Lecture 20

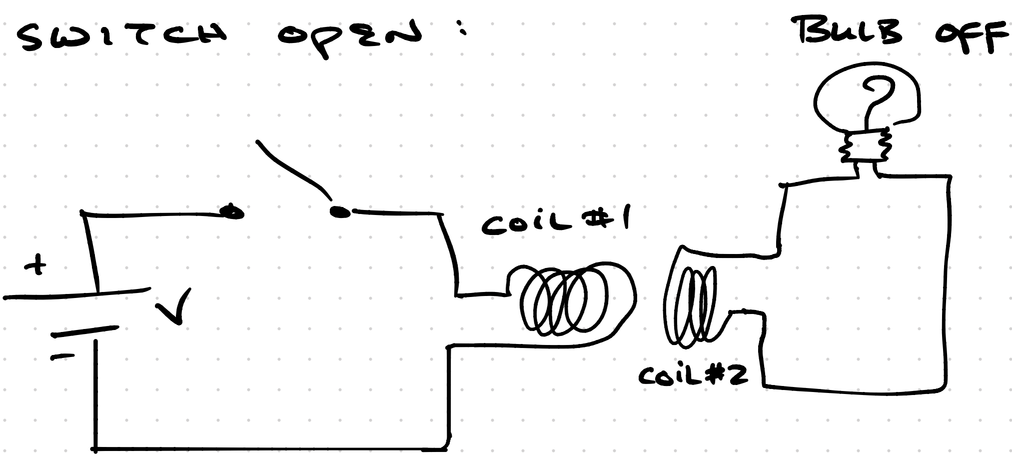
- EMF, Faraday's Law, & Lenz' Law

HISTORY:

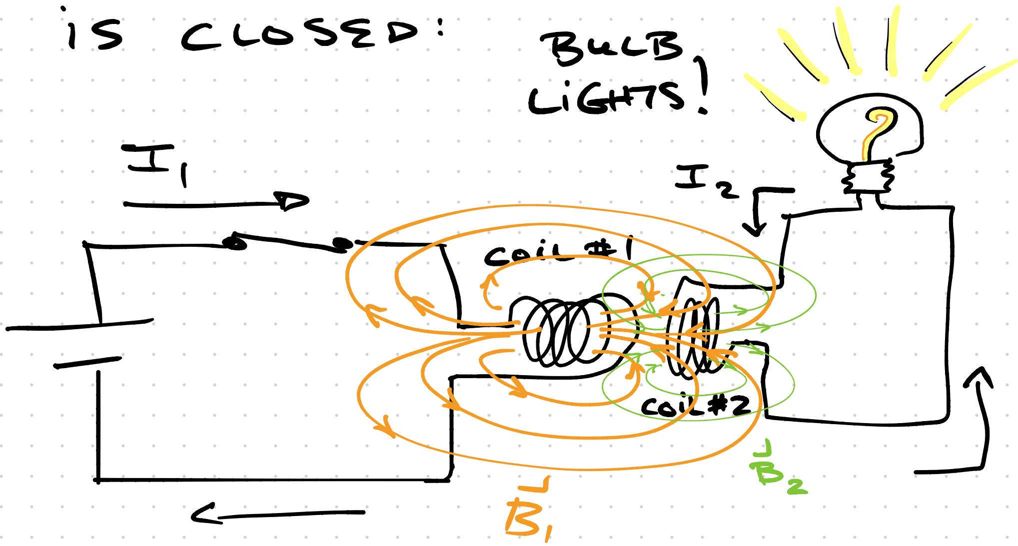
1831, MICHAEL FARADAY (ENGLAND) & JOSEPH HENRY (USA) DISCOVERED THAT A <u>CHANGING</u> MAGNETIC FIELD INDUCED AN ELECTRIC CURRENT*:

* SEE J.T. DEMO:

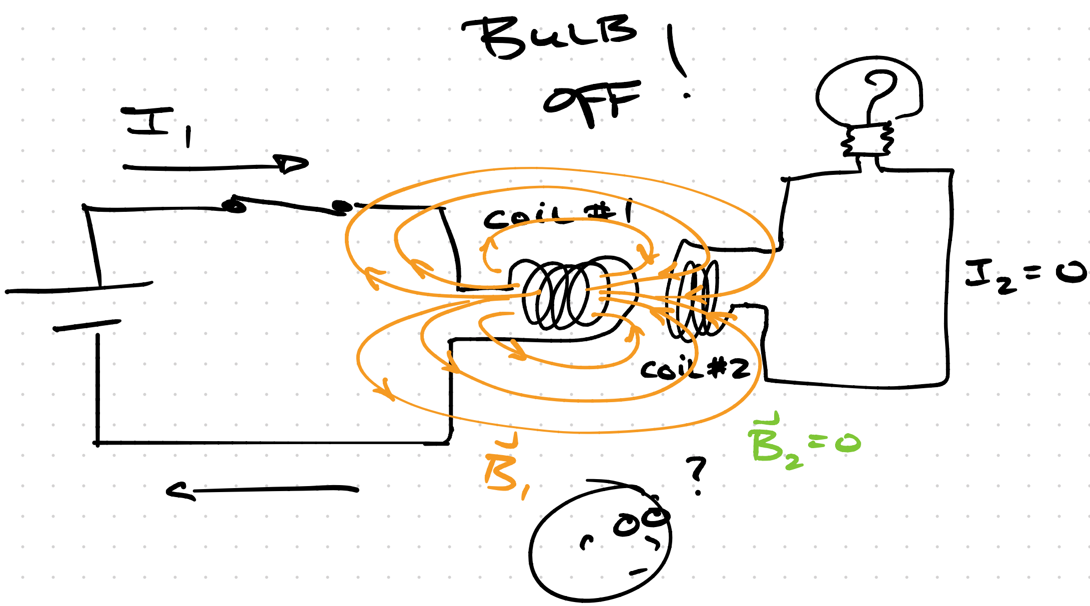
SWITCH OPEN:



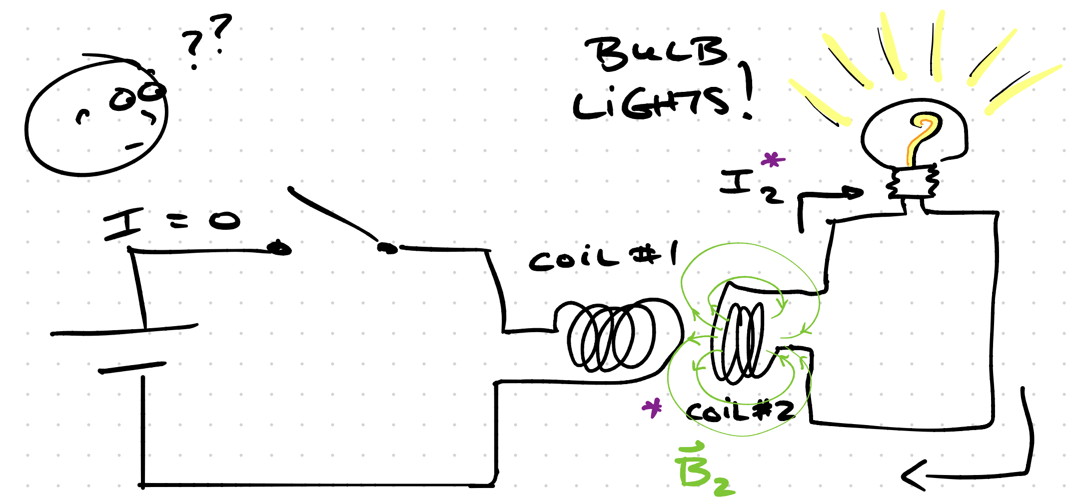
@ THE MOMENT SWITCH IS CLOSED:



AFTER SWITCH IS CLOSED:

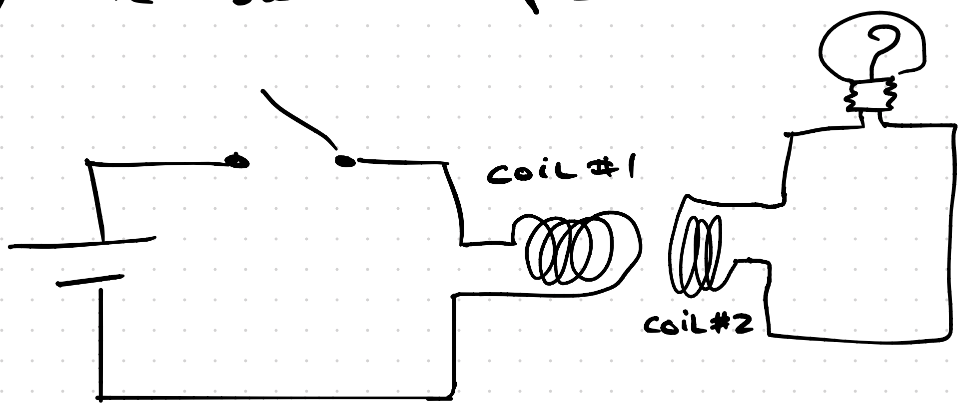


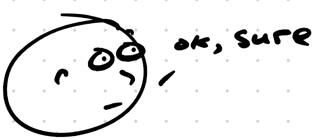
@ MOMENT SWITCH OPENS:



* NOTE THE CHANGE IN DIRECTION!

AFTER SWITCH OPEN: BULB OFF





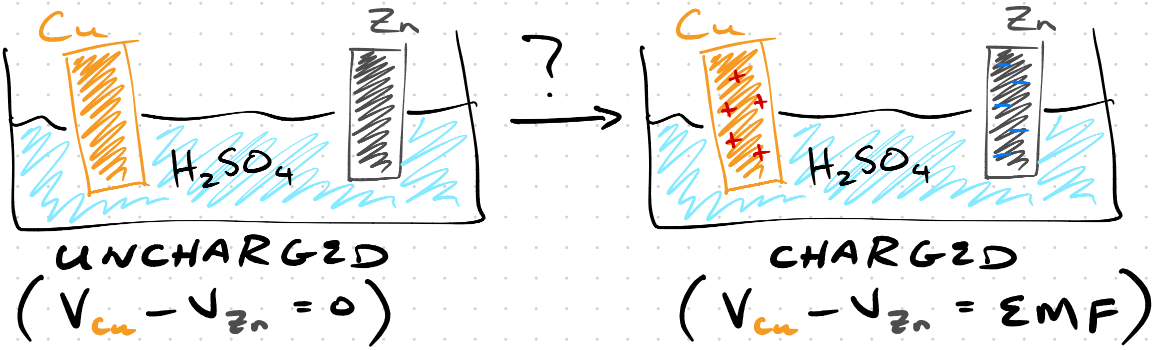
SO WHAT IS GOING ON HERE?!

"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:

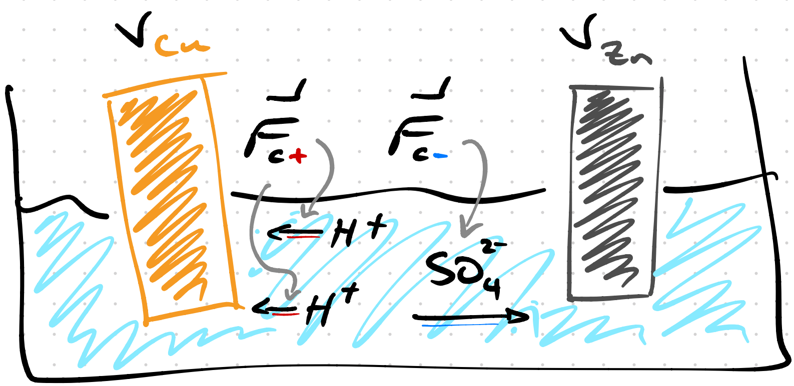


- WHEN THE PLATES ARE UNCHARGED, THE VOLTAGE ACROSS THE BATTERY IS ZERO, SO WHAT IS DRIVING THE TRANSFER OF ELECTRONS FROM Cu → Zn? i.e., HOW DOES A BATTERY CHARGE UP?

ANSWER:

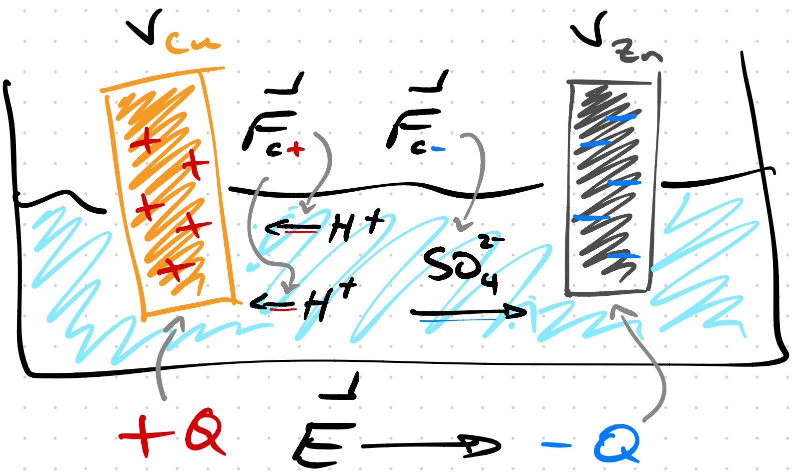
THERE IS A FORCE ON THE CHARGES IN THE BATTERY, NOT DUE TO A VOLTAGE DIFFERENCE, WHICH IS CAUSING CHARGE TRANSFER.

- 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 $\vec{F}_c$:



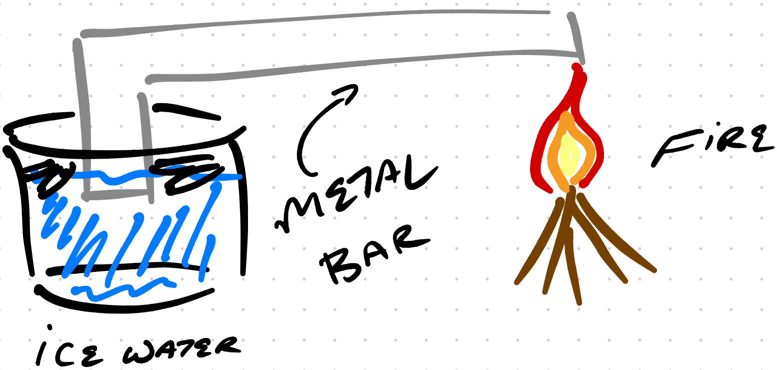
@ $V_{Cu} - V_{Zn} = \text{EMF}$:

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

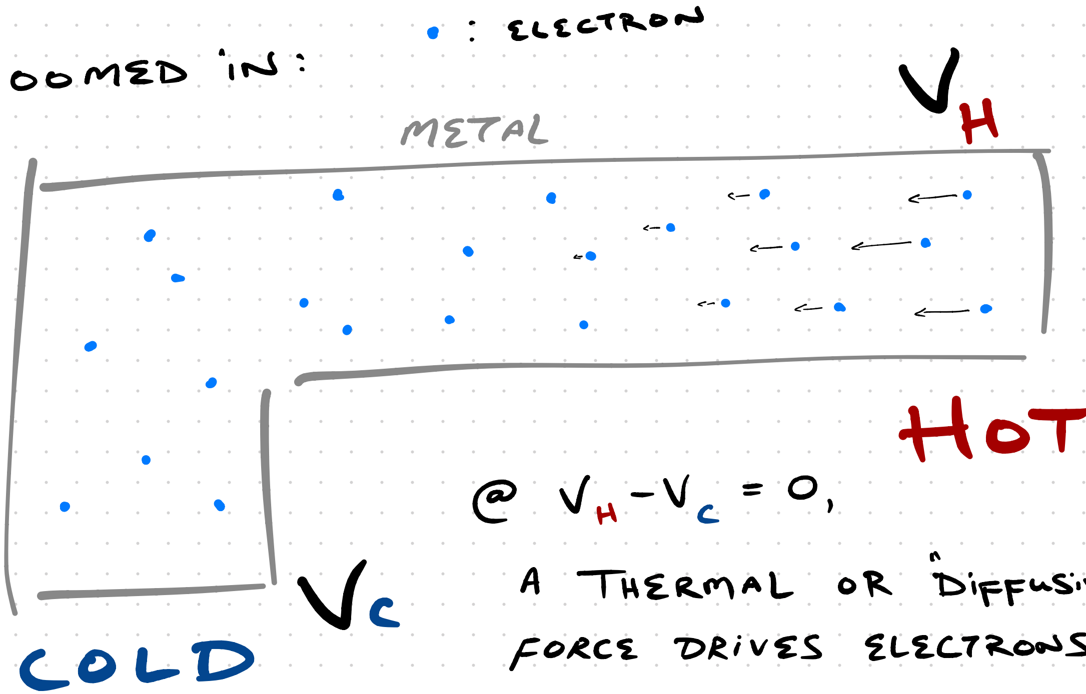
$$\vec{F}_{c-} + (-2e)\vec{E} = 0$$

→ CHARGING STOPS!

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



ZOOMED IN:



@ $V_H - V_C = 0$,

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

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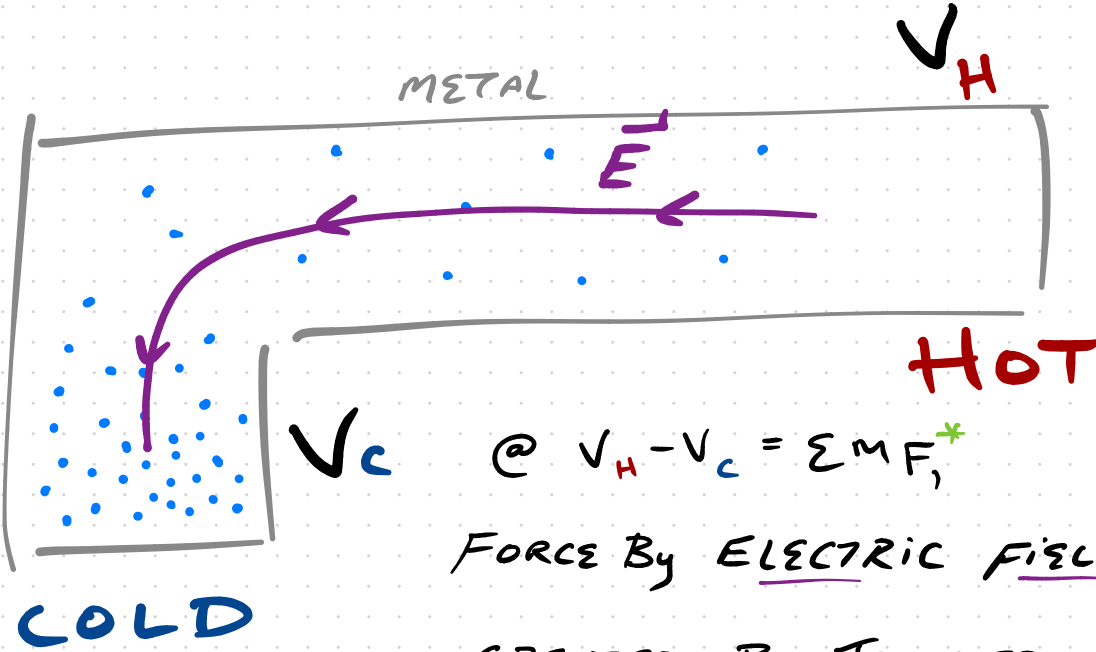
* Skip if you like



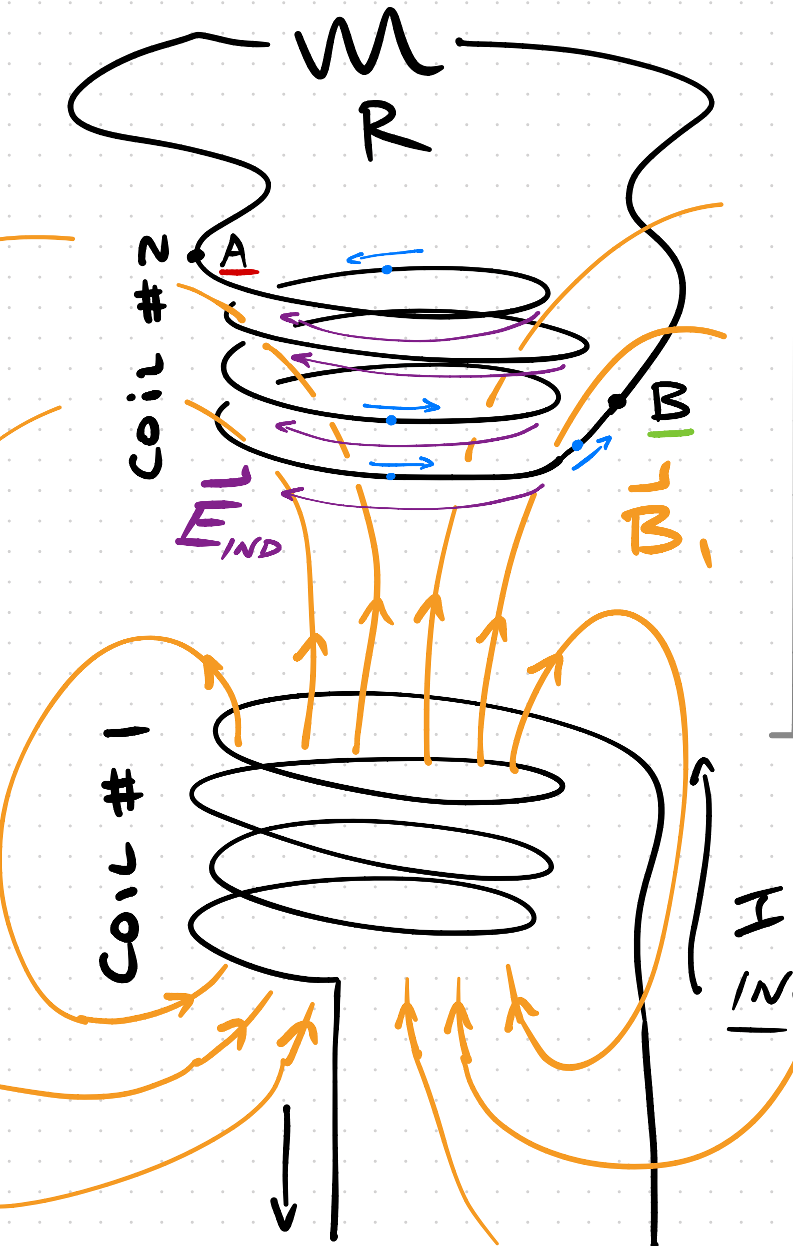
@ $V_H - V_C = EMF$,*

FORCE BY ELECTRIC FIELD CREATED BY TRANSFER OF ELECTRONS FROM HOT → COLD CANCELS THE THERMAL FORCE.

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

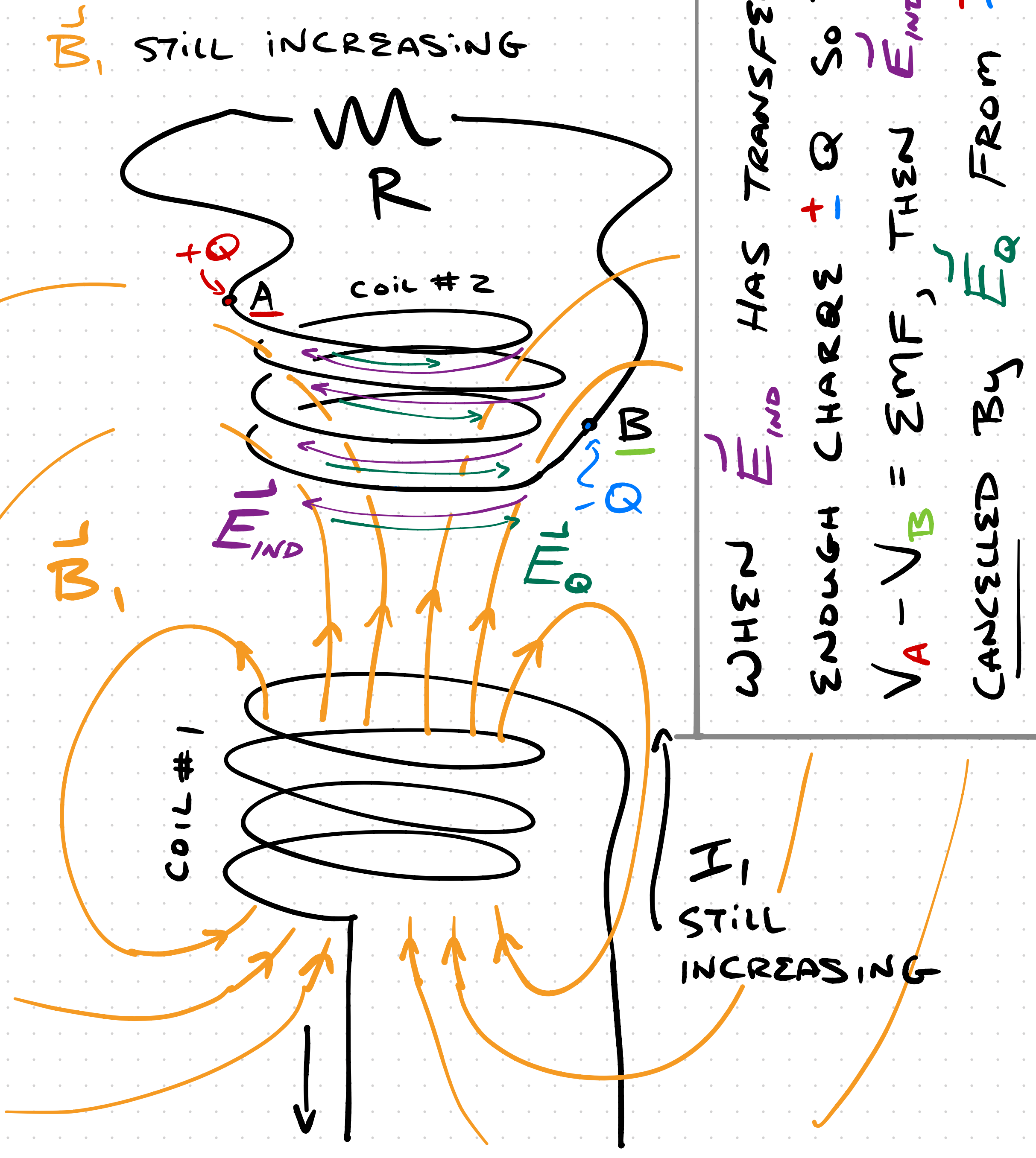
Induced Electric Field [$\vec{E}_{IND}$]

E.G. $\vec{B}_1$ increasing:



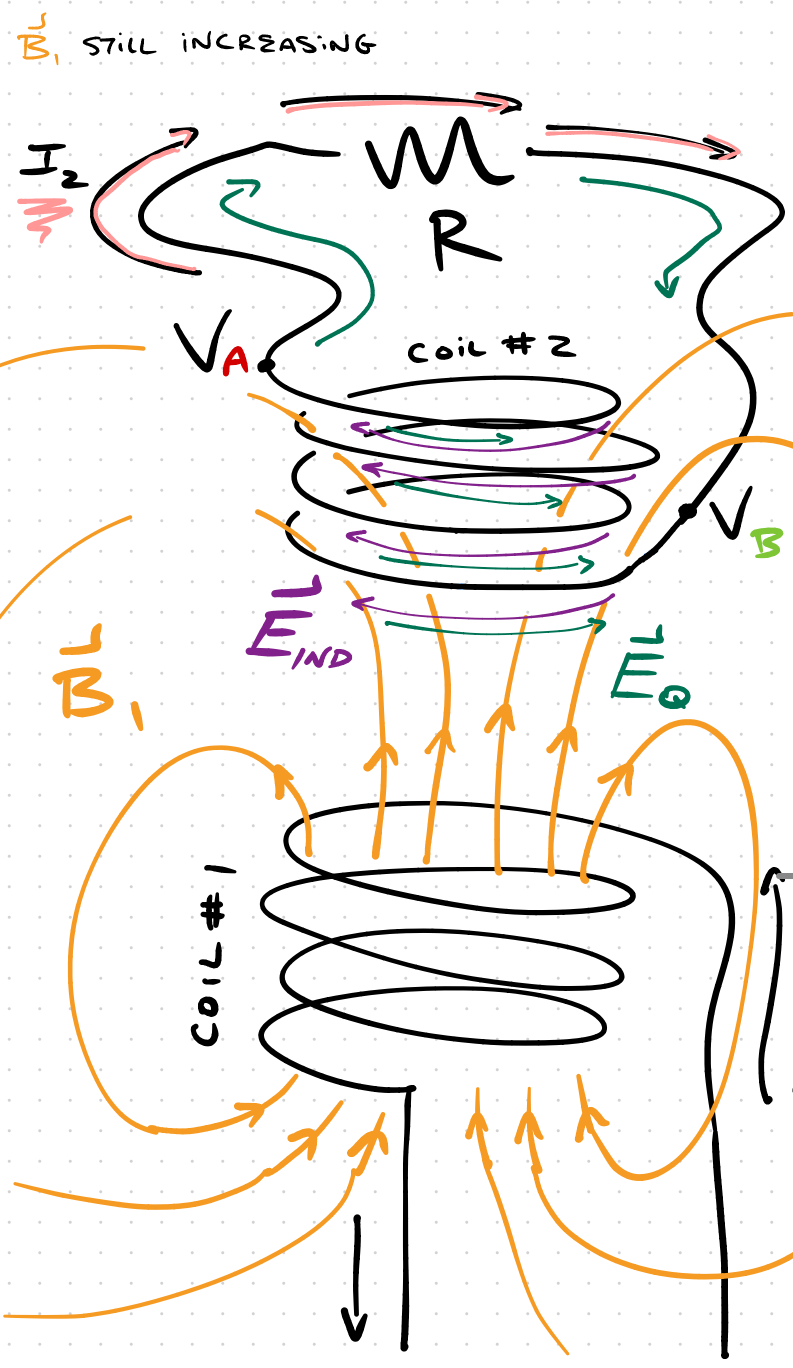
When $\vec{B}$ is changing, there is an electric field induced in coil #2, which drives electrons from one end of coil (A) to other (B).

INDUCED VOLTAGE $[V_A - V_B]$



WHEN $\vec{E}_{IND}$ HAS TRANSFERRED ENOUGH CHARGE $\pm Q$ SO THAT $V_A - V_B = EMF$, THEN $\vec{E}_{IND}$ IS CANCELLED BY $\vec{E}_Q$ FROM $\pm Q$.

INDUCED CURRENT $[I_2]$



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

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.

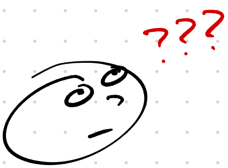
You may then (rightly) wonder what FORCE is driving the current in coil #2, since we said the induced field $\vec{E}_{IND}$ is cancelled by the field $\vec{E}_{Q}$ created by the charge transfer. The answer here is that the fields do not perfectly cancel, so that there is a small net electric field which 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 $\vec{B}$, ?

- "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."



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

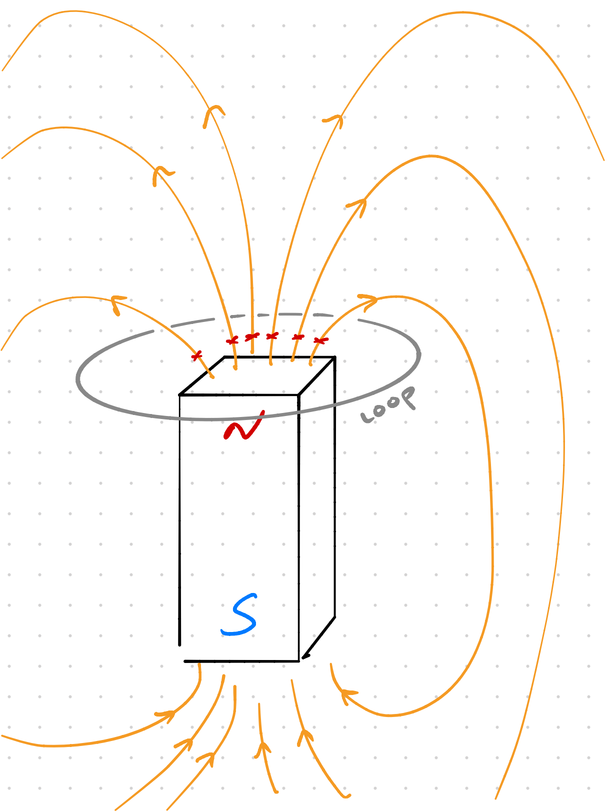
Faraday's Law

- What is magnetic flux?

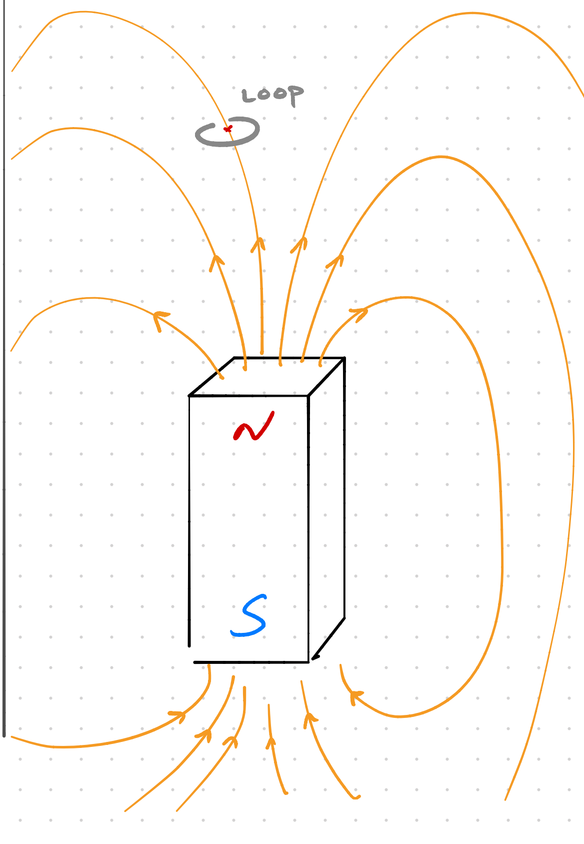
MAGNETIC FLUX Φ (CONCEPTUAL)

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

LOOP W/ HIGH FLUX Φ

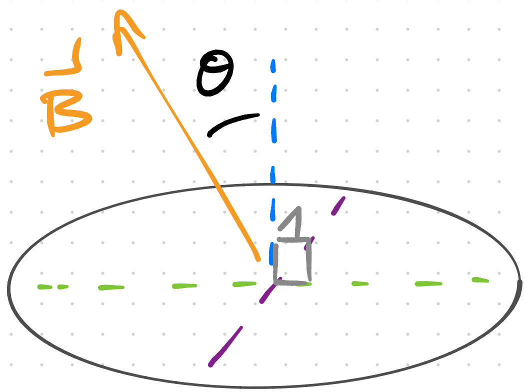


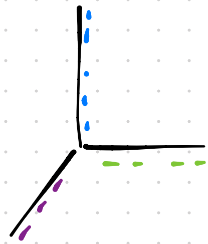
LOOP W/ LOW FLUX Φ



MAGNETIC FLUX Φ (TECHNICAL)

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



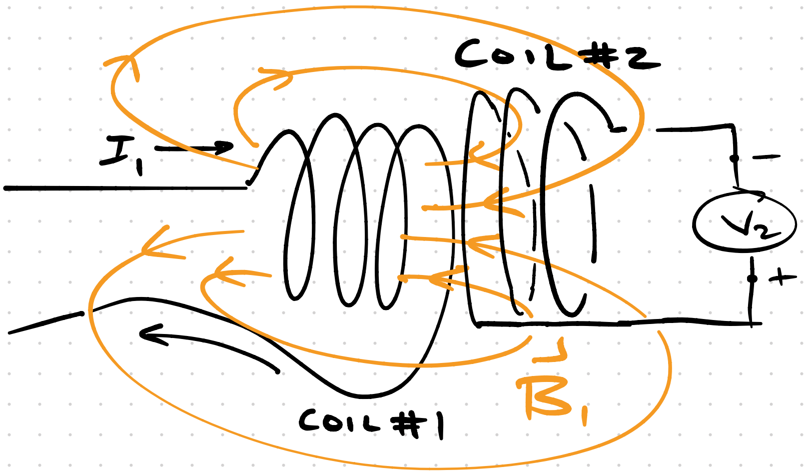


$$\Phi = A B \cos\theta$$

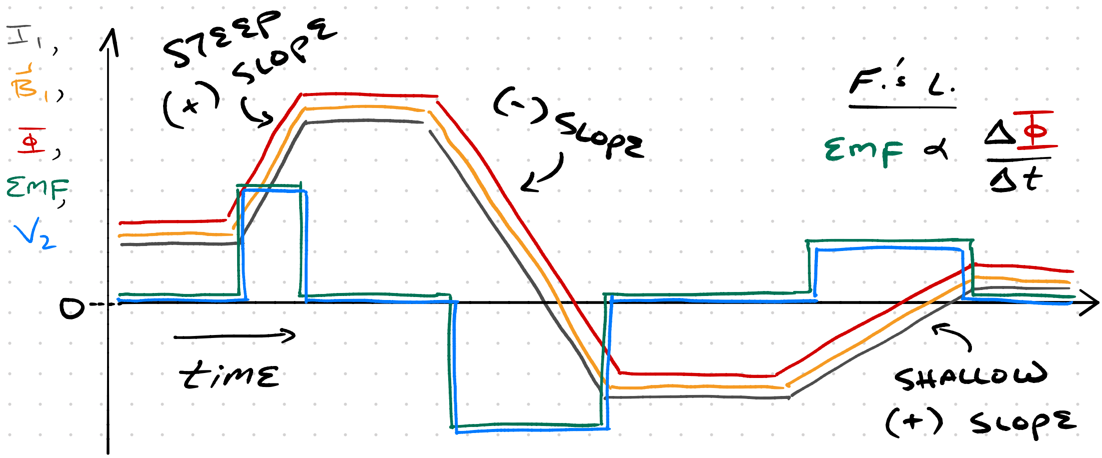
A = AREA OF LOOP

- TRIVIA: S.I. UNIT OF MAG. FLUX IS THE "WEBER" $\left[1\,Wb = 1\,Tm^2\right]$

FARADAY'S LAW EXAMPLE:

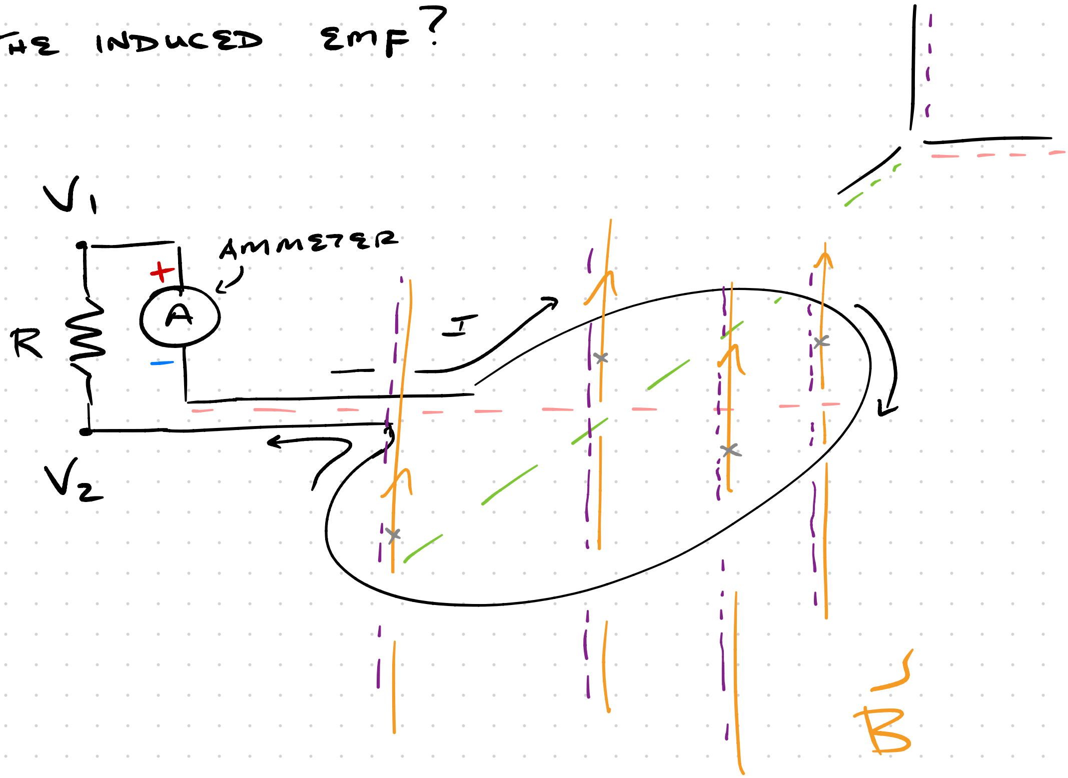


- NOW LET'S CHANGE I_1 & MONITOR RESULTING CHANGE IN V_2:



LENS' LAW:

- How do we determine the polarity of the induced emf?



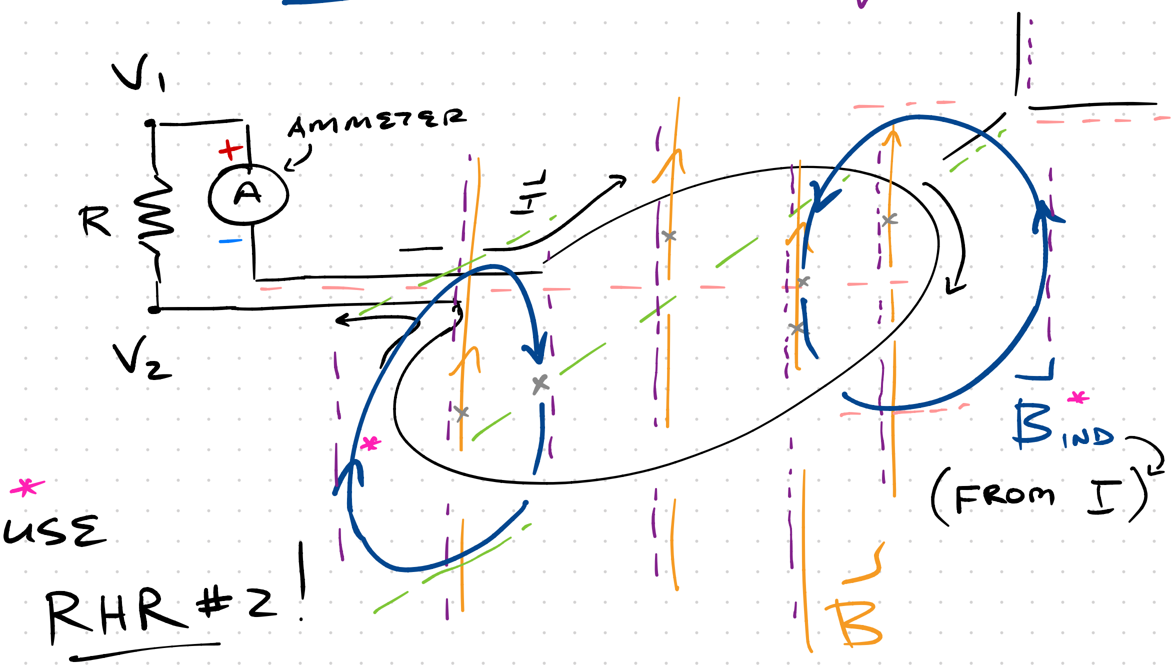
Suppose B is increasing w/ time:

- Is I positive or negative?
- (Equivalently):

is $V_2 - V_1$ equal to +emf or −emf?

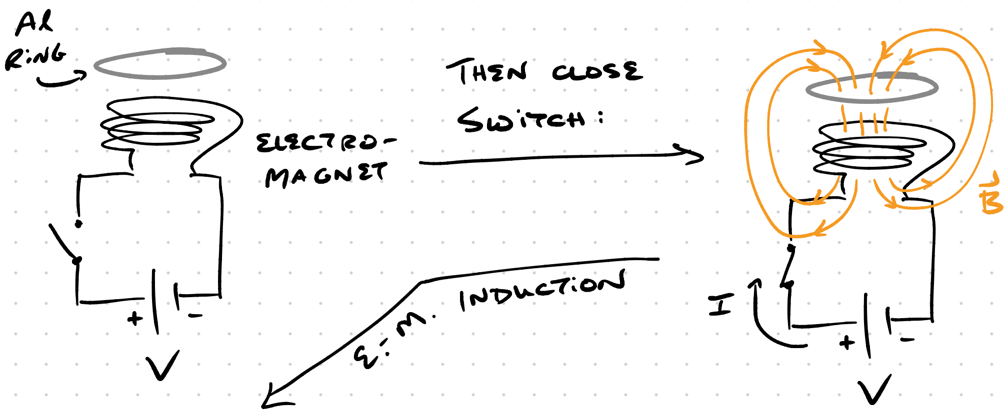
LENS' LAW:

- 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 I TO GENERATE A DOWNWARDS↓ FLUX:

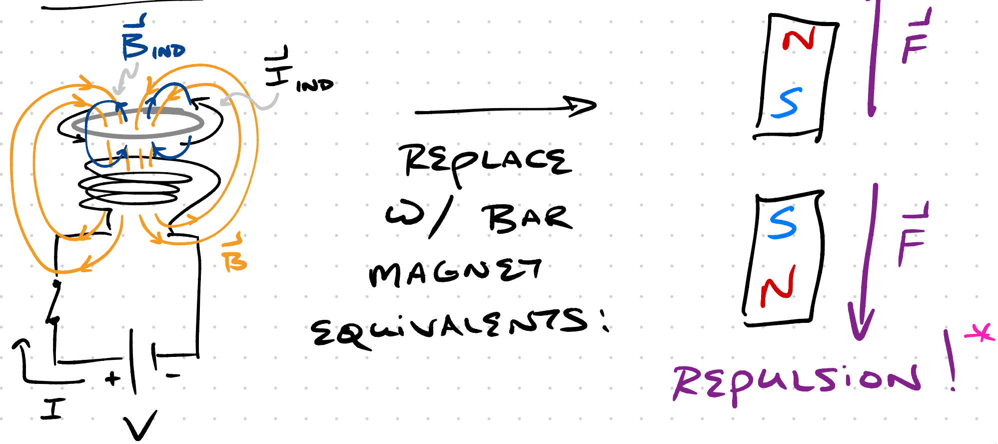


LENS' LAW EXAMPLE: "JUMPING RING":

- PLACE AN ALUMINUM [WHICH IS NON-MAGNETIC!] RING ABOVE AN ELECTROMAGNET:



LENS' LAW:



* 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 Lens' Law.