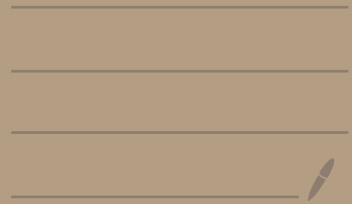


Lecture 20

- EMF, FARADAY'S
LAW, & LENZ' LAW

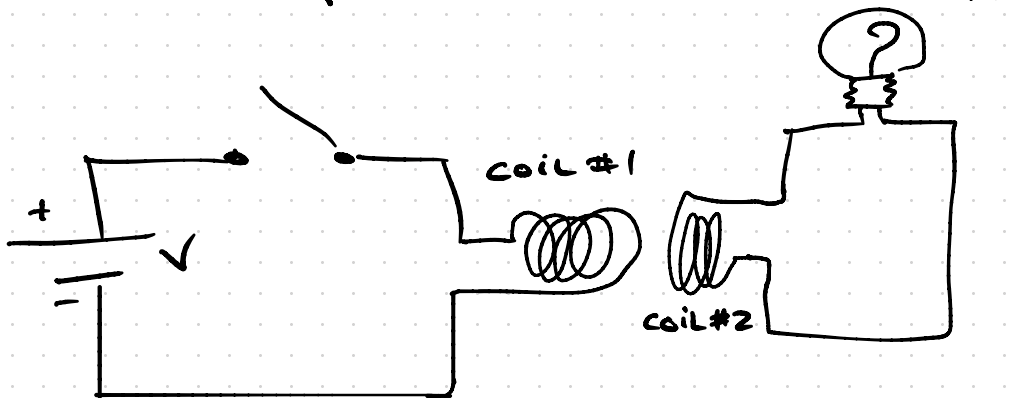


History:

1831, MICHAEL FARADAY
(ENGLAND) + JOSEPH HENRY
(USA) DISCOVERED THAT
A CHANGING MAGNETIC
FIELD INDUCED AN
ELECTRIC CURRENT:

SEE Y.T. DEMO

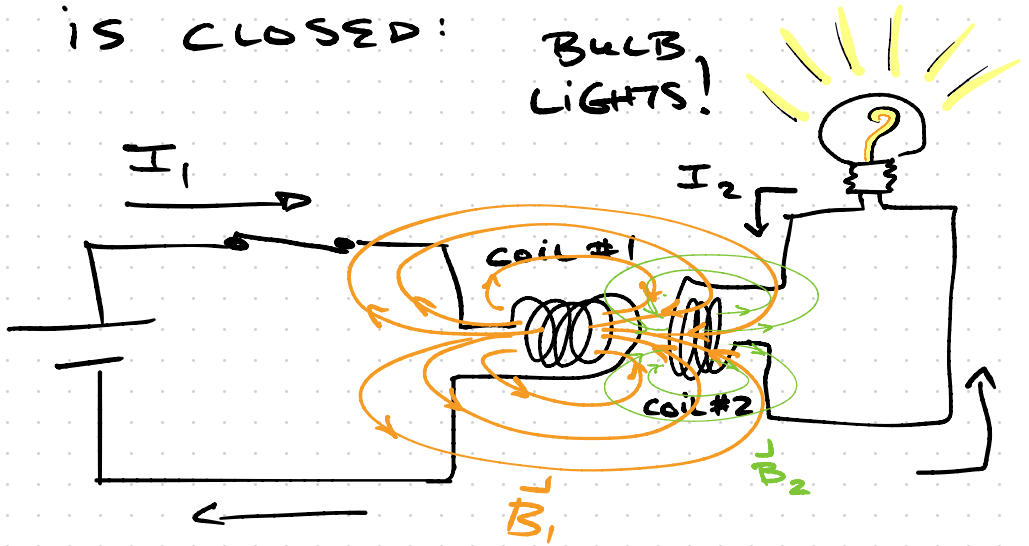
SWITCH OPEN:



② THE MOMENT SWITCH

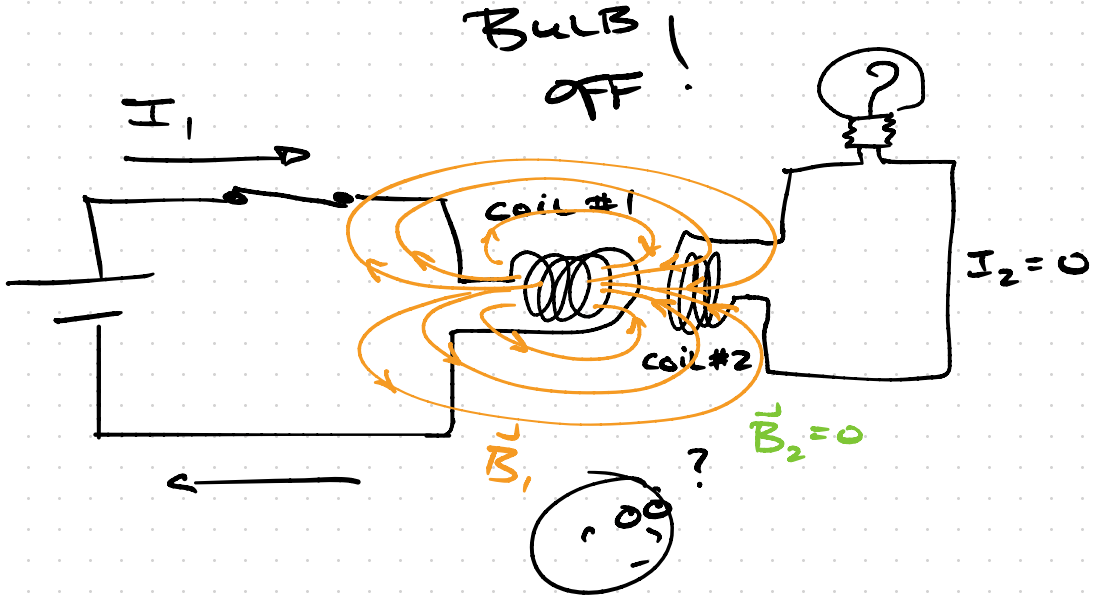
IS CLOSED:

BULB
LIGHTS!

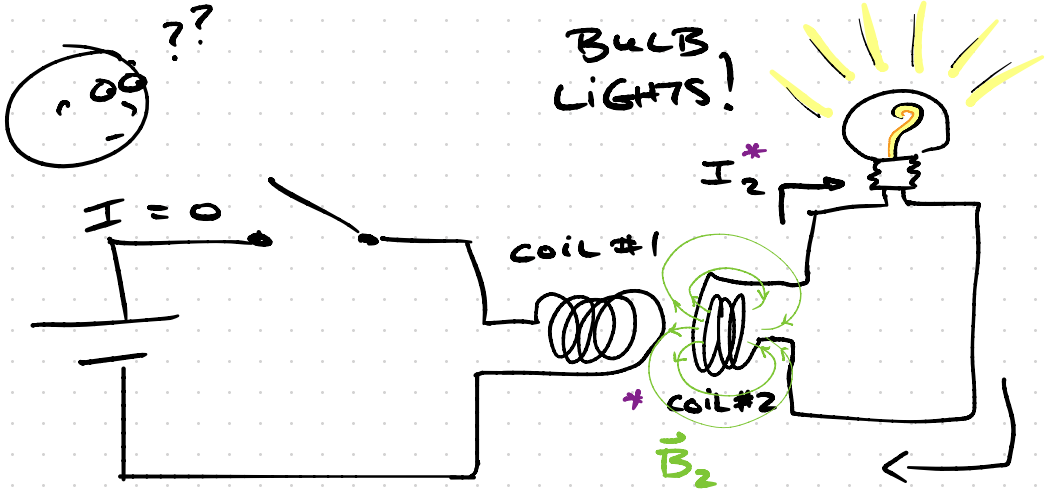


AFTER SWITCH IS CLOSED:

BULB
OFF!

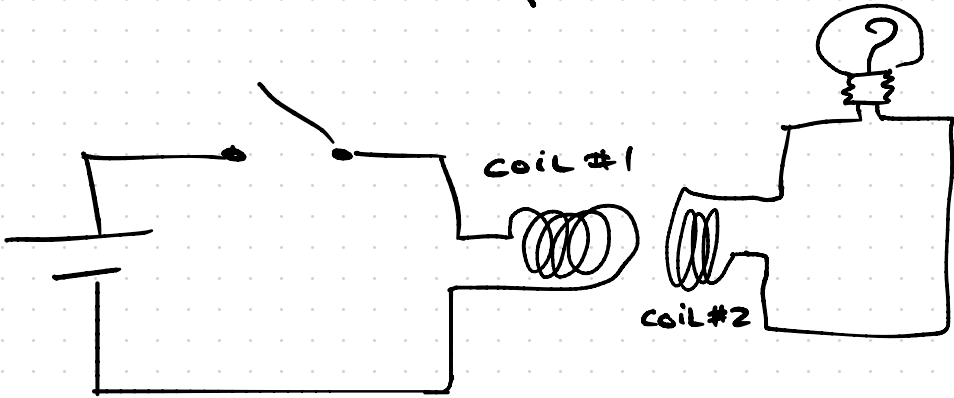


3 MOMENT SWITCH OPENS:



* NOTE THE CHANGE IN DIRECTION!

AFTER SWITCH OPEN: BULB OFF



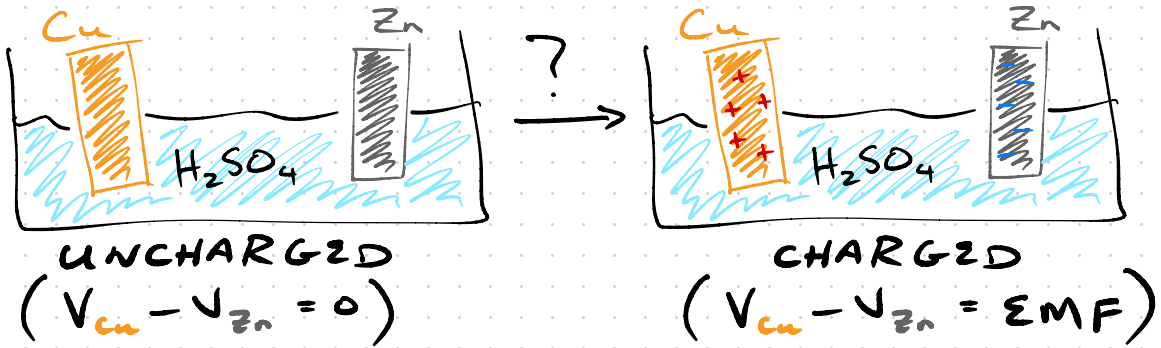
SO WHAT IS GOING ON HERE?!

"ELECTROMAGNETIC INDUCTION":

- THE CHANGES IN THE
MAGNETIC FIELD DUE
TO THE CHANGES IN THE
CURRENT IN COIL #1 ARE
INDUCING AN EMF ^{???} IN
COIL #2, WHICH INDUCES
A VOLTAGE ACROSS COIL #2,
WHICH DRIVES A CURRENT
THROUGH THE LIGHTBULB.

EMF (REVISITED)

- RECALL THE $Zn + Cu$ BATTERY:

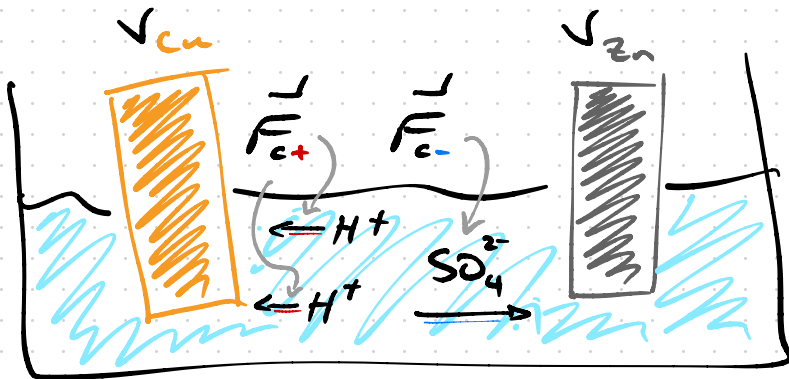


- WHEN THE PLATES ARE UNCHARGED, THE VOLTAGE ACROSS THE BATTERY IS ZERO, SO WHAT IS DRIVING THE TRANSFER OF ELECTRONS FROM $Cu \rightarrow Zn$? i.e., HOW DOES A BATTERY CHARGE UP?

ANSWER:

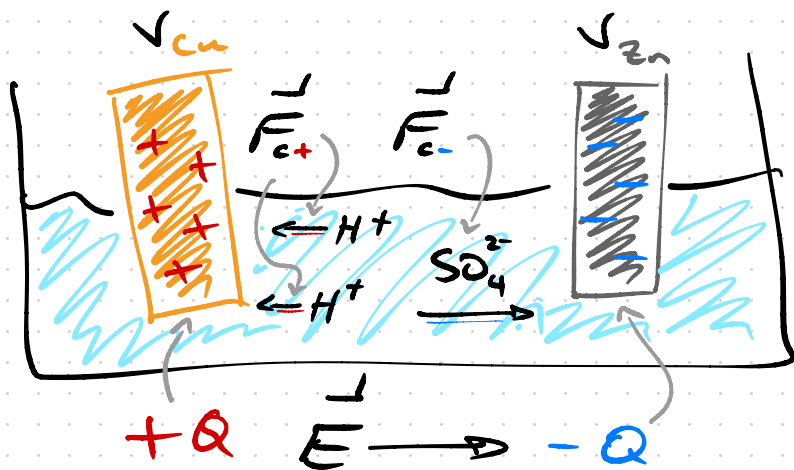
THERE IS A FORCE ON THE CHARGES IN THE BATTERY, NOT DUE TO A VOLTAGE DIFFERENCE, WHICH IS CAUSING CHARGE TRANSFER.

- FOR A BATTERY, THIS FORCE IS CHEMICAL (CALL IT \vec{F}_c), & ACTS TO PUSH + CHARGE TO Cu, & - CHARGE TO Zn:



$V_{Cu} - V_{Zn} = 0$: \vec{F}_c CHARGES PLATES

- \vec{F}_c IS CHARACTERIZED BY AN EMF, WHICH IS THE VOLTAGE $V_{Cu} - V_{Zn}$ NECESSARY TO CREATE AN ELECTRIC FIELD STRONG ENOUGH TO CANCEL \vec{F}_c :



@ $V_{Cu} - V_{Zn} = \text{EMF} :$

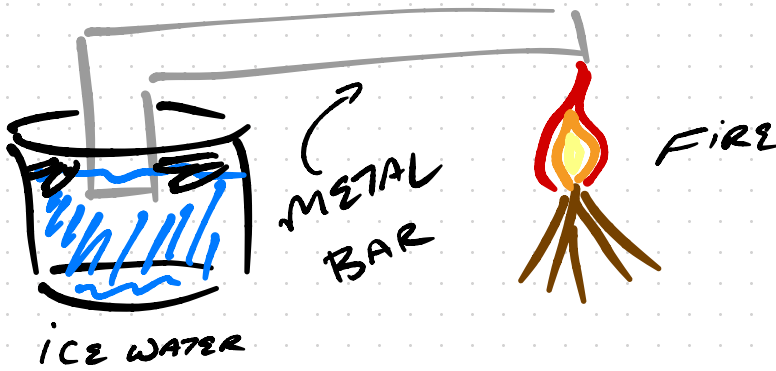
$$\vec{F}_{c+} + (+e)\vec{E} = 0$$

$$\vec{F}_{c-} + (-2e)\vec{E} = 0$$

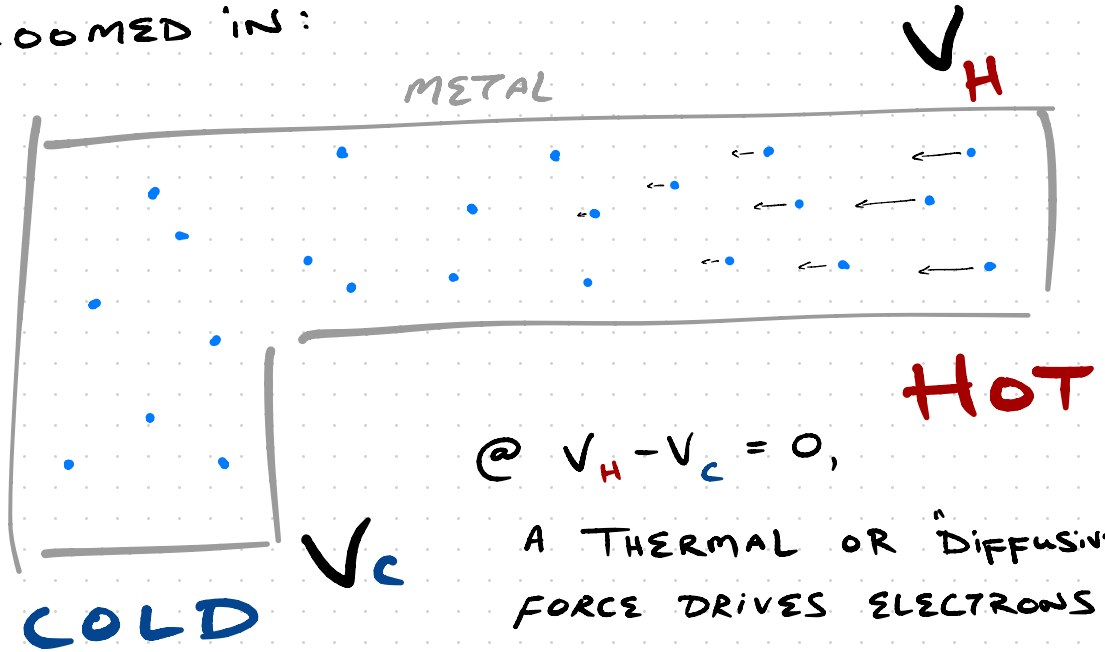
CHARGING

Stops!

ANOTHER EXAMPLE OF EMF*: "THERMO-ELECTRIC EFFECT"



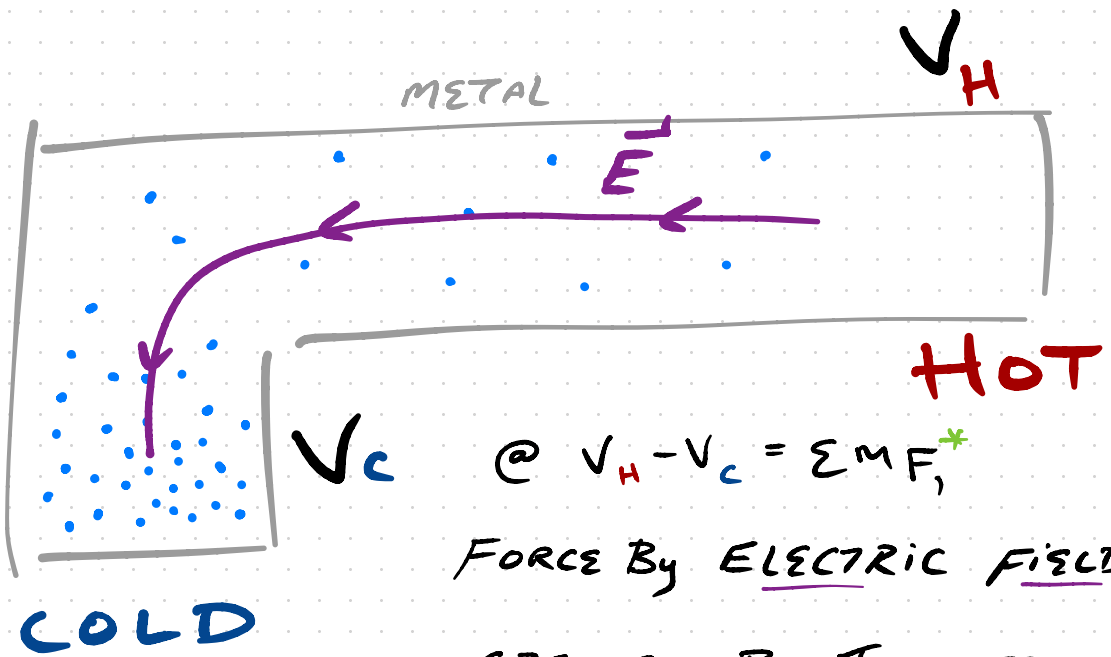
ZOOMED IN: • : ELECTRON



$$@ V_H - V_C = 0,$$

A THERMAL OR "DIFFUSIVE"
FORCE DRIVES ELECTRONS
FROM HOT \rightarrow COLD.

* SKIP IF YOU LIKE



@ $V_H - V_C = \Sigma MF^*$

FORCE BY ELECTRIC FIELD

CREATED BY TRANSFER

OF ELECTRONS FROM

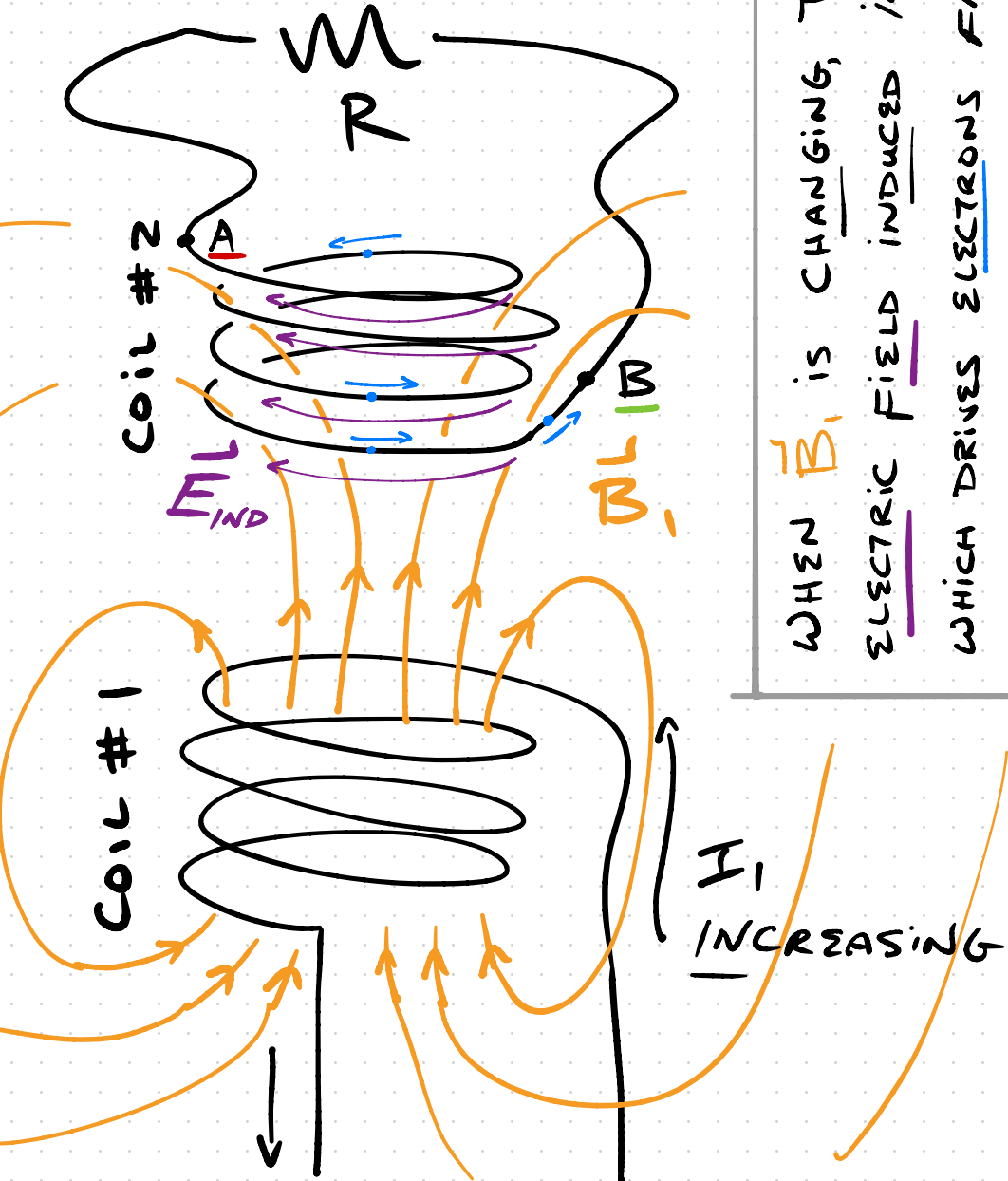
HOT \rightarrow COLD CANCELS

THE THERMAL FORCE.

-
- * NOTE: ΣMF HERE DEPENDS ON TEMPERATURE OF BOTH ENDS (T_H / T_C)
 - & TYPE OF MATERIAL (IRON, PLATINUM, ETC.)

INDUCED ELECTRIC FIELD (E_{IND})

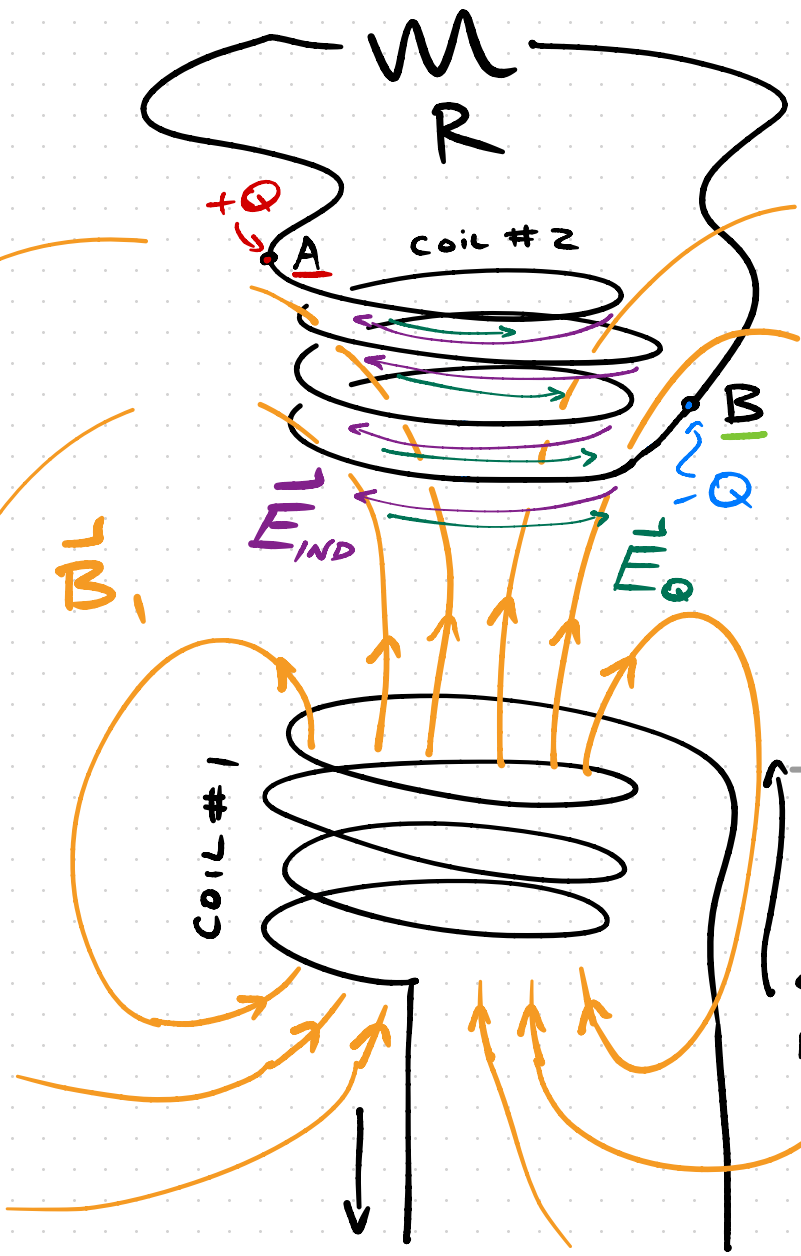
E.G. B_1 INCREASING:



WHEN B_1 IS CHANGING, THERE IS AN ELECTRIC FIELD INDUCED IN COIL #2, WHICH DRIVES ELECTRONS FROM ONE END OF COIL (**A**) TO OTHER (**B**).

INDUCED VOLTAGE $[V_A - V_B]$

B_L STILL INCREASING

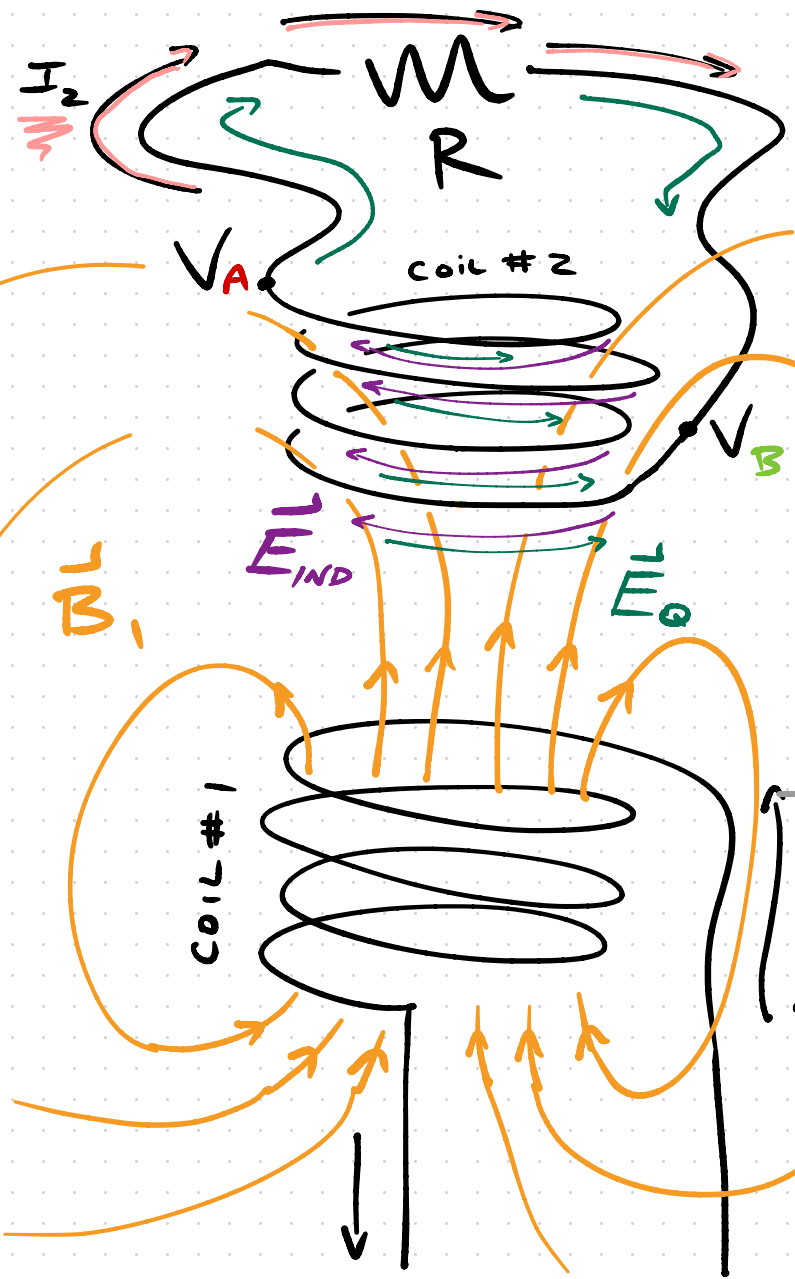


WHEN E_{IND} HAS TRANSFERRED ENOUGH CHARGE $+Q$ SO THAT $V_A - V_B = \Sigma EMF$, THEN E_{IND} IS CANCELLED BY E_Q FROM $+Q$.

I_1 STILL INCREASING

INDUCED CURRENT (I_2)

$\frac{dI_1}{dt}$ STILL INCREASING



BUT NOW THERE IS A
 VOLTAGE DROP $V_A - V_B = \text{EMF}$
 ACROSS THE RESISTOR,
 CAUSING A CURRENT $I_2 = \frac{\text{EMF}}{R}$

I_1
 STILL
 INCREASING

Points of clarification:

Because the coil is made of conducting material, all these steps occur extremely quickly, so that a current is induced in the resistor as soon as the magnetic field from coil #1 is changing.

You may be wondering, since there is a current induced in the resistor, whether there is a current induced in coil #2. The answer is that there is, and it is equal to the resistor current, as required by Kirchoff's current law.

You may then (rightly) wonder what is ^{FORCE} driving the current in coil #2, since we said the induced field \vec{E}_{IND} is cancelled by the field \vec{E}_Q created by the charge transfer. The answer here is that the fields do not perfectly cancel, so that there is a small net electric field which drives current around the coil. Since, again, the coil is made from conducting material, its resistance r_c is extremely low ($r_c \ll R$), so that only a negligible small electric field is necessary to sustain the current. This is equivalent to saying that $V_A - V_B$ is actually slightly less than the EMF of the induced field \vec{E}_{IND} .

Pause here and make sure it is clear how the emf from electromagnetic induction is similar to the emfs associated with the battery and the thermoelectric effect. In all three cases there is a force on charged particles, not due to a voltage, which drives a transfer of charge, which creates an electric field which cancels the non-voltage force. The voltage associated with this electric field ($V = Ed$) is equal to the emf of the non-voltage force. Electromagnetic induction is unique in the sense that the non-voltage force is another electric field!

FARADAY'S LAW

- So HOW IS THE EMF OF \vec{E}_{IND} RELATED TO \vec{B}_1 ?
- "THE EMF INDUCED IN A COIL W/ N TURNS (I.E. LOOPS) IS EQUAL TO THE (TIME) RATE OF CHANGE OF THE MAGNETIC FLUX THROUGH THE COIL."



$$\underline{\text{EMF}} = \underline{N} \frac{\underline{\Delta \Phi}}{\underline{\Delta t}}$$

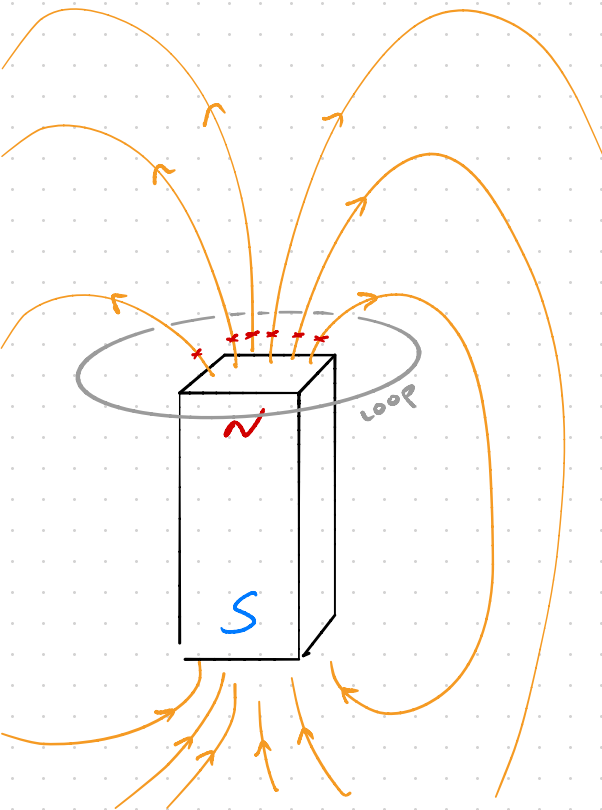
FARADAY'S LAW

- WHAT IS MAGNETIC FLUX?

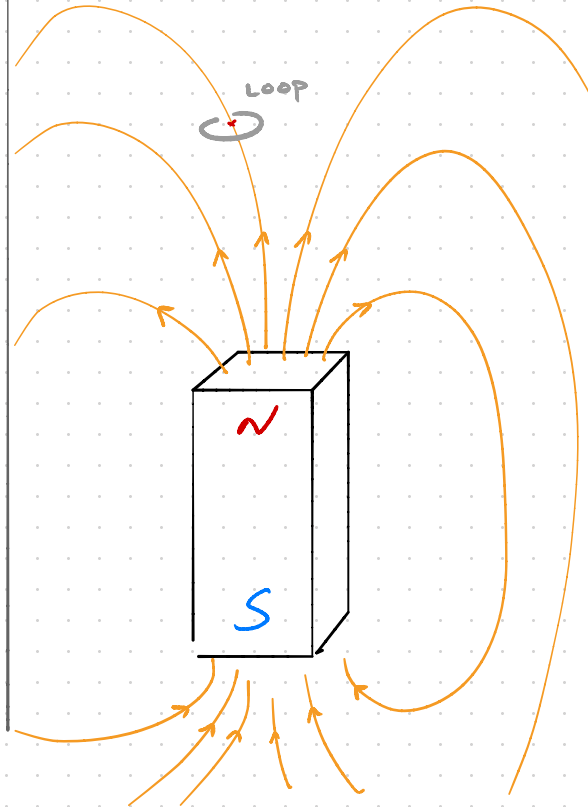
MAGNETIC FLUX Φ (CONCEPTUAL)

- # of \vec{B} FIELD LINES PIERCING SOME SURFACE:

Loop w/
HIGH FLUX Φ

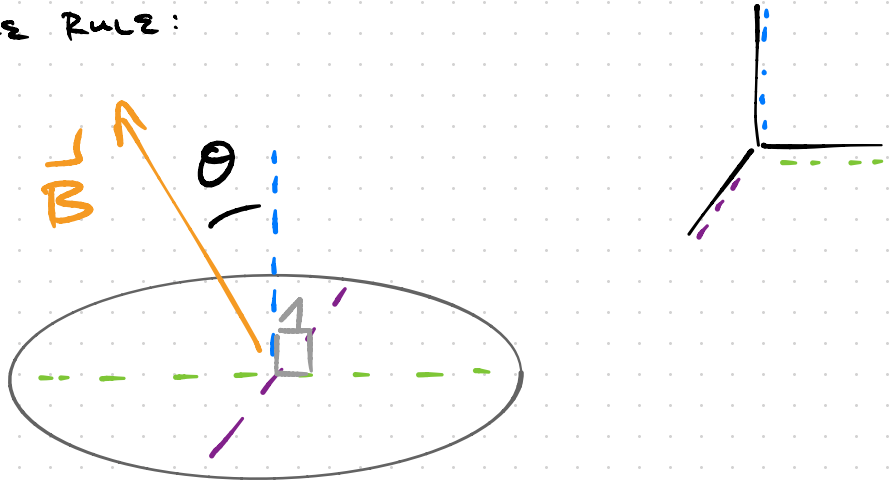


Loop w/
LOW FLUX Φ



MAGNETIC FLUX Φ (TECHNICAL)

- DIFFICULT TO DETERMINE IN GENERAL.
- FOR UNIFORM MAGNETIC FIELDS, WE HAVE SIMPLE RULE:

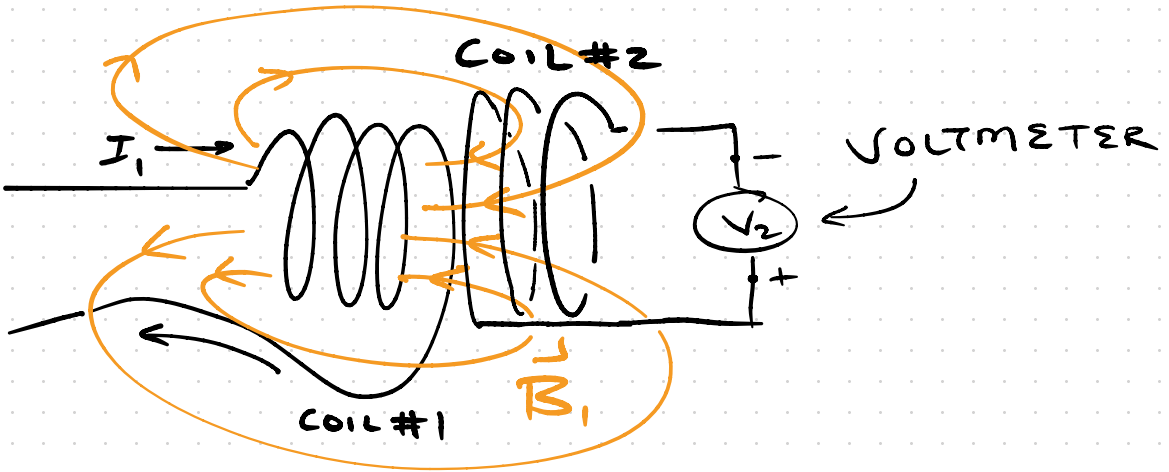


$$\underline{\Phi} = A \underline{B} \cos \theta$$

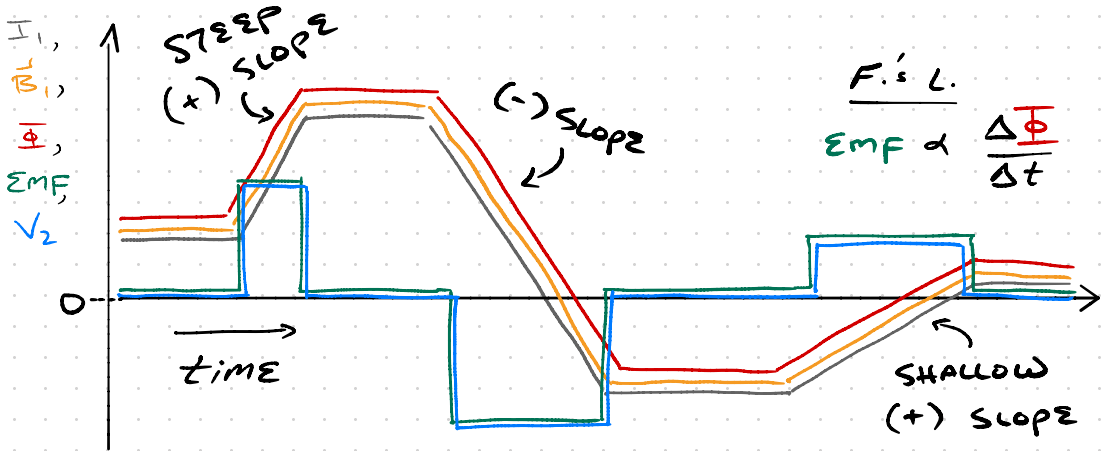
A = AREA OF LOOP

- TRIVIA: S.I. UNIT OF MAG. FLUX IS THE "WEBER" ($1 \text{ Wb} = 1 \text{ Tm}^2$)

FARADAY'S LAW EXAMPLE:

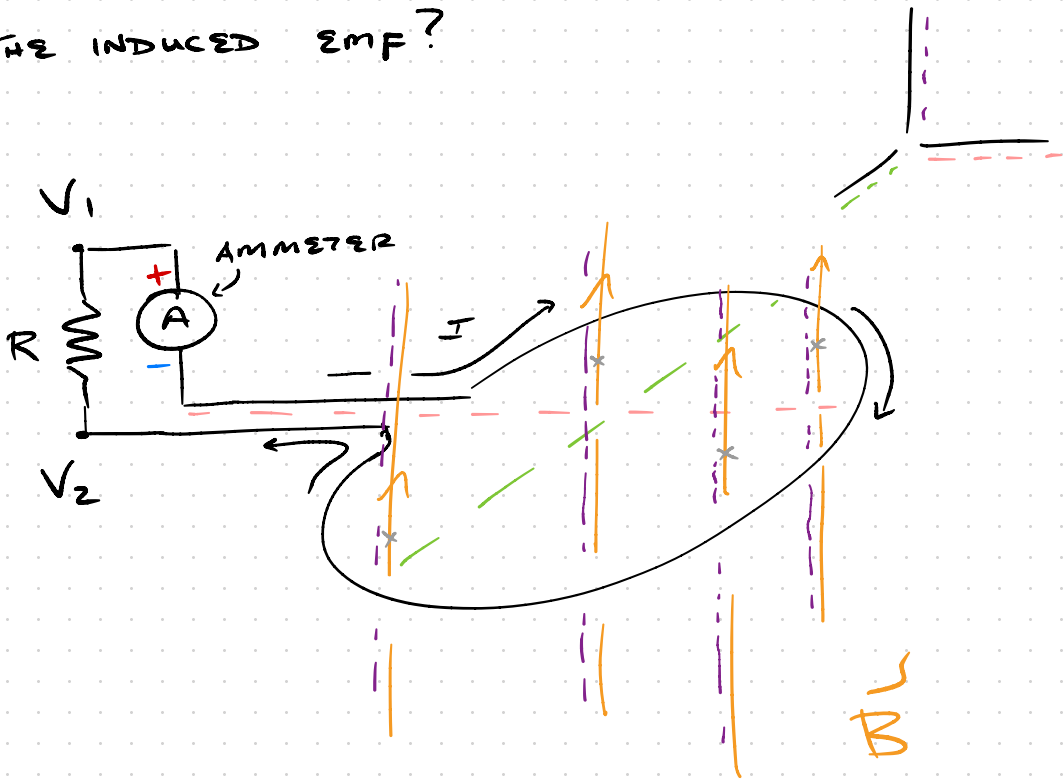


• NOW LET'S CHANGE I_1 & MONITOR RESULTING CHANGE IN V_2 :



LENS' LAW:

- How do we determine the POLARITY of the induced EMF?



Suppose B is INCREASING w/ TIME:

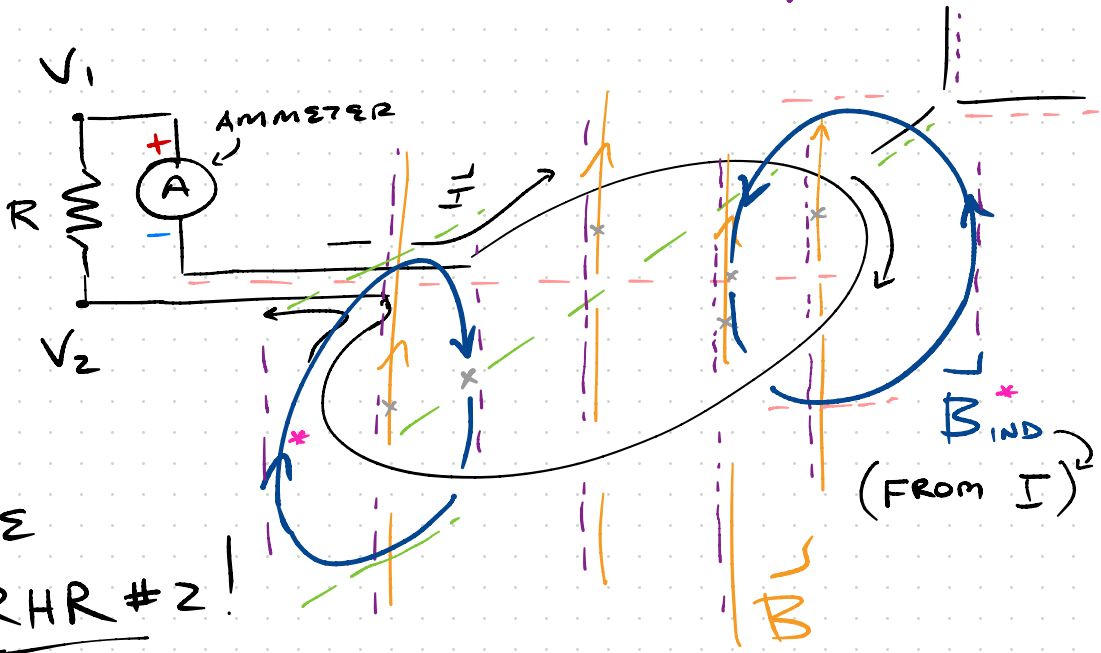
- IS I POSITIVE OR NEGATIVE?

• (EQUIVALENTLY):

IS $V_2 - V_1$ EQUAL TO $+EMF$ OR $-EMF$?

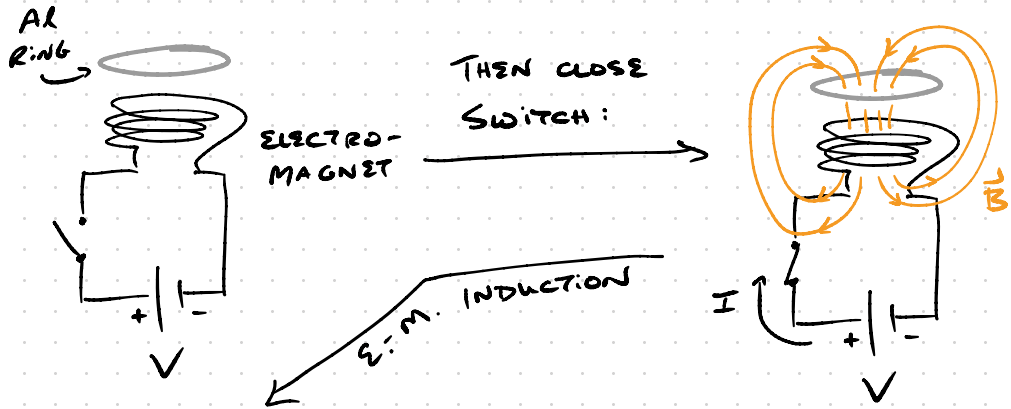
LENS' LAW:

- HOW DO WE DETERMINE THE POLARITY OF THE INDUCED EMF?
- ANSWER: "THE INDUCED CURRENT ALWAYS ACTS TO OPPOSE THE CHANGE IN MAG. FLUX (Φ)" (LENS' LAW)
- IN THIS EXAMPLE, FLUX UP INTO THE LOOP IS INCREASING, SO WE WANT \vec{I} TO GENERATE A DOWNWARDS FLUX:

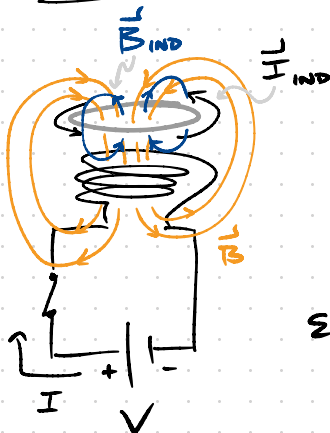


LENS' LAW EXAMPLE: "Jumping Ring"

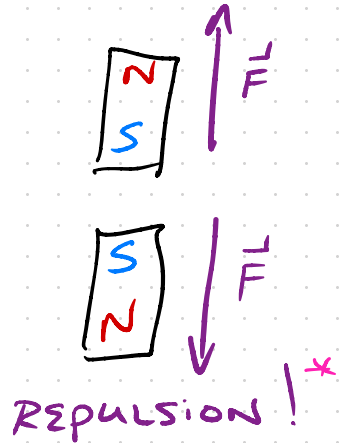
- PLACE AN ALUMINUM (WHICH IS NON-MAGNETIC!) RING ABOVE AN ELECTROMAGNET:



LENS' LAW:



REPLACE
W/ BAR
MAGNET
EQUIVALENTS:



* SEE YOUTUBE VIDEO!

Checks for understanding:

Go back to the beginning of the lecture with the light bulb and the two coils. Look at the directions of the induced currents and the induced magnetic fields and verify that they agree with your expectation in terms of Lenz' Law.