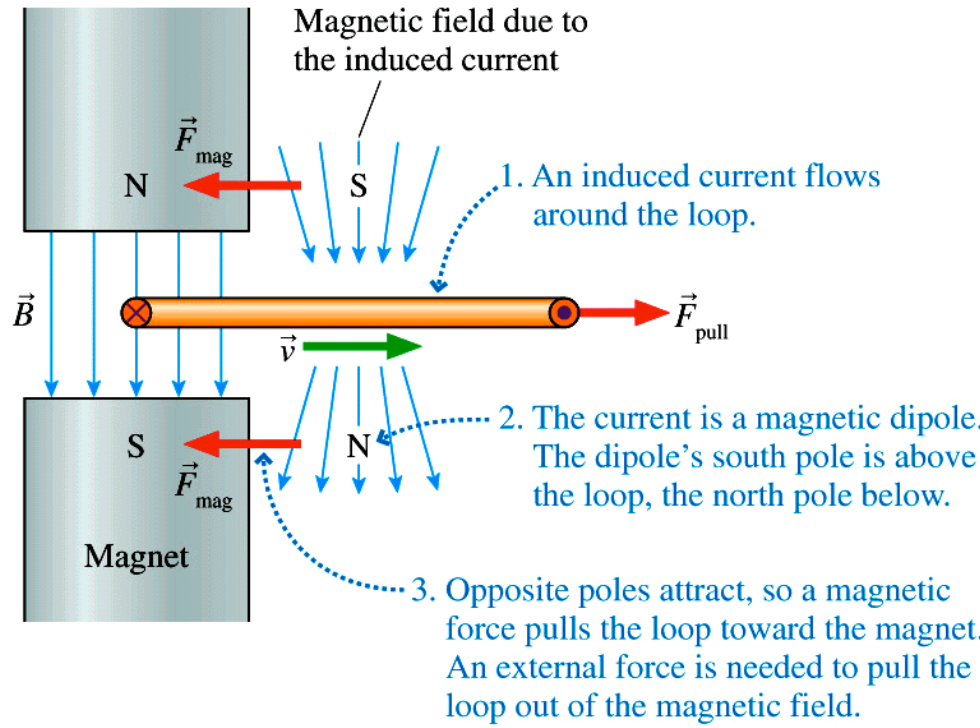
* Who's Eddy? Name will be explained in a moment!

Forces on Eddy Currents

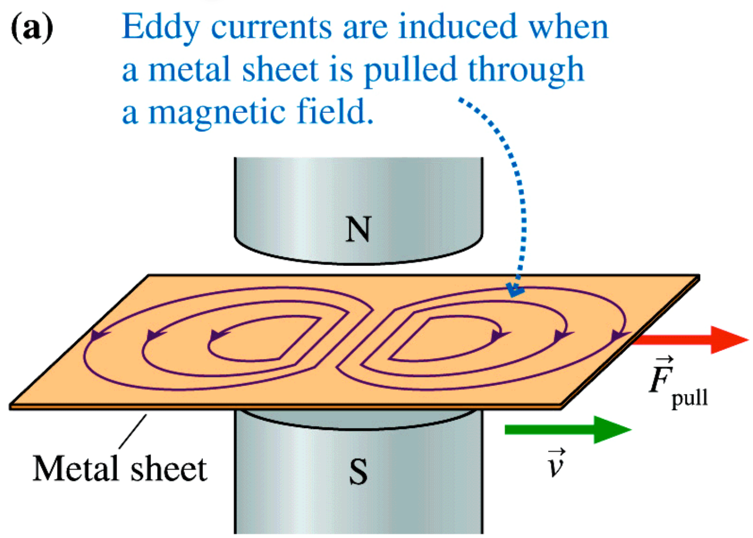
Another explanation:

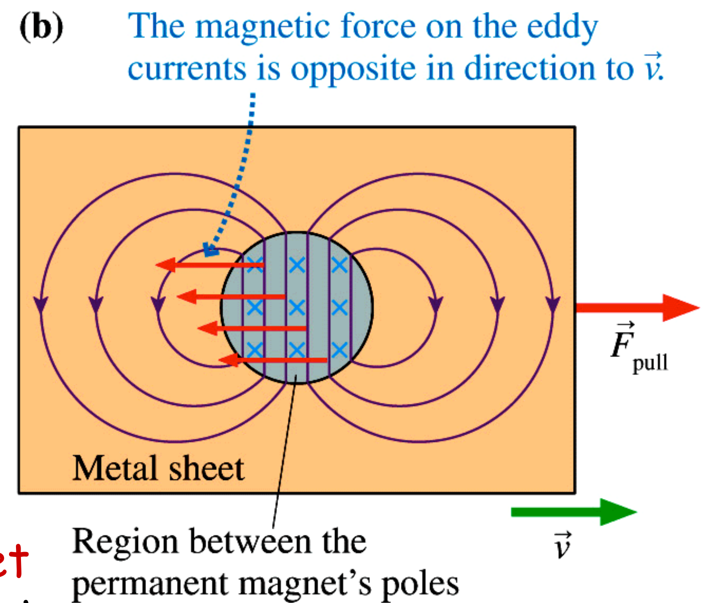
The magnetic field produced by the current in the loop acts like a magnetic dipole with its S pole near the N pole of the magnet, and vice versa.

to pull the dipole out of the magnet, the attractive forces between these unlike poles must be overcome by an external force.



Eddy Currents in conducting sheets

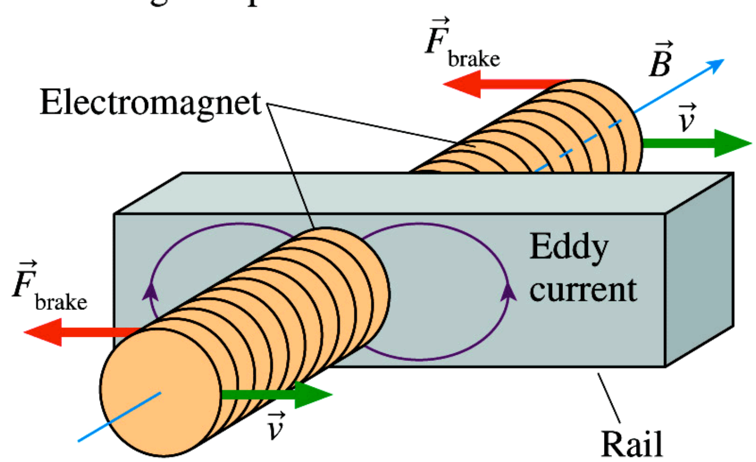




Replace the wire loop with a solid sheet of conductor pulled through the magnet.

- Same induced current, and forces as before, but now there are no well - defined current paths.
- Two opposite "whirlpools" of current appear in the conductor: one on the side where flux is increasing, and another where it is decreasing.

These are called ***eddy currents***.



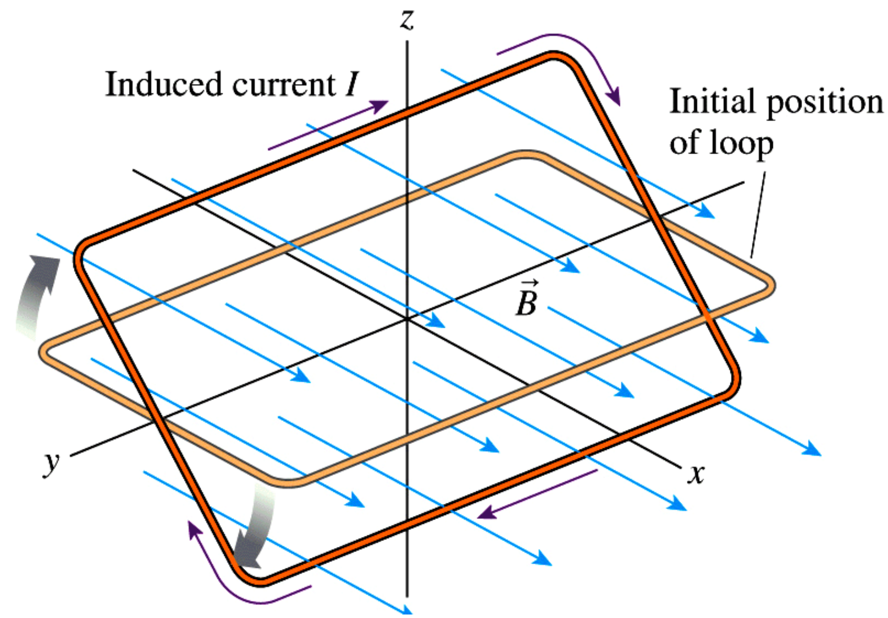
A magnetic braking system.

In water: eddy = whirlpool

Induced current in a **rotating** loop

A loop of wire is initially in the xy plane in a uniform magnetic field in the x direction. It is suddenly rotated 90^0 about the y axis, until it is in the yz plane. Flux changes due to changing area presented to B field.

In what direction will be the induced current in the loop?



Initially: no flux through the coil.
During rotation: increasing flux, pointing in the +x direction.

Induced current in the coil opposes this change by creating flux in the –x direction.
Therefore, the induced current must be clockwise, as shown in the figure.
If rotation stops, current stops.