Unit 5 - Students Absolutely Must Learn…

Weekly Activity 9: Motors
- How motors work:
    - Lorentz force law for wires.
    - Brush contacts.
- How generators work.
- Skill working with wire.
- How to measure power being consumed by a motor.
- Advanced features of oscilloscopes.

Weekly Activity 10: Solenoids
- How to use Ampere's law.
- Phase lag of inductors.
- How to use Faraday's law.
- How induction works: external, self and mutual.
- How to use Lenz's law.
- Advanced features of oscilloscopes.

Unit 5 - Grading Guidelines

Staple the lab report, then graphs, and finally worksheets together. Please put your worksheets in order. Turn in your work to your TA at the beginning of the next lab meeting following the completion of the unit.

Unit Lab Report [50%, graded out of 25 points]
Write a separate section using the section titles below (be sure to label these sections in your report). In order to save time, you may add diagrams and equations by hand to your final printout. However, images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner may make you both guilty of plagiarism. Pay close attention to your teacher for any changes to these guidelines.

- **Title [0 points]** – A catchy title worth zero points so make it fun.

- **Concepts & Equations [9 points]** – *{One small paragraph for each important concept, as many paragraphs as it takes, 2+ pages.}* Go over the lab activities and make a list of all the different concepts and equations that were covered. Then simply one at a time write a short paragraph explaining them. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
  Some example concepts for this unit report include (but are not limited to):
    - Explain how a motor works. Be sure to describe the physical laws that enable a motor to work.
    - Explain how a generator works.
    - Explain Faraday's Law and Ampere's Law.
    - Explain what causes the back EMF in a solenoid (self-inductance).
    - Explain why $\varepsilon_L(t)$ (voltage across the inductor) is 90° phase-shifted before $V_R(t)$.
    - Explain why I_R decreases when the driving frequency ω_{drive} is increased.
    - Explain how to induce current in an unpowered circuit and the use of Lenz's Law.
    - Explain how to transmit electrical power in wires that don't touch.
    - Derive $B_{\substack{\text{inside} \\ \text{solenoid}}} = \mu_o n I_L$.
    - Derive $\varepsilon_L = NA\dfrac{dB}{dt}$.
    - Derive $L_{\text{solenoid}} = A \cdot \mu_o \cdot N \cdot n$.
    - Compare the frequency dependence of the inductive reactance to the capacitive reactance.
    - Any other equations that were used in the activities will need explained.
    - Any other specific TA requests:

      - _____

- ▪   _____

- ▪   _____

- ▪   _____

- **Selected In-Class Section [6 points]:** *{3-5 paragraphs, ~1 page}*
  This week's selection is: Weekly Activity 10, In-Lab Section 5
  Write a "mini-report" for this section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
  - o **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - o **Results:** Do not bother to rewrite tables of data, but rather refer to the page number on which it is found. State any measured values, slopes of ilnes-of-best-fit, etc.   Do not *interpret* your results, save any interpretation for the discussion.
  - o **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.

- **Open-Ended / Creative Design [6 points]** – *{3-5 paragraph, ~1 page}* Choose one of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*

- **Graphs [4 points] - {attach to typed report}** Graphs must be neatly hand-drawn <u>during lab</u> and placed directly after your typed discussion (before your quizzes and selected worksheets). Your graphs must fill the entire page (requires planning ahead) and must include: a descriptive title, labeled axes, numeric tic marks on the axes, unit labels on the axes, and if the graph is linear, the line of best fit written directly onto the graph.

Thoroughly Completed Activity Worksheets [30%, graded out of 15 points]

- **Week 9 In-Class [7 points]:** Pages assigned to turn in:

    _TA signature page, Post-lab pages,_____

    _____

- **Week 10 In-Class [8 points]:** Pages assigned to turn in:

    _TA signature page, Post-lab pages,_____

    _____

The above lab report and worksheets account for 80% of your unit grade. The other 20% comes from your weekly quizzes, each worth 10%. These will be entered into D2L separately.

Weekly Activity 9: Motors

Pre-Lab

! **You must complete this pre-lab section before you attend your lab to prepare for a short quiz. Be sure to complete all pages of the pre-lab.**

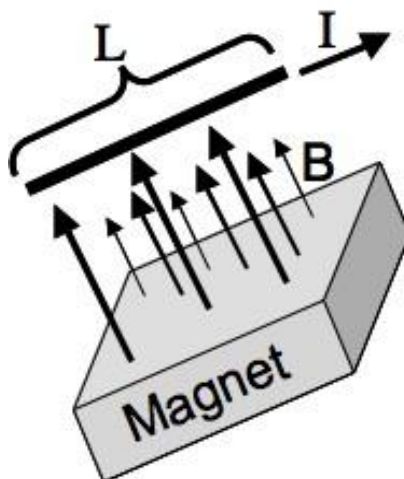**Continue until you see the stop pre-lab picture:**

A magnet has a strong magnetic field near its surface, but this field becomes very weak away from the magnet surface.

B_{Far} is ~ zero

B_{Close} is strong
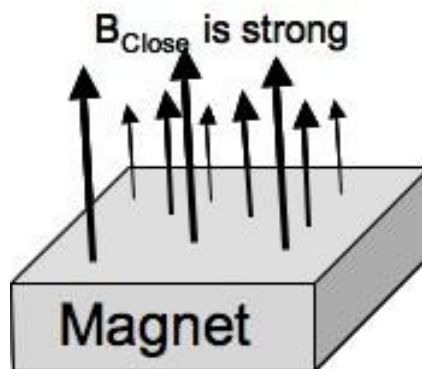
Magnet

When a current carrying wire of length L passes through a magnetic field, the magnetic field provides a force **on the wire** given by $\vec{F}_{\text{from B–field}} = L \cdot \vec{I} \times \vec{B}$.

L   I

B

Magnet

The force on the wire above is out of the page as determined by the right hand rule.

Note that **I** is written as a vector to describe the direction of the current, and the cross product indicates that the right hand rule must be used to find the direction of the force.

! **Whatever you do, don't switch the order of I with B! In other words, don't use $\vec{F}_{\substack{\text{from}\\\text{B-field}}} \neq L \cdot \vec{B} \times \vec{I}$ or you will be off by a negative sign (your force will point 180° in the wrong direction).**

You can use this simple concept to make the real motor. The motor is made of current carrying wire loops that can rotate about an axis shown as a dashed line in the picture below. The part of the wire loop that passes through the magnetic field experiences a magnetic force $\vec{F}_{\text{from B-field}} = L \cdot \vec{I} \times \vec{B}$ upon it. This magnetic force causes a net torque on the wire loop yielding angular acceleration. The wire loop will therefore rotate faster and faster until the torque from the magnetic force equals any frictional torque in the motor. At this time, the loop will reach a constant angular speed ω. (Also, there will be an increasing back EMF induced in the loop as it rotates faster, but this concept will be discussed in the next lab.)
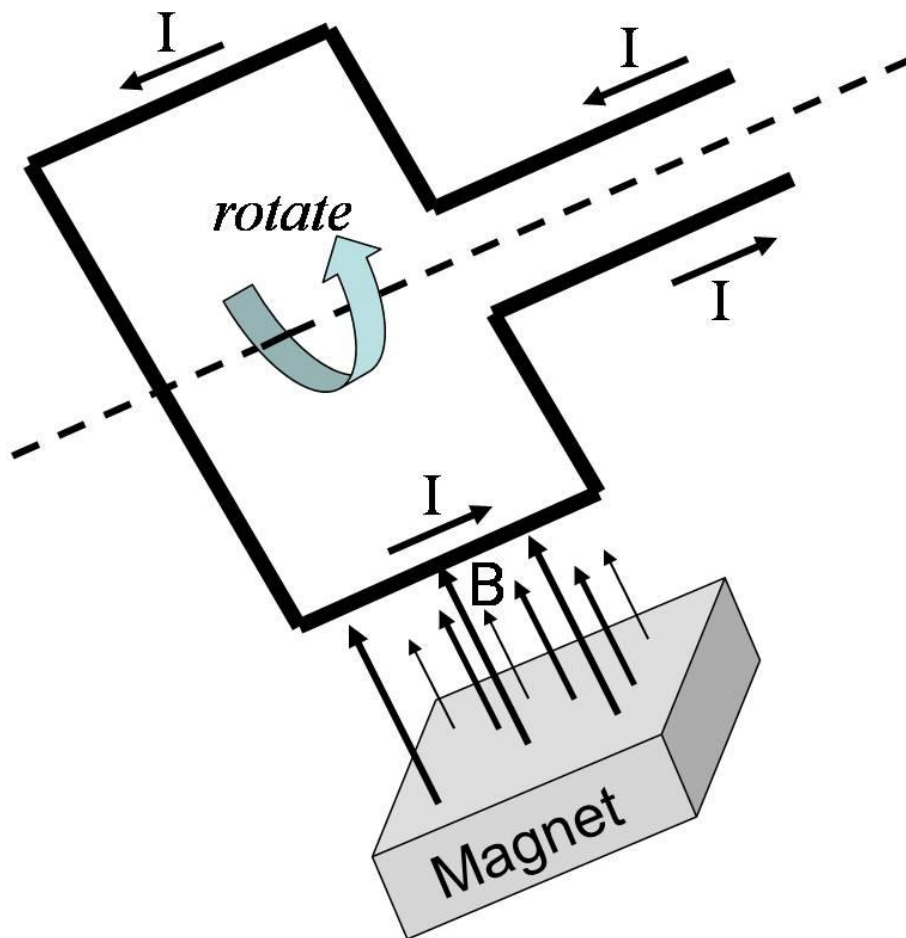
In this picture, the magnetic force pushes the segment of the loop out of the page.

¿ 0-1

How could you make a more powerful motor using an extra amount of wire?

¿ 0-2

How could you make a more powerful motor using an extra magnet? Provide a small sketch with your answer.

The only difficulty in making a motor is to ensure that the current always travels in the same direction as it passes through the magnetic field no matter how the loop itself is oriented. Examine the following picture to better understand what this difficulty is if the current supplied to the wire loop is always the same for each lead of the wire loop:

PROBLEM:
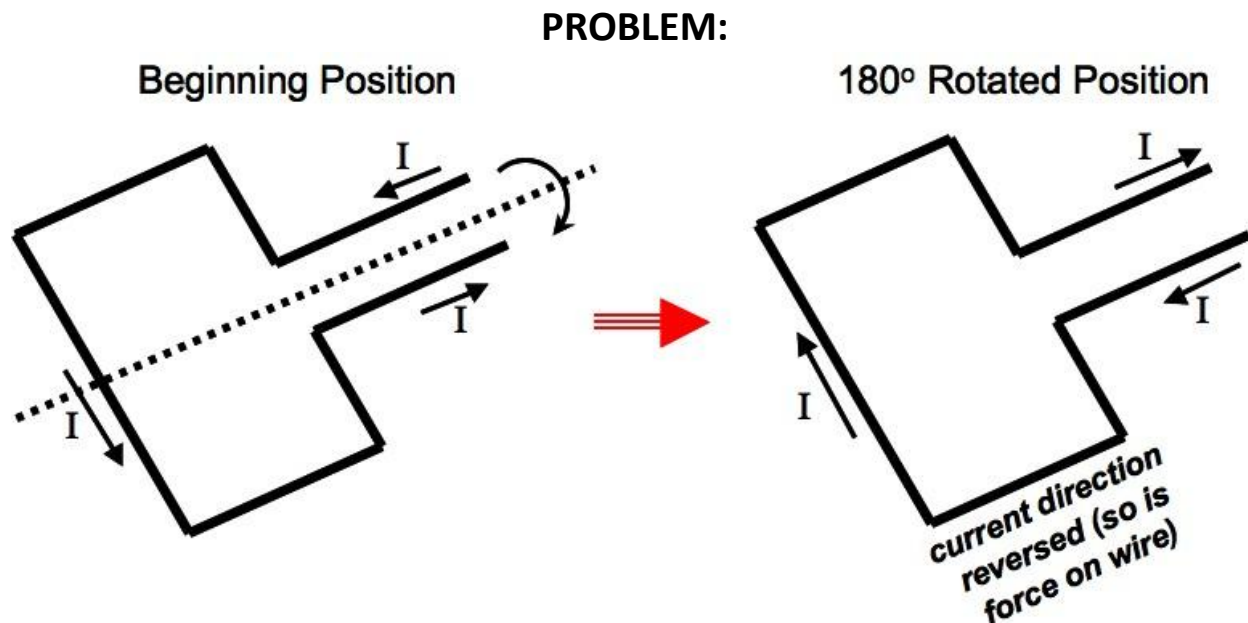
In this before-and-after picture, you can see that when the wire loop rotates 180° the force will now push the loop in the opposite direction because the direction of the current through the magnetic field will be reversed. Unless you want to make a fancy electronic rocking chair, this is not good motor design.

Instead, you will need to design your motor so that the current always flows in the same direction for the part of the wire loop inside the magnetic field as is shown in the next picture:
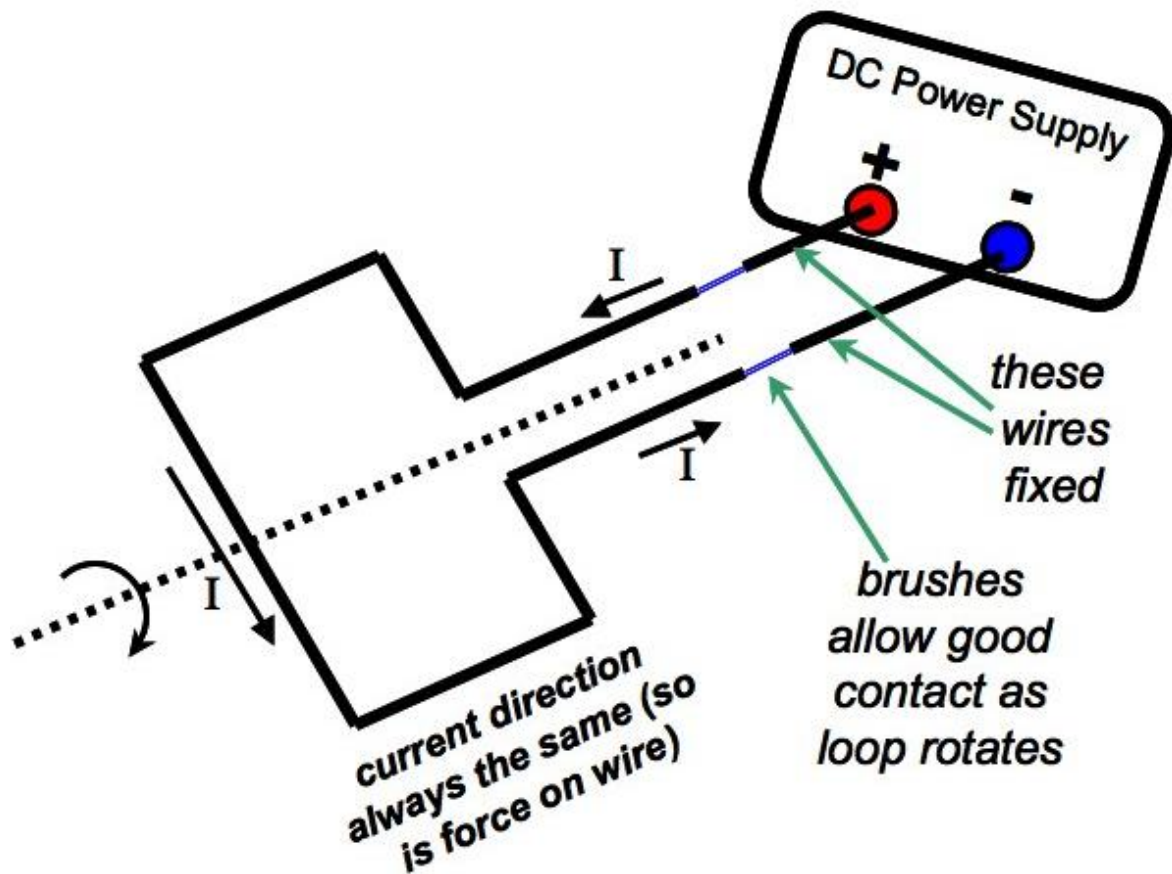
In this motor set-up (previous picture), when the wire loop rotates 180°, the manner in which current is supplied to the loop is changed in order to get the current to flow in the same direction for the part of the loop experiencing the magnetic force.

¿ 0-3
Explain why a simple rotational motor must utilize brush contacts.
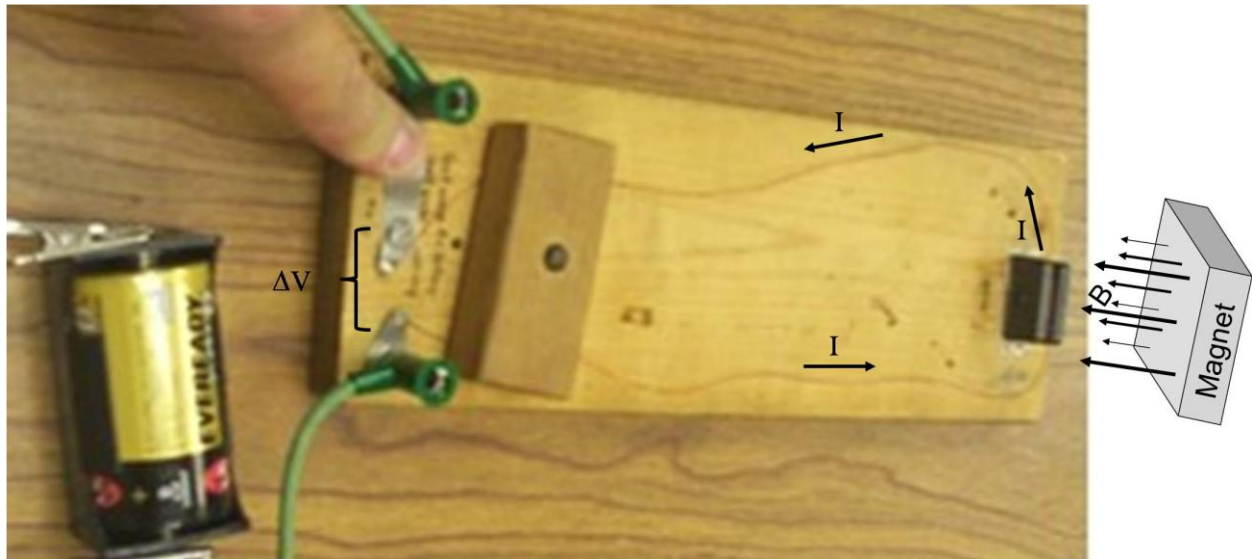
The above picture shows a current carrying loop of wire with a small segment passing through a magnetic field. The arrows indicating the direction of current and the cartoon addition of the magnet which indicates the direction of the magnetic field both indicate (using the right hand rule) that the wire feels a force upward (out of the page).

¿ 0-4

The figure below shows three possible arrangements for a current carrying wire to pass between two magnets. For each case, use the Lorentz force equation to compare the resulting force on the segment of current carrying wire (relative magnitude and direction). You are not provided a numerical value of B so you need to give a qualitative description of the strength of the force.
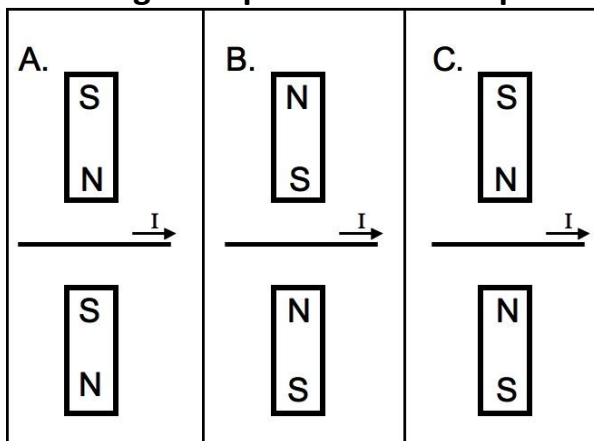
A *generator* is a motor in reverse. Instead of taking electrical power from a current and turning it into mechanical energy (the rotation of the motor), a generator takes mechanical energy and turns it into electrical power. Imagine taking a motor and disconnecting it from its DC power supply and connecting it to a light bulb. If you motor had a hand-crank, then you could provide the mechanical energy to create the current in the light bulb.

¿ 0-5

What would you see on the oscilloscope screen if you connected your motor to one of the oscilloscope channels and turned the motor with your fingers? Would the voltage always be on or would there be separate 'on' and 'off' periods (hint: is the wire always in the magnetic field)? Would the output voltage always have the same intensity (hint: is $\vec{I} \times \vec{B}$ always the same value)? Is the output voltage always positive or does it oscillate from positive to negative (hint: what are the brush contacts for)? Draw your answer below.
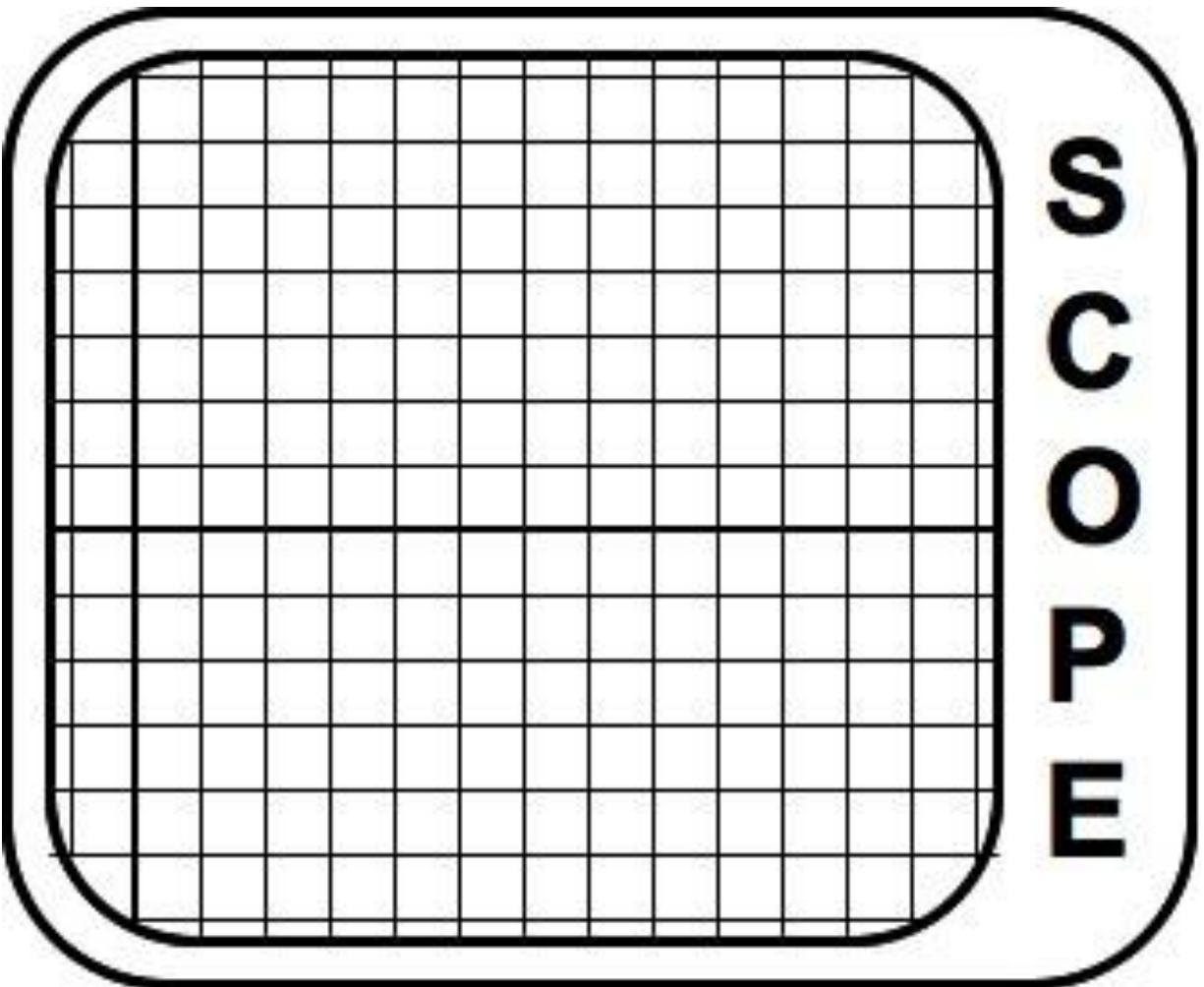
Power & Efficiency

At some time as the motor rotation rate speeds up, the angular speed ω reaches an equilibrium value where the opposing torques balance the torque caused by the magnetic force, $\vec{T}_{\text{from}\atop B-field} = \sum \vec{T}_{\text{opposing}}$. These opposing torques come from friction and any load you place on the motor (work you make the perform). In this experiment, it will be difficult to directly analyze the magnetic force being applied to the motor so that the force-torque perspective will not be useful. Therefore, it is better to examine the energy perspective of the motor.

Conservation of energy indicates that power in must equal power out:

$$P_{\text{input}\atop\text{power}} = P_{\text{output}\atop\text{power}} + P_{\text{friction}}.$$

Thinking of the motor as any other circuit component, we know that the electrical power being used by the component is P=IV. So the input electrical power can be measured in the lab as

$$P_{\text{input}\atop\text{power}} = I_{\text{through}\atop\text{motor}} V_{\text{across}\atop\text{motor}}.$$

The output power is equal to the rate of work energy that the motor performs per second,

$$P_{\text{output}\atop\text{power}} = W_{\text{by motor}\atop\text{on environment}} / \Delta t.$$

Since work is given by

$$W_{\text{by motor}\atop\text{on environment}} = \vec{F}_{\text{on object}} \bullet \vec{d}_{\text{object}\atop\text{travels}},$$

this is easy to calculate if the motor were to be lifting an object vertically upward since in this case

$$\vec{F}_{\text{on object}\atop\text{by motor}} = -\vec{F}_{\text{on object}\atop\text{by gravity}} = -m_{\text{object}}\vec{g}$$

so that

$$W_{\text{by motor}\atop\text{on environment}} = -m_{\text{object}}\vec{g} \bullet \vec{d}_{\text{object}\atop\text{travels}} = mgd.$$

But *mgh* is the familiar formula for gravitational potential energy, so we know we are doing things correctly.

Of course, $I_{\substack{\text{through}\\\text{motor}}}$ or $V_{\substack{\text{across}\\\text{motor}}}$ may not be constant as the motor operates, but we can treat these as average values for now. Also, the motor will not always be able to make contact through the wire brushes so that current does not flow to the motor at all times. If the motor is only in contact with the source for 30% of the time, then

$$P_{\substack{\text{input}\\\text{power}}} = 0.3 \cdot I_{\substack{\text{through}\\\text{motor}}} V_{\substack{\text{across}\\\text{motor}}}.$$

The oscilloscope in the lab is very useful in determining what percentage of the time current is flowing through the motor.

¿ 0-6

A motor is 'on' 50% of the time at 4 [V] and 0.03 [A]. It lifts a 0.02 [kg] of paper clips upward 0.8 [m] in 2 [s]. Calculate the electrical power going into the motor, the power output by the motor as work, and the power lost as friction.

In order to measure the current through the motor, a rather imprecise value is obtained from the power supply readout. A much better value for the current may be obtained by placing the motor in series with a 1 Ω resistor and using the oscilloscope to find the current through the resistor (and therefore the motor). (Remember to get the current in the resistor by measuring voltage and dividing by R.)

The efficiency of the motor is given by $\varepsilon_{\text{efficiency}} = P_{\substack{\text{output}\\\text{power}}} \Big/ P_{\substack{\text{input}\\\text{power}}}$. If the motor is made to lift objects vertically,   then   the   output   power   can   be   found   via   the   force   of   gravity: $E_{\text{output}} = mgh$ so that $P_{\substack{\text{output}\\\text{power}}} = \dfrac{\Delta E_{\text{output}}}{\Delta t} = mg\dfrac{\Delta h}{\Delta t}$.

¿ 0-7

Calculate the efficiency of the motor from the previous question.

Speed of Rotation

The rotational speed of a motor is typically measured in revolutions per minute [RPM]. You will need to use the oscilloscope to find the time of one full oscillation (the period), turn this into frequency, and finally into RPMs. Use simple factor labeling to do this:

$$f\left[\frac{cycles}{seconds}\right] \cdot 60\left[\frac{seconds}{1\,minute}\right] = 60f\left[\frac{cycles}{minute}\right] \text{ or } 60f\left[\frac{revolutions}{minute}\right] \text{ or } 60f\ [RPMs].$$

¿ 0-8

A motor turns once in 0.02 [s], how many RPMs is it rotating at?

Observing the Motor Parameters

The easiest way to observe the behavior of the motor is with a middle ground measurement between a 1 Ω resistor and the motor in series. This will provide the following graph on the oscilloscope screen, though it may take some effort to find the correct time scale. The percent of time that the motor is on is simply $(t_1+t_2) / T$. Using the run/stop button to collect data from the oscilloscope is useful for this because the triggering will be very sensitive and the will continuously lose the signal.
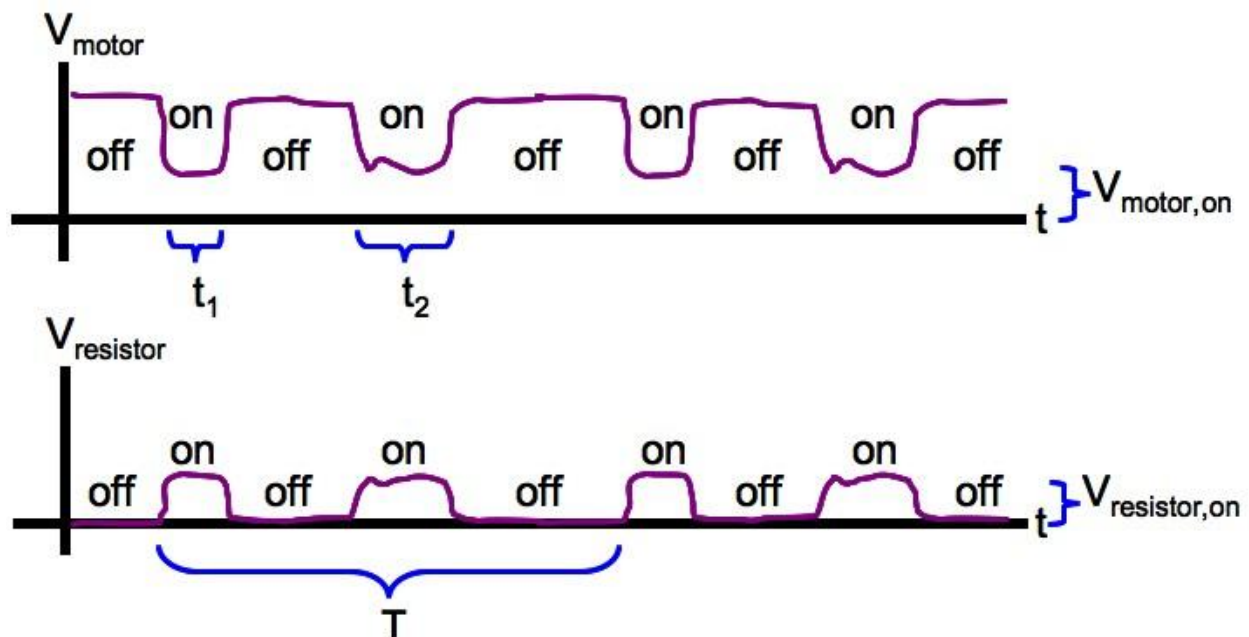
In the previous picture, why is the voltage across the motor larger when the motor is off than when it is on? You may want to explain with circuit diagrams.

Later in the lab you will need to measure these two components (motor and resistor) simultaneously in order to calculate the RPMs and the power. Since

$$P_{\text{motor,on}} = I_{\text{motor,on}} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time on})$$

$$= I_{\text{resistor,on}} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time on})$$

$$= \frac{V_{\text{resistor,on}}}{R} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time on})$$

you can obtain the power used by the motor (friction) using only the pictured measurements.

STOP PRELAB

In-Lab Section 1: constructing the motor

! **The wire's insulation melts at approximately 5 amps of intermittent current (depending on applied voltage). Once the insulation melts, all the motor loops are shorted out so that you only have one loop to drive the motor (i.e., the motor is ruined).**

- **Do not use too large of an input power.**
- **Do not let the motor get stuck with current flowing through its nearly resistanceless wires. (Otherwise the wires are the only resistor in the circuit and become very hot.)**
- **If the motor stops spinning, IMMEDIATELY shut off the voltage supply or your motor will begin to turn into a gaseous state!**

1) Begin with your card. Write your name on the card by the box containing the word "magnet".
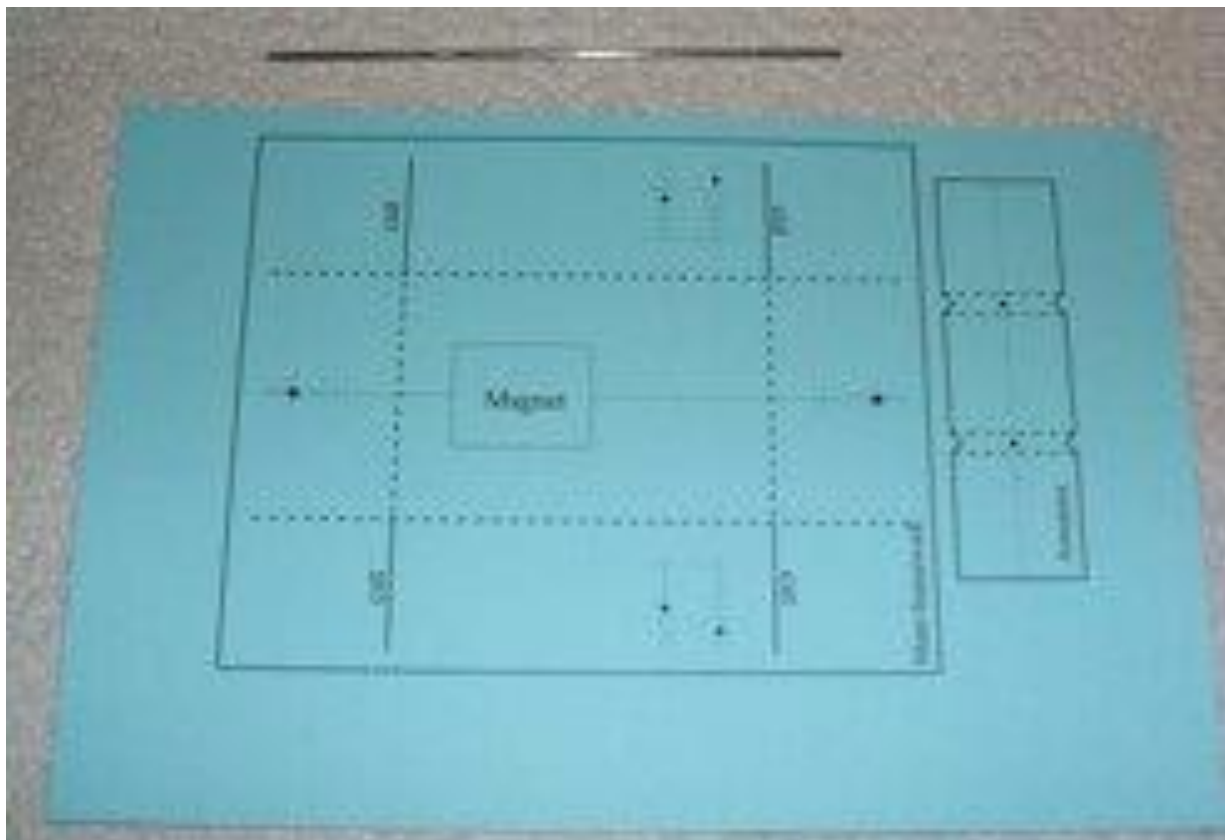
2) Cut along the solid lines and fold along the dotted lines. Taking your time to make things nice in the motor construction will ensure your motor runs well and is easily fixed if it breaks down.
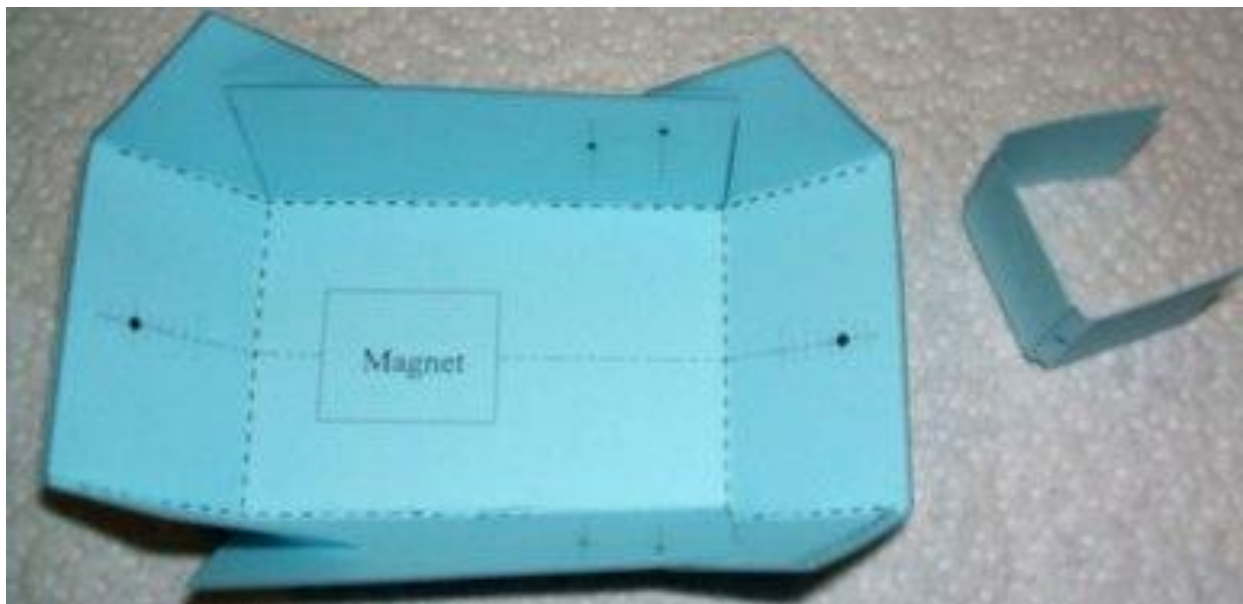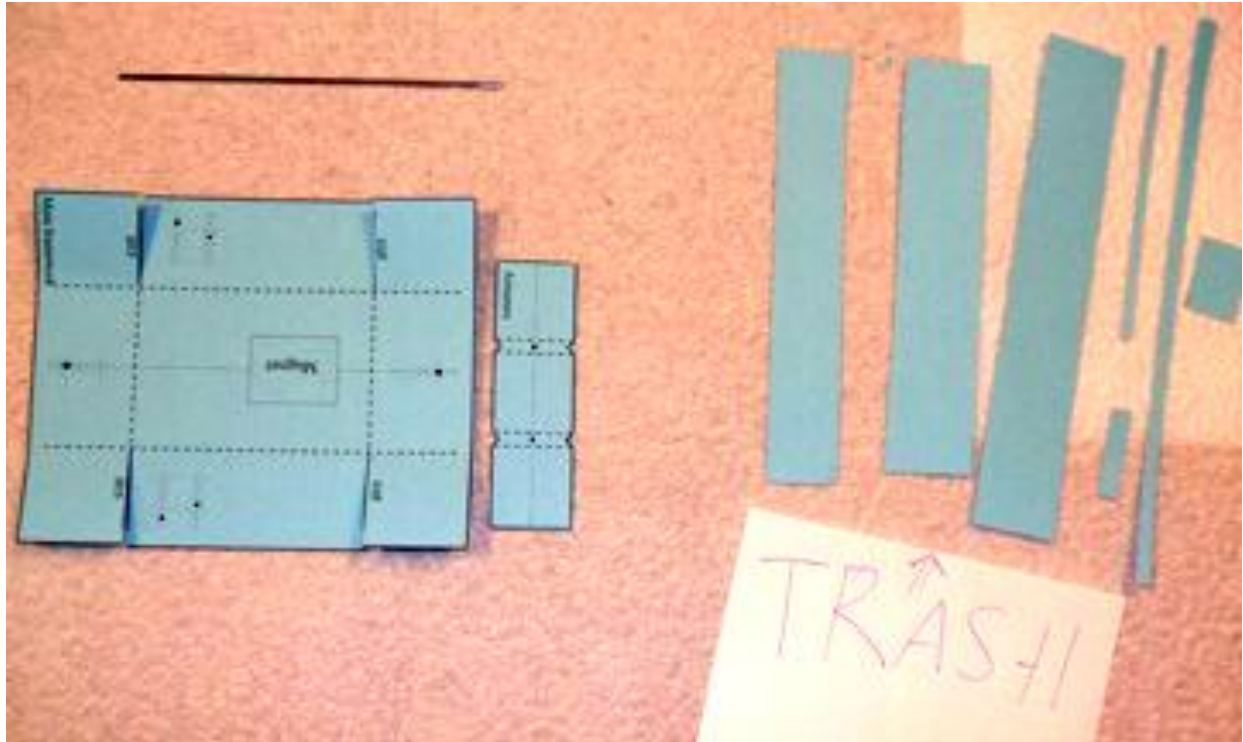
3) Carefully use a sharp poker to poke out the marked black dots. Wiggle the two axial dots so that the motor axis will turn easily (with low friction). **Never poke through the paper with your finger on the other side. Always lay the paper flat on the table surface and poke so that the poker strikes the table when exiting the paper.**
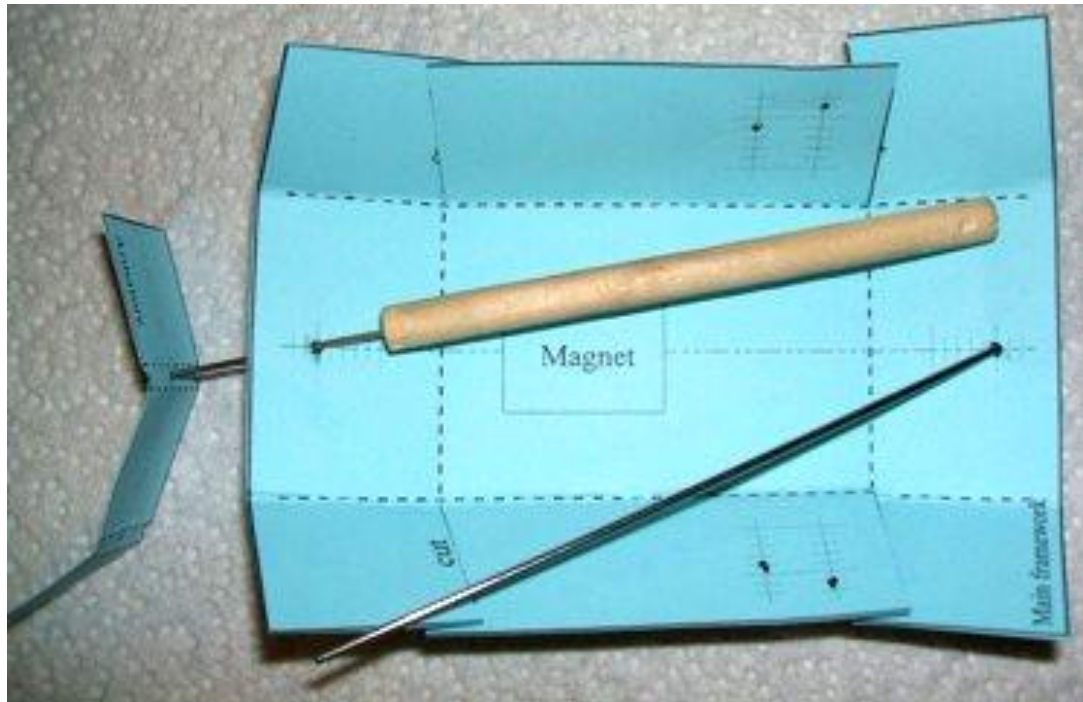
4) Use masking tape or clear tape to tape up your motor-enclosure box and armature box.
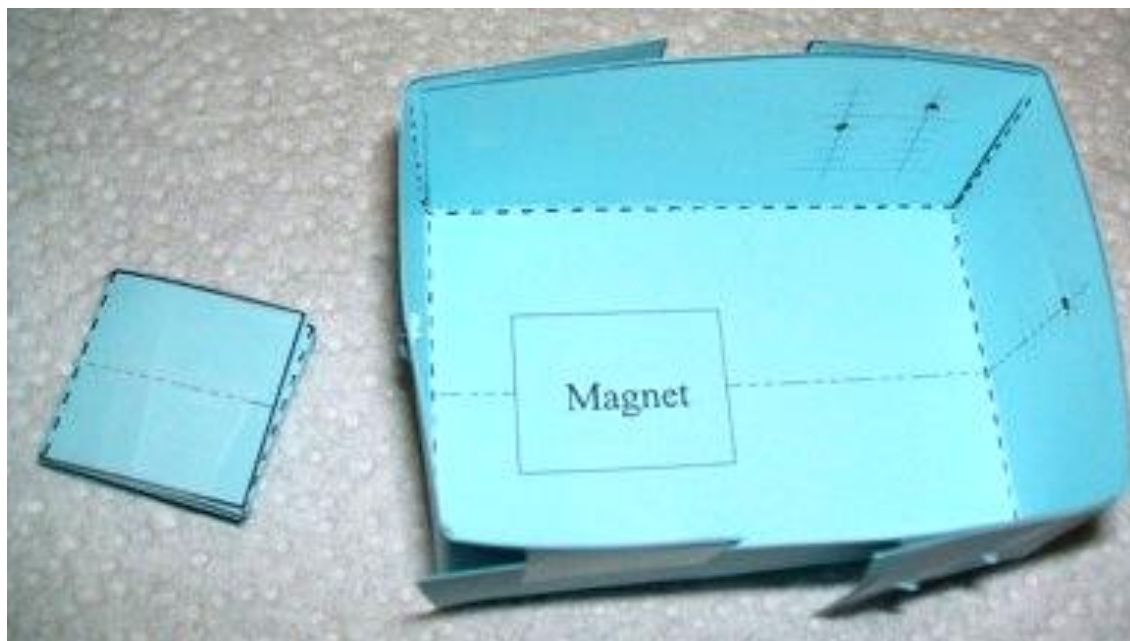
5) At this point, examine what a finished motor should look like.
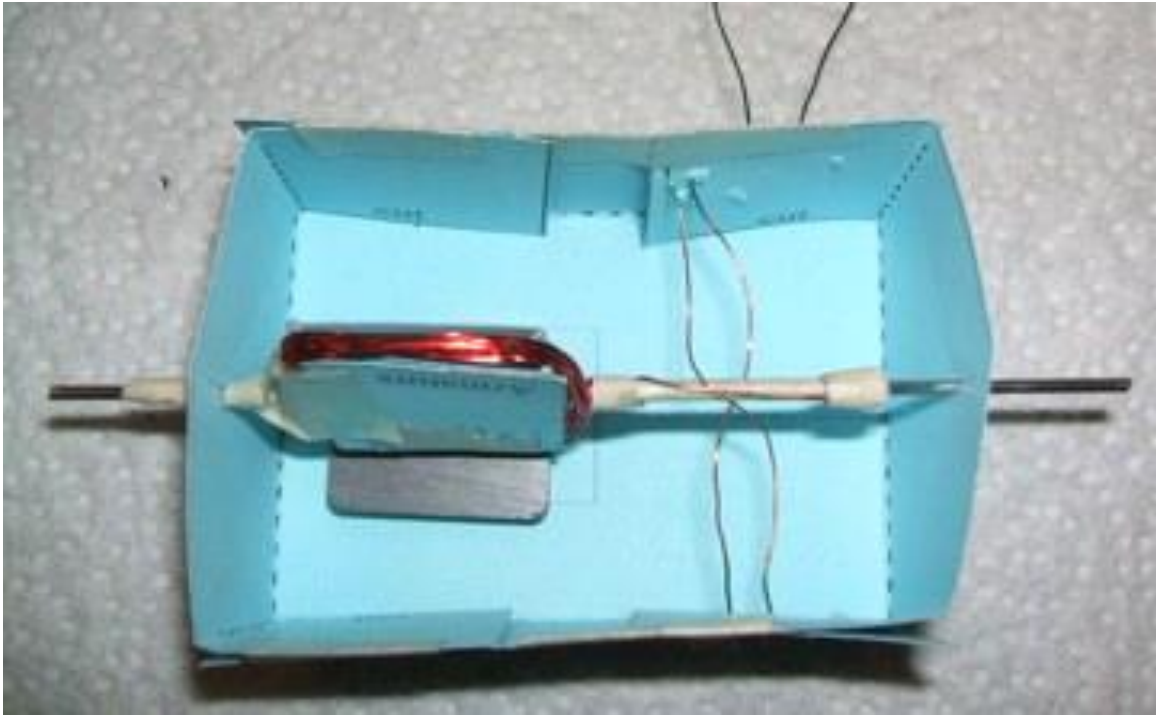
6) Tape your magnet into your box, and add tape to the axle rod. The tape in the axle rod serves the dual purpose of insulating wires from the metal rod as well as keeping the rod positioned correctly in the motor-enclosure box: so the armature box stays above the magnet. Pay careful attention to locate the insulating tape on the correct location of the rod by repeatedly placing the rod into the motor-enclosure box and spinning it with your fingers.

7) Add some tape as neatly as possible to affix the axle rod to the armature box.

8) Take ~2 metes of wire and wrap the armature box. Both ends of the wire should protrude from the winding box along the axle insulation. You will eventually bare the two ends and tape them down to the axle, but leave them free until you learn how to bare the wires. Notice that the two ends of the winding protrude to the left of the armature box and are taped down **flat against the axle** and **in the place of the armature box**. If the leads are not in the plane of the armature box, the coil will receive current when the coil is 90° rotated away from the magnet (not good).
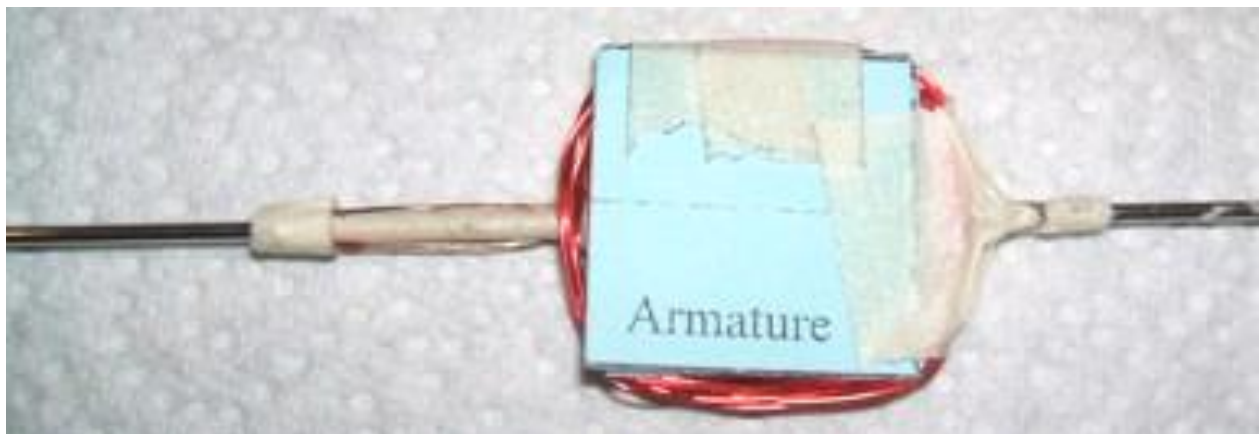
9) Wherever good electrical contact is desired, the colored insulation must be burned and sanded off that part of the wire so that clean, bright copper can be seen. To bare the wire you must burn off the insulation along the part of the wire you wish to bare. Burn the insulation thoroughly; it will appear blackened. Then use sandpaper to clean the charred wire insulation and leave a nice bright, bared length of copper wire.

10) Place the axle into the motor-enclosure box. You may eventually need to add tape to other parts of the axle in order to keep the axel from shifting around too much in the motor-enclosure box during operation.

11) Finally you must insert two bared wires to act as brushes for your motor. These "power lines" are the most difficult part of the motor to get correct. The axle leads must make **precise** contact with these power lines as the motor turns. Motors that work best tend to have very straight brushes that lie tightly against the axle. Note that the location of the power lines (the punched holes in the sides of the motor-enclosure box) may need to be changed depending on the final position of your axle leads.


These wires not connected.

Wires bared to act as brushes.

Wires bared to act as leads.
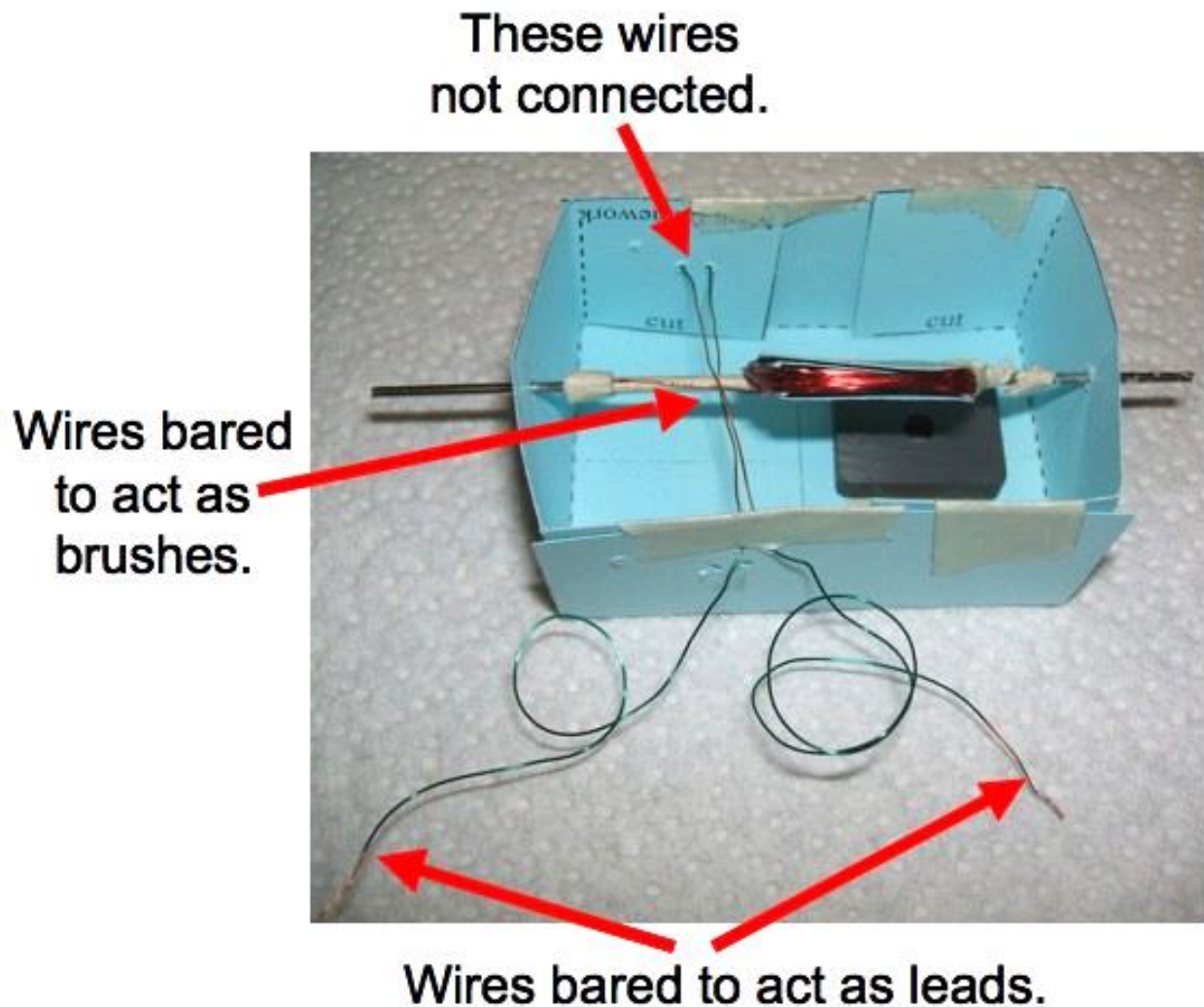
(*See the next page for power line hints.*)

Note on testing your motor:
Always start with low voltage (~2 Volts) when connecting your motor to the DC power supply. Then start the motor by spinning it with your fingers. You should be able to *feel* with your fingers which way the motor is being pushed to rotate. This will tell you which way to spin it. You may have to keep increasing the supply voltage to keep your motor spinning. Never let your motor stay connected to the source with current running through it when it is not spinning because the insulation will rapidly melt away. **(You will hear the TA shouting from time to time during this lab, "Unhook it! Unhook it!")**

Other power line configurations have shown improvement over the original design. One idea is to double up the power lines so that they make better contact and are more durable:

These power lines are doubled up to allow better connectivity with the axle leads as well as to strengthen the power lines so that they are less quickly deformed by the operation of the motor.
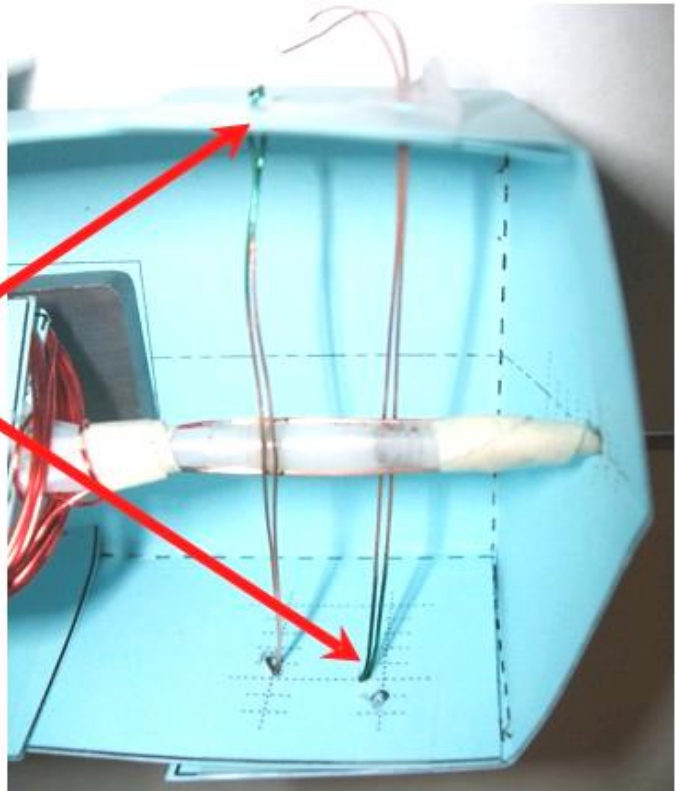
Another idea is to change the location of the power lines so that they "hug" the axle more than in the original positioning:

This doubled power line starts and ends near the bottom of the motor-enclosure box and contacts the axle leads from the top.

This doubled power line starts and ends near the top of the motor-enclosure box and contacts the axle leads from the bottom.
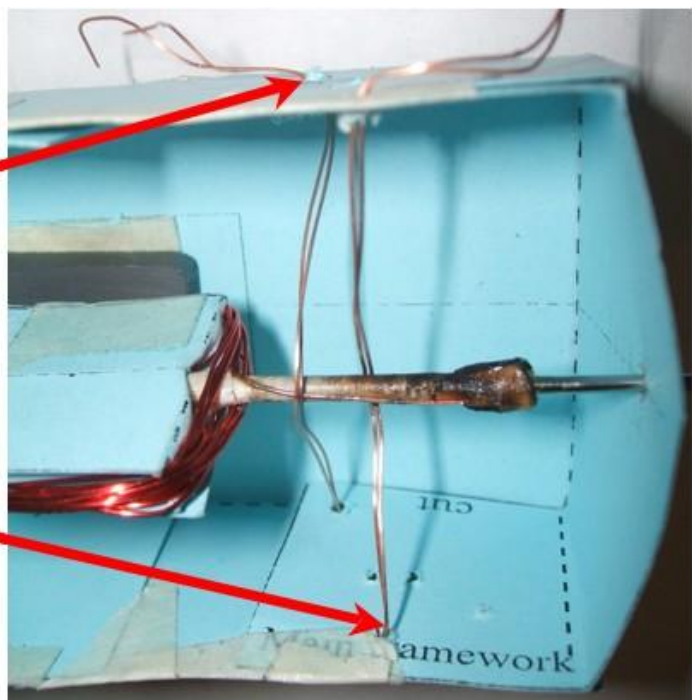
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In-Lab Section 2: authentic assessment

Always start with low voltage (~2 Volts) when connecting your motor to the DC power supply. Then start the motor by spinning it with your fingers. You should be able to *feel* with your fingers which way the motor is being pushed to rotate. This will tell you which way to spin it. You may have to keep increasing the supply voltage to keep your motor spinning. Never let your motor stay connected to the source with current running through it when it is not spinning because the insulation will rapidly melt away.

¿ **2-1**

Show your TA ~~a student in a different group~~ that you can successfully build a working motor. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student build a motor that successfully runs (on electrical input power). This will be an indispensible skill should they find themselves lost at sea!"

! TA signature: _____

~~**Student Signature**~~:**_____**

In-Lab Section 3: open-ended / creative design

Imagine you wish to sell your motor on Ebay. You will need to describe as many of your motor's features in addition to your own intense emotional attachment to your motor. Design a way to calculate the minimum source voltage required to operate your motor $V_{source,min}$, the RPMs at this voltage RMS_{min}, and the power loss due to frictional torque $P_{motor,on}$. Note that you cannot obtain an accurate measure of voltage or current with the built-in source meters so must use the oscilloscope to find these values. Also you should report the maximum safe source voltage $V_{source,max}$ and corresponding $RPM_{SafeMax}$ your motor can operate safely at (but don't find $RPM_{MotorFailure}$).

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 3-1

hypothesizing/planning:

¿ 3-2

observations/data:

¿ 3-3

calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: _____**

Post-Lab (authentic assessment): Motors

! **You must complete this post-lab section after you attend your lab.**

Make your motor work for a non-physics person (parent, friend, English major, etc.) and have them sign the below affidavit confirming that they saw your motor working. However, you do <u>not</u> need to have the affidavit notarized.

¿ X-1

Show a non-physics person that you can successfully build a working motor. Note: if someone is stuck, please get advice from another student!

"Yes, I have seen this student build a motor that successfully runs (on electrical input power). I am considering getting one myself."

Non-physics person signature:_____

Weekly Activity 10: Solenoids

Pre-Lab

! You must complete this pre-lab section before you attend your lab to prepare for a short quiz. Be sure to complete all pages of the pre-lab.

Continue until you see the stop pre-lab picture: 🛑 STOP PRELAB

Subsection 0-A: how solenoids create magnetic fields using current

A current carrying wire creates a magnetic field around the wire. This magnetic field may be found using the Biot-Savart Law $d\vec{B} = \dfrac{\mu_o}{4\pi} \dfrac{I \cdot d\vec{s} \times \hat{r}}{r^2}$. However, this law can be difficult to use. If there is a high degree of symmetry, you may choose to find the magnetic field produced by the current carrying wire using Ampere's Law:

$$\oint_{\substack{whole \\ Amperian \\ loop}} \vec{B} \bullet d\vec{s} = \mu_o I_{\substack{total\,enclosed\,by \\ Amperian\,loop}}.$$

Ampere's Law simplifies finding a magnetic field in the same manner that Gauss's Law simplifies finding an electric field.

Examine the ideal solenoid (also called "inductor") where a very long coil of wire carries a current I is found to have a nearly uniform magnetic field inside the coils and a nearly zero magnetic field outside the coils. A cross sectional picture is provided (along with an actual solenoid, a compass inside its coils can be seen interacting with the magnetic field.):


29
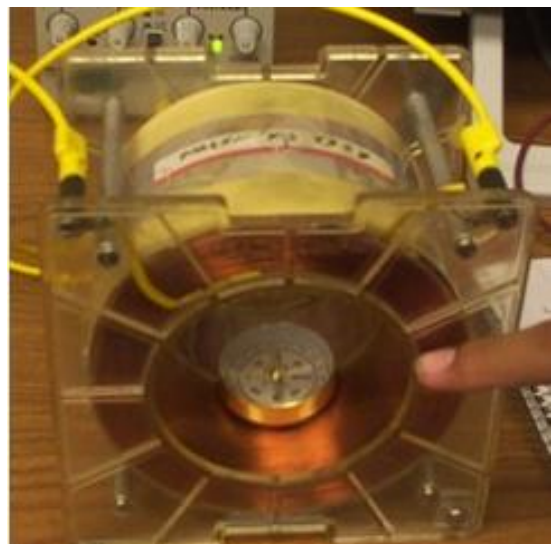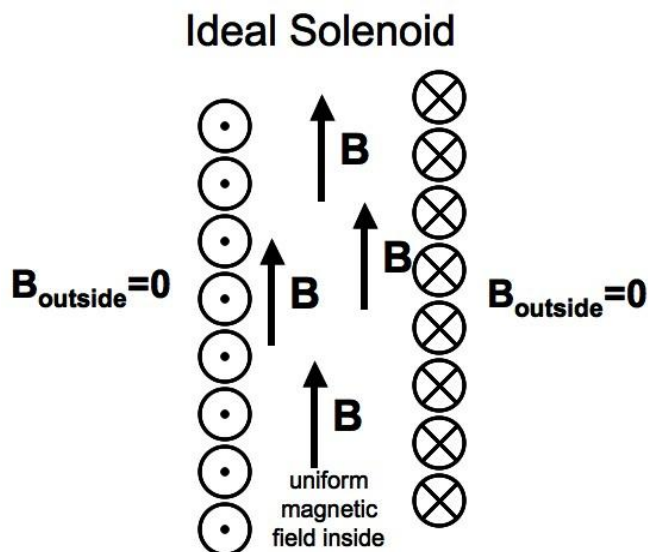
In the laboratory, an experimenter may easily control the current through a solenoid, and so it is desirable to determine the strength of the magnetic field inside the solenoid as a function of the current. Because of the high degree of symmetry in the ideal solenoid, Ampere's Law may be used to find the magnetic field inside the solenoid.

Ampere's Law:

$$\oint_{\substack{\text{whole} \\ \text{Amperian} \\ \text{loop}}} \vec{B} \bullet d\vec{s} = \mu_o I_{\text{total enclosed by} \atop \text{Amperian loop}}$$

N solenoid loops enclosed in the Amperian loop, each with current $\mathbf{I}$.

n is "loop density" N/L of solenoid.
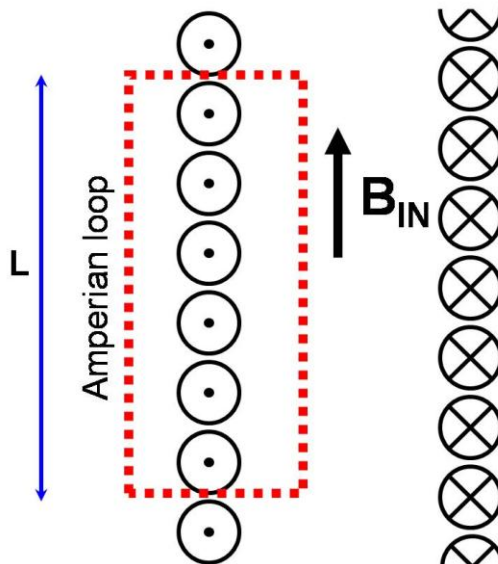
¿ 0-A-1

Go over the following derivation with your lab partner since you will need to understand it for your lab report. Explain each step beside the given derivation:

$$\oint_{\text{wholeloop}} \vec{B} \bullet d\vec{s} = \mu_o I_{\substack{\text{total} \\ \text{enclosed}}}$$

$$\int_{\substack{\text{inside} \\ \text{solenoid}}} \vec{B} \bullet d\vec{s} = \mu_o NI$$

$$\int_0^L B_{\text{in}} dy = \mu_o NI$$

$$B_{\text{in}} \int_0^L dy = \mu_o NI$$

$$B_{\text{in}} L = \mu_o NI$$

$$B_{\text{in}} = \frac{\mu_o NI}{L}$$

$$B_{\text{in}} = \mu_o nI$$

¿ 0-A-2

A solenoid with a winding density of 10,000 [turns per meter] has a current of 0.3 [A] going through it. Calculate the magnitude of the magnetic field inside the solenoid (SI units).

When the current in a wire changes, the strength of the magnetic field created by the current also changes. Therefore, if you know the time dependent behavior of the current, you can find the time dependent behavior of the magnetic field inside the solenoid.

¿ 0-A-3

If the solenoid is carrying a sinusoidally oscillating current, what is the time dependence of the varying magnetic field inside the coils? (What mathematical function describes the magnetic field in time?)

Subsection 0-B: how solenoids make voltages using magnetic fields

Two very important concepts in the study of electricity and magnetism are Ampere's Law and Faraday's Law. Ampere's Law states that a current in a wire creates a magnetic field. Faraday's Law states that if the magnetic field changes (oscillates) the changing magnetic field will create a voltage in the wire (with the strange choice of epsilon ε_L as the variable to represent this voltage):

$$\varepsilon_{\mathrm{L}}(t) = -\frac{d\phi_B}{dt}$$

ϕ_B is the magnetic flux, which has units of magnetic field times area. If a magnetic field is uniform over a certain area A, then the magnetic flux is easy to calculate $\phi_B = B \cdot A \ \left[\mathrm{T \cdot m^2}\right]$. This voltage ε_L that is created by the changing magnetic field is call the "back EMF" or the "self-induced EMF". EMF stands for electromotive force, which seems a very bad convention since it is really a voltage and not a force (blame history)! The crucial point is that it is the rate of change of the magnetic flux that determines the amount of the voltage across the inductor (solenoid).

¿ 0-B-1

If a magnetic field is uniform within a solenoid of cross sectional area $A = 2 \ [\mathrm{m}^2]$ with a sinusoidal time dependence $B = 3\sin(200t) \ [\mathrm{T}]$, what is the magnitude of the induced voltage across the solenoid's terminals (SI units)?
**{Did you get 1,200 [V]?}**

Faraday's law does not specify whether the magnetic field (flux) producing the voltage ε_L is from an external source or from the magnetic field that the solenoid itself created.

External Inductance

$\varepsilon_{induced}$ by B acts like battery.
Current flowing through resistor is easily measured.
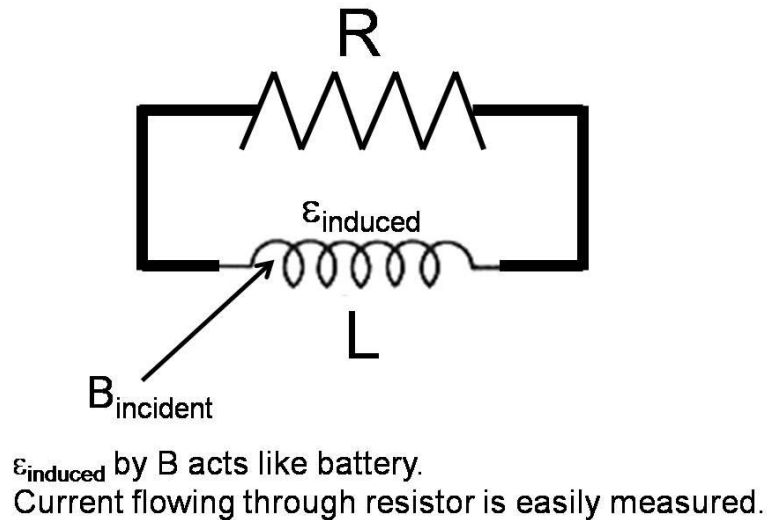
If the magnetic field is from an external source like a radio wave that happens to travel through the solenoid, then the induced voltage ε_L created across the solenoid could be used to detect the presence of the magnetic field. The induced voltage will act like a voltage source and cause a current that can be measured.

Self Inductance
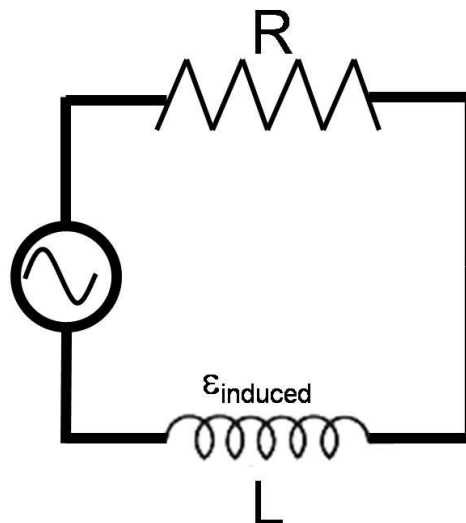
Oscillating voltage source causes oscillating B inside inductor.
Oscillating B inside inductor induces voltage $\varepsilon_{induced}$ (back EMF).
Back EMF makes inductor seem like a resistor to the voltage source.

If the magnetic field is created by the solenoid itself, then the induced voltage ε_L created across the solenoid will oppose the voltage source of the circuit and the inductor will effectively act like a resistor (with some special features).

¿ 0-B-2

When an inductor is in series with a resistor, why must the current inside the wires of the inductor always be the same as the current in the resistor? {Hint: if not, where would the excess charges pile up?}
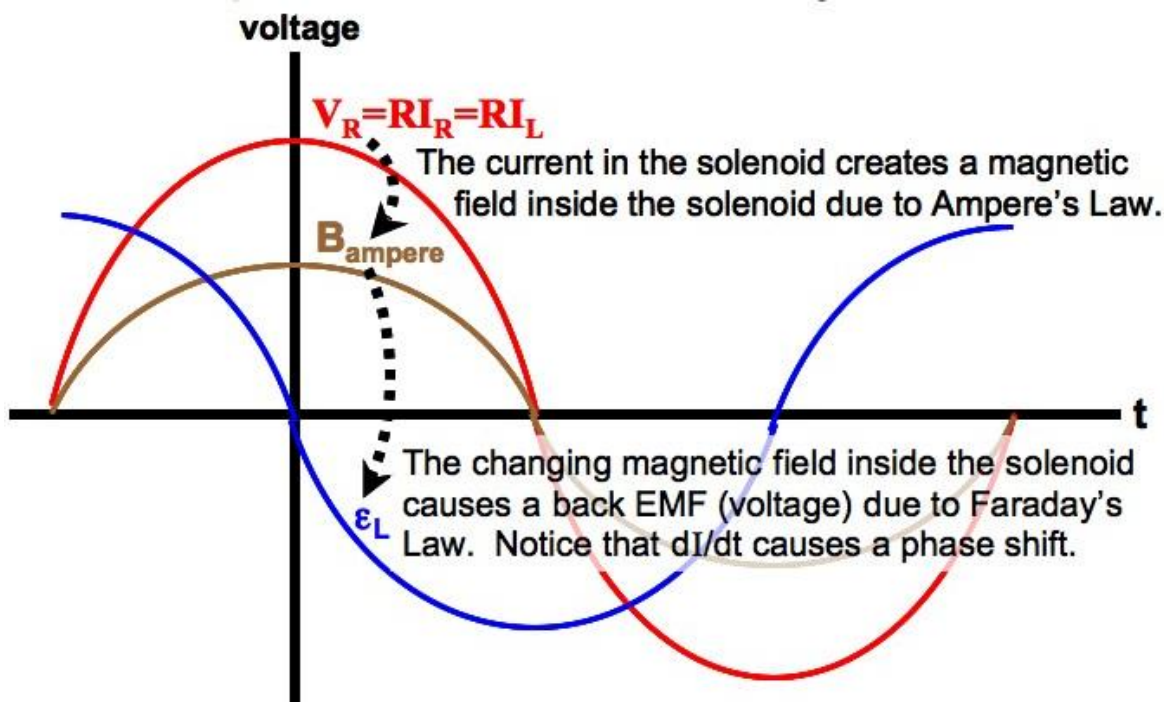
Self Inductance:
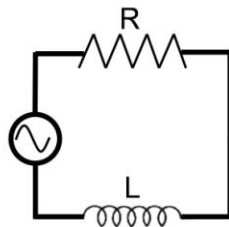
The logical flow of ideas is:
- The oscillating voltage source causes an oscillating current in the circuit (and solenoid).
- The oscillating current inside the solenoid wire causes an oscillating magnetic field inside the solenoid coils.
- The oscillating magnetic fields cause a changing back EMF across the solenoid.

This is shown graphically for an oscillating circuit with a resistor and inductor in series.

$$V_R=RI_R=RI_L$$

The current in the solenoid creates a magnetic field inside the solenoid due to Ampere's Law.

B_{ampere}

The changing magnetic field inside the solenoid causes a back EMF (voltage) due to Faraday's Law. Notice that dI/dt causes a phase shift.

ε_L

The above figure demonstrates the cause and effect relationships responsible for creating the voltage drop across a solenoid *even though it is just one long conducting wire!*

¿ 0-B-3

What physics law is used to calculate the magnetic field inside the solenoid's wires created by the current in the solenoid wires? {Only say the Biot-Savart if you can perform the monstrous calculus (and then prove it!).}

¿ 0-B-4

What physics law is used to calculate the induced voltage across the solenoid's terminals created by the *changing* magnetic field inside the solenoid's wires?

¿ 0-B-5

Explain whether or not you can create a constant magnetic field within a solenoid with an applied current.

¿ 0-B-6

Explain whether or not you can create a constant induced voltage across the solenoid's terminals with an applied voltage source.

¿ 0-B-7

What is the phase relationship between the induced voltage across the solenoid's terminals created by a sinusoidally oscillating magnetic field inside the solenoid's wires: both in-phase, the magnetic field 90° ahead of the voltage source, or the magnetic field 90° behind the voltage source? {Use the previous picture.}

Restating:

If a magnetic field is changing through the area of a loop of wire, then Faraday's law says that this changing magnetic field will induce a negative voltage (back EMF) in the circuit:

- Faraday's law: $$\varepsilon_L = -\frac{d\phi_B}{dt},$$

where the magnetic flux ϕ_B is simply the magnetic field integrated over the cross sectional area of the wire loop:

- Magnetic flux: $$\phi_B = \vec{A}_{area} \bullet \vec{B}.$$

Since a solenoid has N loops each with a cross sectional area that is constant in time, this means that:

- Faraday's law for fixed area and N loops: $$\varepsilon_L = -NA\frac{dB}{dt}.$$

Due to the way we think about electronics, we need to remove the negative sign from this equation. This is similar to our use of V=IR for resistors in a circuit when technically the resistor causes a voltage drop (therefore a negative voltage change). Another way to think about this is that we can say that due to conservation of energy, adding all the voltages in a circuit together should yield zero: $V_{source} + V_{resistor} = 0$. But we can always rearrange to have $V_{source} = -V_{resistor}$ so $V_{resistor} < 0$, but we usually are talking about $|V_{resistor}|$ when we say "voltage of a resistor". Thus you should write $|\varepsilon_L| = NA\left|\frac{dB}{dt}\right|$ when describing the electromotive force (induced voltage) of a solenoid. But it becomes tedious to talk about the voltage source as a positive voltage increase and the components as having voltage decreases.

¿ 0-B-7

A solenoid with 38,000 loops per meter is placed in series with a 10 Ω resistor and driven by a sinusoidally varying source voltage. Using an oscilloscope, the voltage across the resistor is found to be $V_{res}(t) = 4.2\sin(325t)$ {does this tell you anything about the current in the circuit ☺ }. Write a time dependent equation with numerical values to describe the time dependent strength of the magnetic field inside the solenoid. Then provide two specific times when the current and magnetic field have both simultaneously reached their respective amplitudes. Note that $\mu_o = 4\pi \times 10^{-7}$ [T m / A] (SI units).
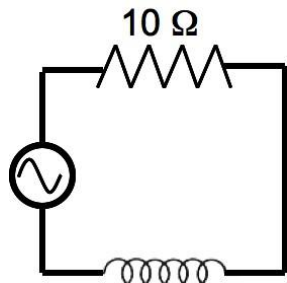
¿ 0-B-8

Find the time dependent back EMF created by the RL circuit in the previous question if the cross sectional area of the inductor is 0.006 [m²]and the inductor is 9 [cm] long (SI units).

Restating the ideas in yet another way:
If you take a single solenoid and apply an alternating source voltage, then it will have an alternating current. The alternating current of this single solenoid will produce an alternating magnetic field within the area of <u>its own coils</u>. Now, there is a changing magnetic field within the area of the coils. The changing magnetic field induces a voltage in this solenoid (the back EMF). This process is called **self-inductance** and is measured in **[henries]** or **[H]**.

The parameter L (SI units of Henry) is used to describe the solenoid's ability to **self-induce** a back EMF ε_L. This parameter is defined as:

$$L_{\text{solenoid}} = \frac{\varepsilon_L(t)}{\left(\dfrac{dI_L}{dt}\right)}$$

because in the lab, we will need to know L so as we control the current, we can predict the induced voltage using the definition of L rearranged: $\varepsilon_L(t) = L_{\text{solenoid}} \cdot \dfrac{dI_L}{dt}$. (In the lab, we can control the current more easily than most other quantities.)

Substituting the previous results obtained using Faraday's law and Ampere's law

$$\varepsilon_L = NA \frac{dB}{dt} \quad \text{and} \quad B_{\substack{\text{inside} \\ \text{solenoid}}} = \mu_o n I_L$$

gives:

$$L_{\text{solenoid}} = \frac{NA\left(\dfrac{dB}{dt}\right)}{\left(\dfrac{dI_L}{dt}\right)} = NA\left(\frac{dB}{dI_L}\right) = A \cdot \mu_o \cdot N \cdot n,$$

so that

$$L_{\text{solenoid}} = A \cdot \mu_o \cdot N \cdot n.$$

This non-trivial derivation provides an excellent way to estimate the self-inductance L of a solenoid (in [henries]).

¿ **0-B-9**

Express the SI unit for inductance [H] in terms of other SI units (for the heck of it to see how inconvenient it would be, and so why a new unit was created).
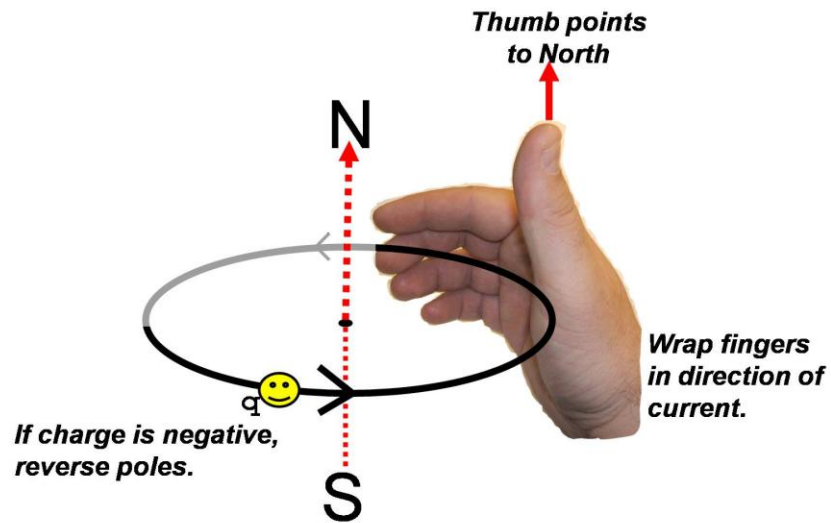
¿ **0-B-10**

Calculate the self-inductance parameter L for the inductor described in 0-B-7 and 0-B-8.

¿ **0-B-11**

If you allow a magnet to swing at the end of a pendulum just above some nonmagnetic sheet of copper, the pendulum-magnet will lose energy through electrical processes only and come to a stop. Explain where the energy goes using the concepts of induced voltage (Faraday's law is not just for solenoids!) and resistivity.

Right-hand-wrap rule for finding direction of
magnetic poles created by moving charges (current).

**Thumb points
to North**

N

**Wrap fingers
in direction of
current.**

q

**If charge is negative,
reverse poles.**

S

The right-hand-wrap rule also works for solenoids, but you must check the
direction of the winding to wrap your hand with the current:

*Thumb points
to North*

N

I

*Wrap fingers
in direction of
current.*

I

S

STOP
PRELAB
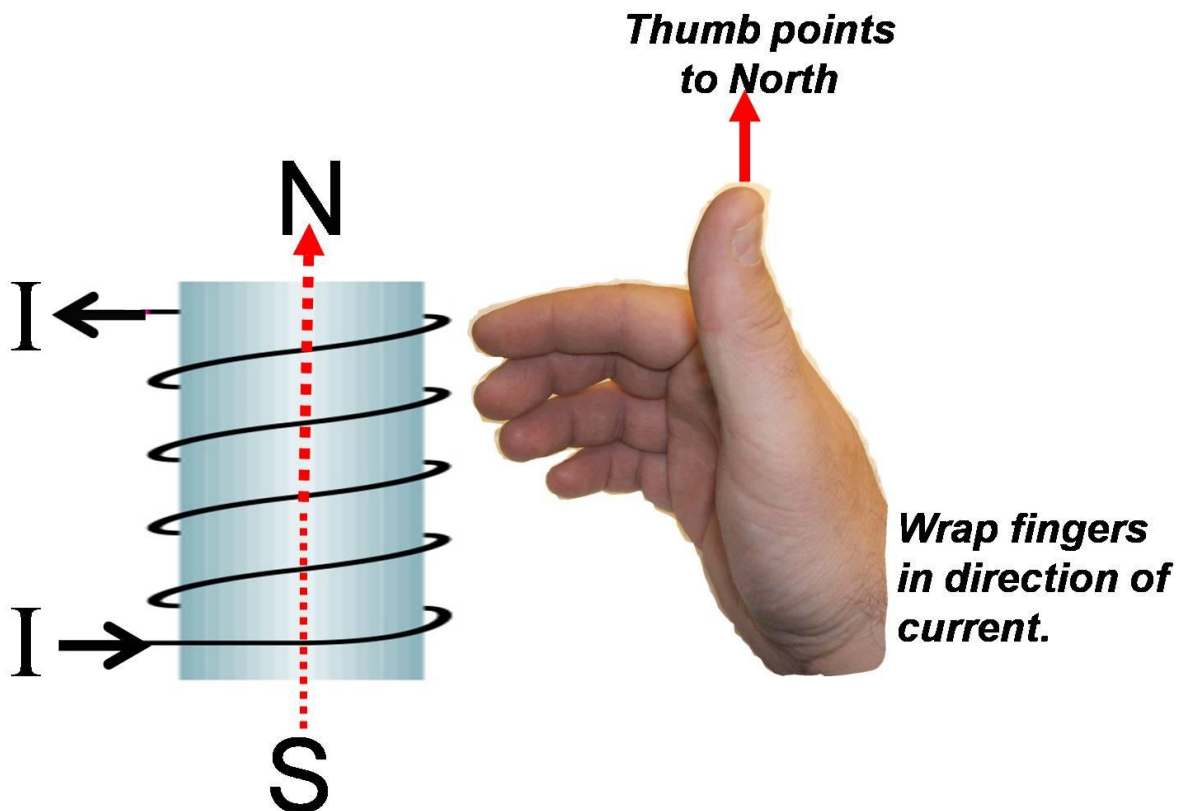
In-Lab Section 1: creating magnetic fields inside the solenoid

Now you will experimentally examine the magnetic field produced by a solenoid with current flowing through it. Note that a real solenoid produces a magnetic field qualitatively similar to a bar magnet of the same dimensions.

First check that your compass has not been "flipped". The compass arrow should align itself with the local magnetic field produced by the Earth. Remember that the Earth's north magnetic pole is at the geographic south pole. This causes the local magnetic field to point toward the north geographic pole. The compass aligns with this magnetic field and thus points toward the north geographic pole. If your compass has been flipped, fix it with a strong magnet or tell your TA so they can fix it.

Examine the direction of the windings of your solenoid. You can tell which way the current circulates by how the wire enters the solenoid. Then you can use the right-handed screw rule to determine the direction of the magnetic field inside the solenoid (which side is north and which is south).

¿ 1-1

Even though the solenoid is made of wire (wound into a coil), it is so long that it actually has some sizeable resistance. Use a DMM to measure the resistance of the solenoid (so this is a real solenoid, not an ideal solenoid).

¿ 1-2

Apply <u>constant</u> current using the <u>constant voltage supply</u> (a few volts should be good) to your solenoid. Find the current in the solenoid using Ohm's law.

¿ 1-3

Use the right-handed screw rule to predict the positive direction (north pole) of the magnetic field produced within the solenoid and the magnetic field surrounding the solenoid in general. Test your prediction using the compass and sketch the magnetic field surrounding the solenoid below. Be sure to draw your solenoid in such a way as to show the reader how the current flows through the solenoid.

In this section you will experimentally observe the process of self-inductance.

¿ 1-4

Place a solenoid in series with a 100 [Ω] resistor and drive this simple RL circuit with a sinusoidal source voltage with 10 [Hz] (very slow) and 5 [volts] source amplitude. Set your oscilloscope to measure the voltage across the resistor. Find how much current is flowing through the resistor and therefore the solenoid.

¿ 1-5

Qualitatively examine what happens to the current in the solenoid (by examining resistor voltage) as you increase the driving frequency from 100 [Hz] to higher frequencies. Your observations:

The impedance χ_L of an inductor is found to be $\chi_L = \omega_{drive}L$ where L is the self-inductance parameter of the solenoid and ω_{drive} is the angular driving frequency. The total circuit impedance without a capacitor is given by $Z = \sqrt{R^2 + \chi_L^2}$. The total circuit impedance Z has units of [ohms] for a reason; it acts as the total "resistance" of the circuit and thus can be combined with the source voltage to determine the circuit's current $I_{amplitude} = \dfrac{V_{source,amplitude}}{Z}$.

¿ 1-6

Since $I_{amplitude} = \dfrac{V_{source,amplitude}}{Z}$, explain how the current would change if the angular driving frequency ω_{drive} was increased. (This is another way to think about question 1-5.)

¿ 1-7

Now using the same circuit as the previous questions, set up your oscilloscope to measure the voltage of both the resistor and inductor using a middle ground configuration (with one channel inverted). Experimentally observe the 90°
phase shift that shows the oscillating inductor voltage leads the oscillating resistor voltage by $\pi/2$ (90°). Make a quick sketch of your observations below, and check with students in other groups to see that you are getting things correct.

! Warning: at very low frequencies, you will not see a phase shift between V_L and V_R (explained in the next passage).

At very low frequencies, the self-induced back EMF goes to zero because dB/dt is nearly zero. You would then think that V_L=0 [V]. However, many inductors are made of such long amounts of wire that they have a sizeable resistance that makes the inductor act in part as a resistor. Two resistors in series will be in phase so that you will not measure any phase shift in this case (when the frequency it too low).

¿ 1-8

Check for yourself that the solenoid acts as a pure resistor at very low frequencies . Below what frequency is it obvious that the phase shift between V_L and V_R is no longer $\pi/2$?

In-Lab Section 2: Lenz's law

Restating previous ideas, Faraday's Law states that a changing magnetic field will induce a back EMF voltage: $\varepsilon_L = -\dfrac{d\phi_B}{dt}$. Technically this equation shows that the back EMF produced is proportional to the rate of change of the magnetic flux, but the magnetic flux is just the magnetic field integrated over the surface area of the circuit. In simple situations where the area is constant, this just becomes $\dfrac{d\phi_B}{dt} = \dfrac{d(A \cdot B)}{dt} = A\dfrac{dB}{dt}$. Since the presence of a back EMF is effectively like adding a battery to a circuit, a current can be induced in a circuit without any other voltage source present!

An interesting example of this is when a magnet approaches a solenoid in series with a resistor:

Inside the solenoid:
$$\frac{dB}{dt} > 0$$

B

V (velocity)

R

Direction of current inside the resistor?
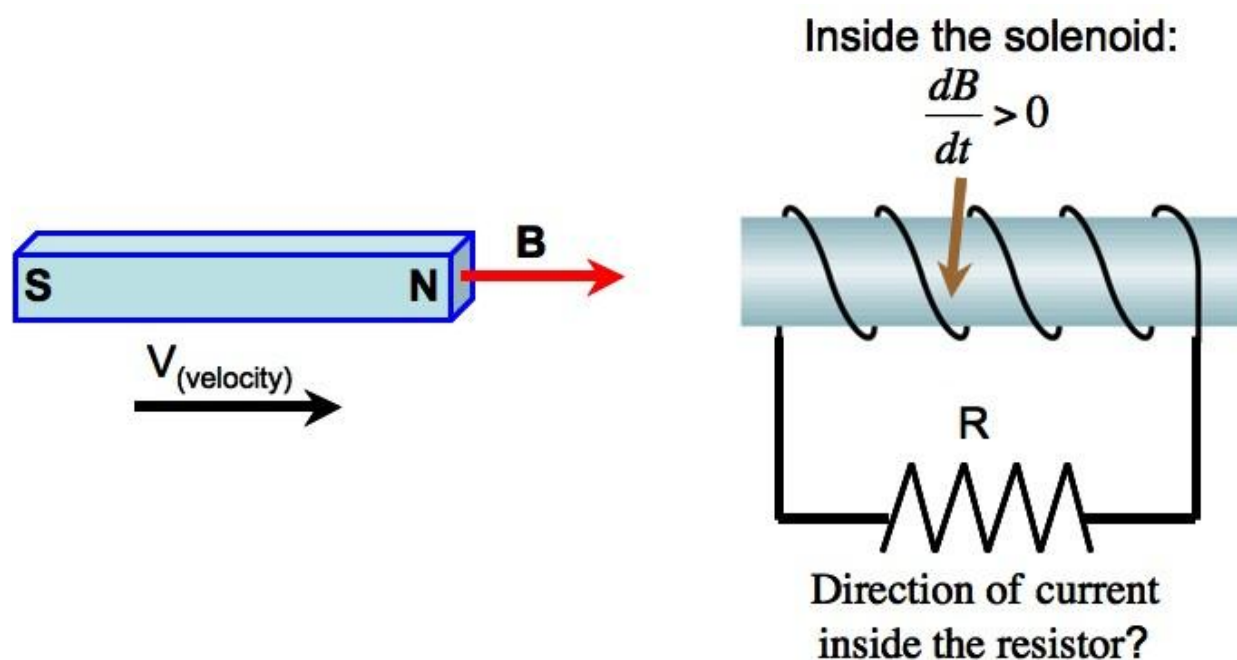
Here the magnet's north pole is approaching the solenoid from the left. The magnetic field strength is growing inside the inductor coils as the magnet approaches $\dfrac{dB}{dt} > 0$. **Lenz's Law** is a very simple rule that allows you to figure out the direction of the current flow caused by the induced back EMF. Lenz's Law states that the back EMF will cause a current that generates its own reactionary magnetic field that opposes that change of the magnetic field inside the solenoid. Huh? Put more simply, Lenz's law says to *fight the change in magnetic field* or *keep B the same in the solenoid*. In this case the right-pointing magnetic field inside the solenoid is growing as the magnet approaches the solenoid. Therefore, Lenz's Law states that there will be an induced current to produce a reactionary magnetic field that points to the left to keep B constant inside the solenoid (next figure).
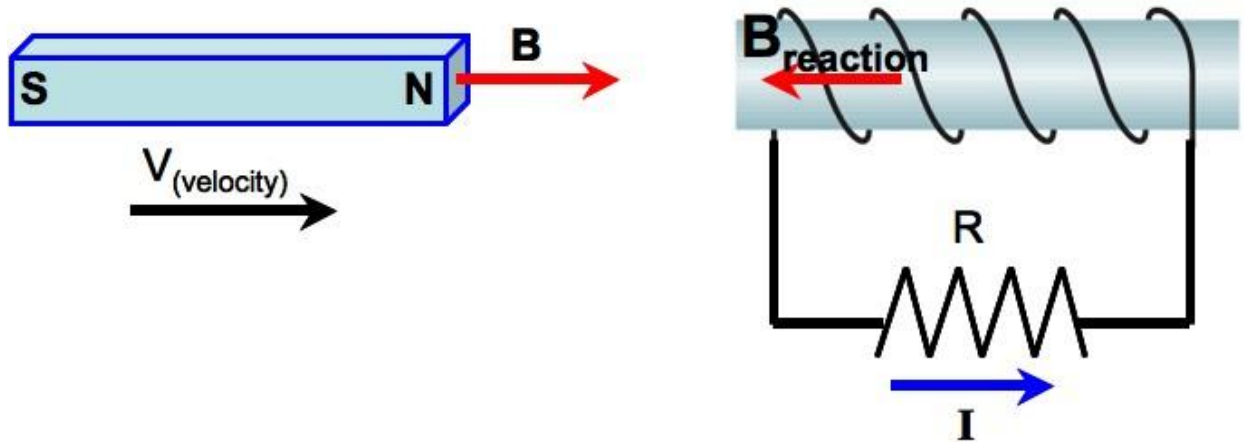
Now you can simply use the right-hand screw rule to find the direction of the current traveling around the inductor coils that will produce the correct reactionary magnetic field and trace this current through the wires to find the direction of the current through the resistor.
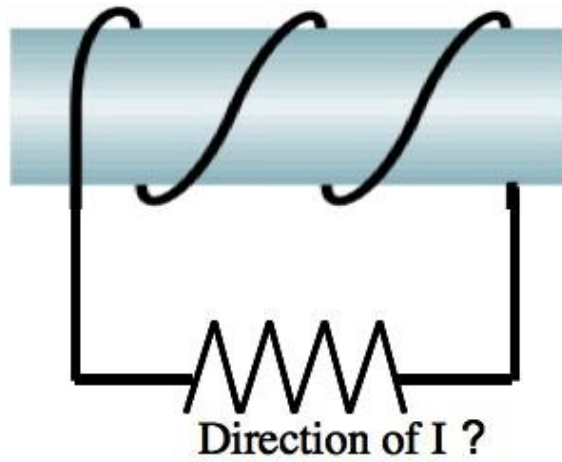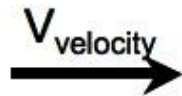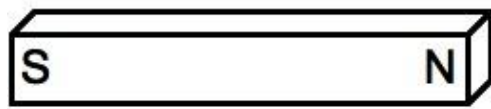
Now solve some "simple" applications of Lenz's Law and the right-hand screw rule for finding the current induced in a circuit with no source voltage present.

¿ 2-1

Direction of I ?

Your answer:

¿ 2-2

S   N

$V_{velocity}$
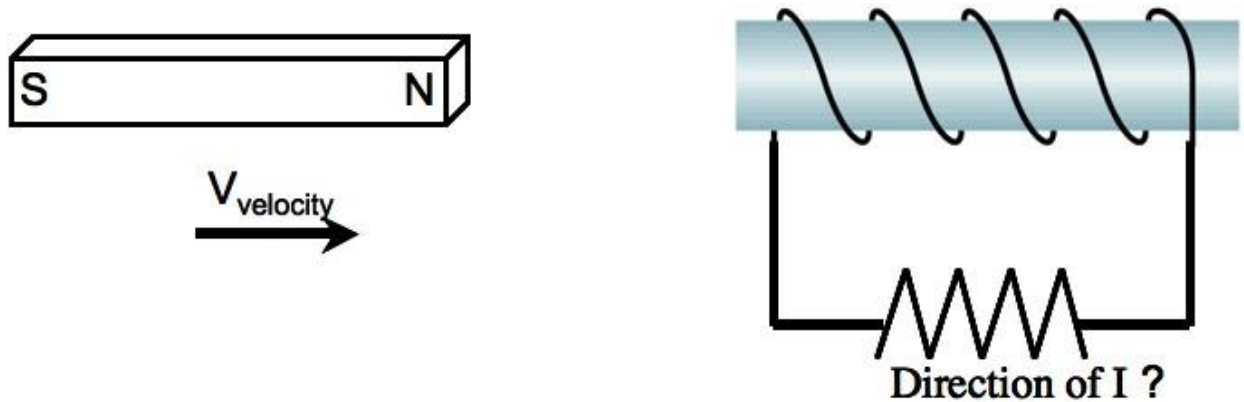
Direction of I ?

Your answer:

¿ 2-3

Direction of I ?

S   N

$V_{velocity}$
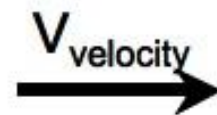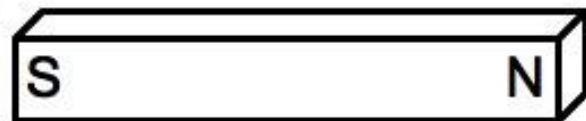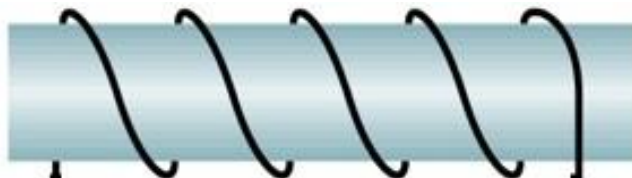
Your answer:

Your answer:

Technically speaking, Lenz's law is not necessary since its results are already implied by Faraday's law. But Lenz's law sure saves time!

In-Lab Section 3: induced solenoid voltage by external magnetic fields

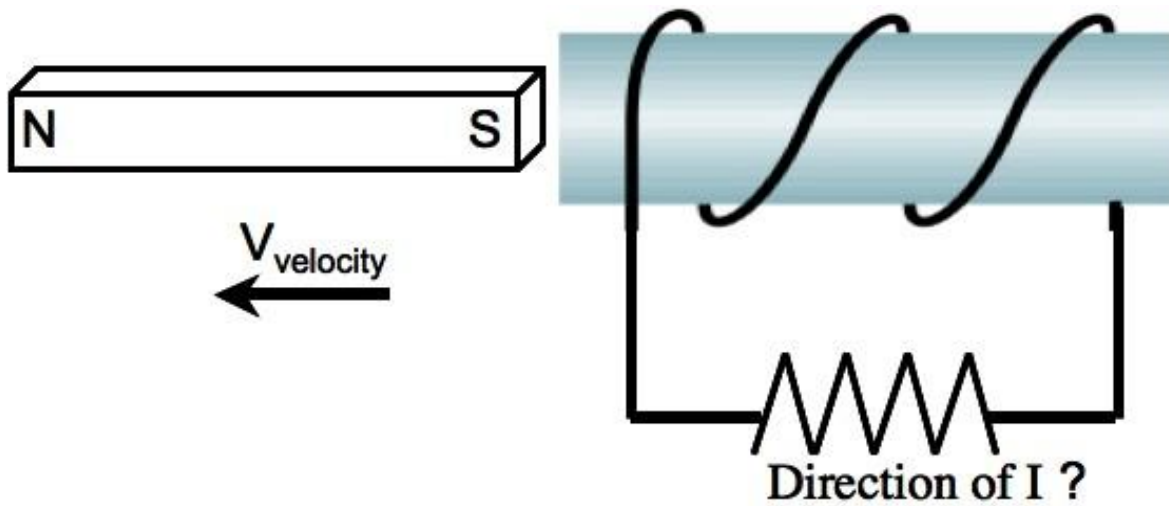Now you will experimentally observe how a changing magnetic field induces a voltage in an unpowered solenoid. Check your bar magnet with your compass to see that it is labeled correctly. Remember that the compass's needle labeled "north" should point to south magnetic poles (like the north geographic pole of the earth).

Hook up your unpowered solenoid directly to the oscilloscope by itself so you can measure the electric potential difference between both ends. Don't bother placing a resistor in series. Instead you will just examine the direction of the back EMF by checking the sign of the voltage across the solenoid caused by the back EMF.

¿ 3-1

Move the <u>north pole</u> slowly toward one side of your solenoid. Write what you see on your oscilloscope (positive or negative induced voltage). You should see some induced voltage or you are moving too slowly. Try using 500 ms/div and 50 mV/div to clearly see the response. Your observations:

¿ 3-2

Move the <u>north pole</u> quickly toward *same* side of your solenoid as in 3-1. Write what you see on your oscilloscope and compare the amplitude of the induced voltage with 3-1. Your observation and comparison:

¿ 3-3

Use the equation for Faraday's Law $\varepsilon_L = -\dfrac{d\phi_B}{dt}$ to explain why the amplitude 3-2 was larger than 3-1.

¿ 3-4

Now move the <u>south pole</u> quickly toward the *same* side of your solenoid as in 3-1 and 3-2. Write what you see on your oscilloscope and compare your result with that of 3-3. Your observation and comparison:

¿ 3-5

Use Lenz's Law to explain the difference between your observations in 3-3 and 3-4. Your explanation:

In-Lab Section 4: finding the mutual inductance

If you take a solenoid and drive it with an alternating current, it will produce an alternating magnetic field inside its coils. If you then take another solenoid that is unpowered and place it nearby so that the changing magnetic field of the first solenoid reaches inside the coils of the second solenoid, then a voltage will be induced in the second solenoid *despite the fact that the wires of each solenoid in no way touch each other*. This is the process of **mutual inductance** and is the basis of *transformers* in transmission lines.
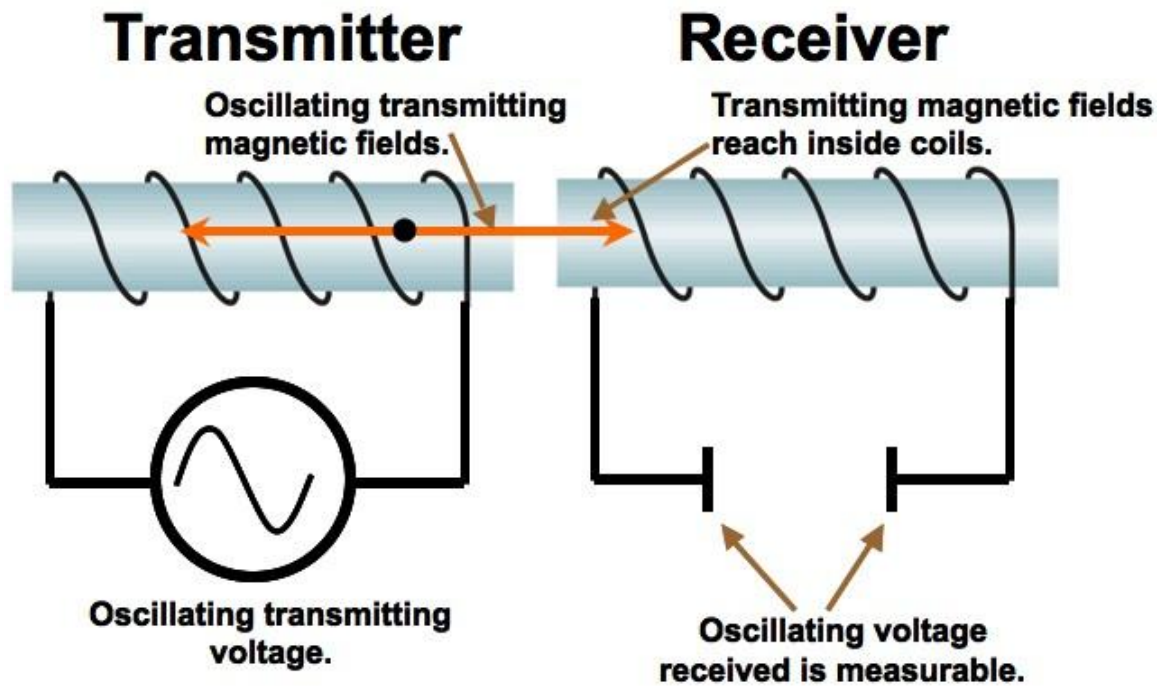
The definition of the **mutual-inductance** is:

$$M_{\substack{\text{transmitter} \\ \text{to receiver}}} = \frac{\varepsilon_{\text{receiver}}}{-\left(\dfrac{dI_{\text{transmitter}}}{dt}\right)}.$$

The mutual inductance parameter M can be used to encapsulate all the geometric information of the combined solenoids. It is used in engineering so that you can calculate the transmitted voltage from an applied current without having to calculate the magnetic field and geometric factors with a rearranged version $\varepsilon_{\text{receiver}} = -M_{\substack{\text{transmitter} \\ \text{to receiver}}} \cdot \dfrac{dI_{\text{transmitter}}}{dt}$ (measured in **[henries]** as with the self-inductance L).

The equation for M is true for all times so it is easiest to determine it experimentally using the time when the right hand side components have simultaneously reached their maximums:

$$M_{\substack{transmitter \\ to\ receiver}} = \frac{\varepsilon_{receiver,\ amplitude}}{\left(\dfrac{dI_{transmitter}}{dt}\right)_{amplitude}}$$

Some digital oscilloscopes can measure derivatives in which case you could determine the denominator using

$$\left(\frac{dI_{transmitter}}{dt}\right)_{amplitude} = \frac{1}{R}\left(\frac{dV_{resistor,\ transmitter}}{dt}\right)_{amplitude}.$$

If not, you would have to take the derivative yourself to find that

$$\left(\frac{dI_{transmitter}}{dt}\right)_{amplitude} = \frac{\omega}{R}V_{\substack{resistor,\ transmitter \\ amplitude}}.$$

Thus

$$M_{\substack{transmitter \\ to\ receiver}} = \frac{\varepsilon_{receiver}R}{-\omega V_{\substack{resistor,\ transmitter \\ amplitude}}}$$

This result can be used to experimentally determine the mutual inductance of combined solenoids.

Now you will experimentally study the process of mutual inductance. Use a function generator to drive a solenoid without any resistance. Use a sinusoidally oscillating source voltage of 5 [volts] amplitude. This solenoid is the *transmitter*. As the current oscillates in the solenoid's wire, an oscillating magnetic field is created inside the solenoid (due to Ampere's law).

Hook up the other undriven solenoid directly to the oscilloscope. This solenoid is essentially the *receiver*. It will detect the presence of *changing* magnetic fields just as you saw in section 3.

Place the solenoids together as close as possible so that you can measure the maximum induced voltage amplitude in the receiver. Placing soft iron inside the coils can increase the magnetic field inside the solenoids so that transmission is increased (this is done in most transformers including the giant transformers in power lines).

¿ 4-1

Make the necessary measurements to experimentally determine the mutual inductance M of your two combined solenoids.   {Record data and make calculations below.}

In-Lab Section 5: finding the self-inductance
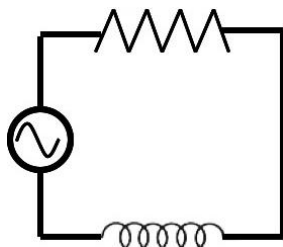
If you are examining an RL circuit driven by a sinusoidal voltage source, then you will obtain the following equations describing the voltages of the components. Notice the similarity to

$$V_{source}(t) = V_{source \atop amplitude} \sin(\omega_D t + \phi)$$

$$V_R(t) = \left(\frac{R}{Z}\right) V_{source \atop amplitude} \sin(\omega_D t)$$

$$V_L(t) = \left(\frac{X_L}{Z}\right) V_{source \atop amplitude} \sin\left(\omega_D t + \frac{\pi}{2}\right)$$

Compare to the RC circuit that is sinusoidally driven: $V_C(t) = \left(\frac{X_C}{Z}\right) V_{source \atop amplitude} \sin\left(\omega_D t - \frac{\pi}{2}\right)$.

Notice that unlike the sinusoidal capacitor voltage that leads the resistor voltage by $\pi/2$ in an RC circuit, the inductor voltage lags the resistor voltage by $\pi/2$ in an RL circuit.

χ_L is the inductive reactance of the solenoid and is given by $\chi_L = \omega_{drive} L$. Compare this to the capacitive reactance of the RC circuit: $X_C = \dfrac{1}{\omega_{drive} C}$. The inductive reactance of an RL circuit is directly proportional to the driving frequency.

¿ 5-1

If you increase the driving frequency in a sinusoidally driven RL circuit, does the voltage you measure across the inductor increase or decrease? What about the resistor? Explain your reasoning.

When you measure $V_{R, amplitude}$ = $\varepsilon_{L, amplitude}$, then you know that that $\chi_L = R$. If you find the frequency where this happens, you can use $\chi_L = \omega_{drive} L$ to find L by substituting R for χ_L:

$$L = \frac{R}{\omega_{drive}}.$$

¿ 5-2

Use this single measurement method to find L for your solenoid.

There is a second multi-measurement method to find L. The voltage amplitudes of the sinusoidally driven RL circuit are very similar to those for the sinusoidally driven RC circuit you encountered a few weeks ago:

$$V(t)_{\text{resistor}} = \frac{R}{Z} V_{\substack{\text{source} \\ \text{amplitude}}} \sin(\omega_{\text{drive}} t)$$

and

$$V(t)_{\text{inductor}} = \frac{\chi_L}{Z} V_{\substack{\text{source} \\ \text{amplitude}}} \sin\left(\omega_{\text{drive}} t + \frac{\pi}{2}\right).$$

This gives the following relationships for the amplitudes:

$$V_{\substack{\text{resistor} \\ \text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source} \\ \text{amplitude}}} \qquad \text{and} \qquad V_{\substack{\text{inductor} \\ \text{amplitude}}} = \frac{\chi_L}{Z} V_{\substack{\text{source} \\ \text{amplitude}}}.$$

Dividing these two equations gives

$$\frac{V_{\substack{\text{inductor} \\ \text{amplitude}}}}{V_{\substack{\text{resistor} \\ \text{amplitude}}}} = \frac{\left(\dfrac{\chi_L \cdot V_{\substack{\text{source} \\ \text{amplitude}}}}{Z}\right)}{\left(\dfrac{R \cdot V_{\substack{\text{source} \\ \text{amplitude}}}}{Z}\right)} = \frac{\chi_L}{R}.$$

Therefore,

$$\chi_L = R \frac{V_{\substack{\text{inductor} \\ \text{amplitude}}}}{V_{\substack{\text{resistor} \\ \text{amplitude}}}}.$$

In order to test the relationship $\chi_L = \omega_{\text{drive}} L$ and experimentally determine L for your solenoid, simply combine the last two equations:

$$\omega_{\text{drive}} L = R \frac{V_{\substack{\text{inductor} \\ \text{amplitude}}}}{V_{\substack{\text{resistor} \\ \text{amplitude}}}}.$$

Therefore if you graph

$$R \frac{V_{\text{inductor amplitude}}}{V_{\text{resistor amplitude}}} \quad \text{vs. } \omega_{\text{drive}},$$

you should obtain a linear graph with a slope equal to L.

¿ 5-3

Find L by collecting data for multiple driving frequencies, making a graph on separate graph paper and finding the slope. Make your observations and graph now. Then write your work and result for L:

In-Lab Section 6: authentic assessment

¿ 6-1

Use your solenoid to search for stray alternating magnetic fields in the lab. There are many strange high-frequency electromagnetic oscillations (radio waves) permeating the laboratory. Use an unpowered solenoid to detect the oscillating magnetic fields of these radio waves in order to measure the frequencies of these signals.

This is the perfect opportunity to learn the use of your oscilloscopes FFT (fast Fourier transfer) math function. The FFT math operation changes the time-axis to a frequency-axis. You may then adjust the frequency scale using the "seconds/div knob", zoom in using the "math > FFT zoom function", horizontally scan using the "horizontal shift knob". Show your results to a student in a different group:

"Yes, I have seen this student detect oscillating magnetic fields in the air."

Student Signature:_____

In-Lab Section 7: open-ended / creative design

Transformers in power lines use metal contained inside their solenoid coils to help increase the mutual inductance. Investigate what kinds of metals and shapes thereof help increase the mutual inductance in a transformer. Use two large solenoids for this, the function generator and your oscilloscope. Various test metal pieces are available in the lab. Take only one or two at a time and put them back immediately when you are done (i.e. share).

Sinusoidal electromagnetic waves (light) transmitted from one solenoid to another can be blocked by highly conducting objects. This is for the same reason that good conductors (metals) are shiny, they reflect light so it cannot pass. Investigate what kinds of metals are good or poor conductors using this effect. Use two large solenoids (with a gap between them) for this, the function generator and your oscilloscope. Metallic sheets are in one part of the room. Take only one or two at a time and put them back immediately when you are done.

Determine what shapes and metals placed inside solenoids maximize mutual inductance. Determine if stainless steel is a good or bad conductor.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the following page.

¿ 7-1

hypothesizing/planning:

¿ 7-2

observations/data:

¿ 7-3
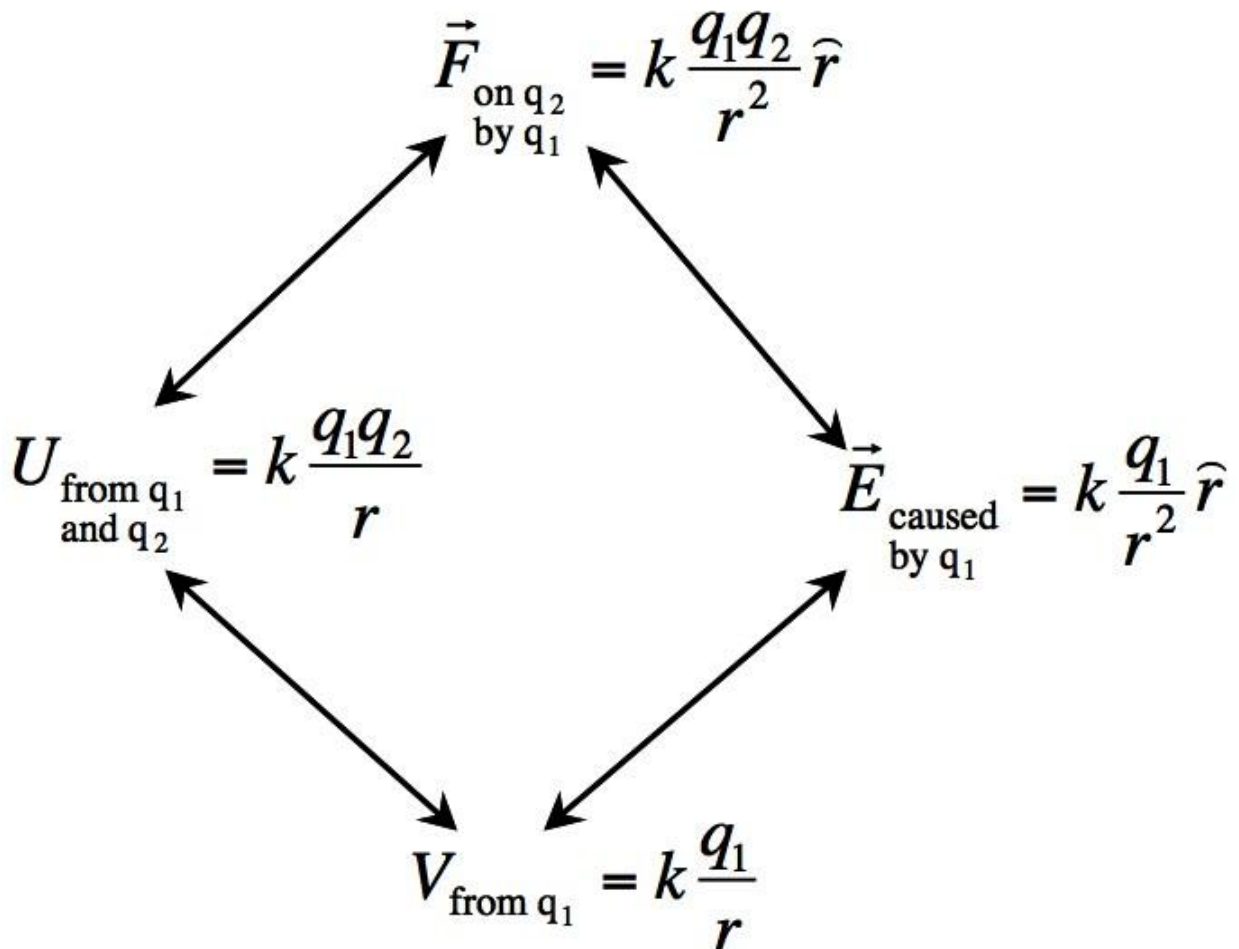
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! TA signature: _____

## Post-Lab: Solenoids - REVIEW PRACTICE WORK, ENERGY AND ELECTRIC POTENTIAL

! **You must complete this post-lab section after you attend your lab. You may work on this post-lab during lab if you have time and have finished all the other lab sections.**

The following picture is helpful for remembering how several concepts are related:

$$\vec{F}_{\substack{\text{on } q_2 \\ \text{by } q_1}} = k\frac{q_1 q_2}{r^2}\hat{r}$$

$$U_{\substack{\text{from } q_1 \\ \text{and } q_2}} = k\frac{q_1 q_2}{r}$$

$$\vec{E}_{\substack{\text{caused} \\ \text{by } q_1}} = k\frac{q_1}{r^2}\hat{r}$$

$$V_{\text{from } q_1} = k\frac{q_1}{r}$$

¿ X-1

The grid below is made of 1 [cm] squares. There are three charged objects on the grid.   Calculate the electrical potential energy associated with this configuration of charge (SI units).
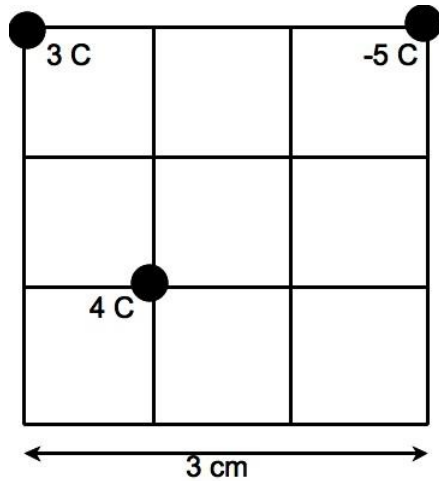
¿ X-2

Now calculate the potential energy associated with the configuration of the three previous charges and with one other charge q given as a variable. Write your answer given in terms of the variable q. (Hint: use your previous answer to save time.)
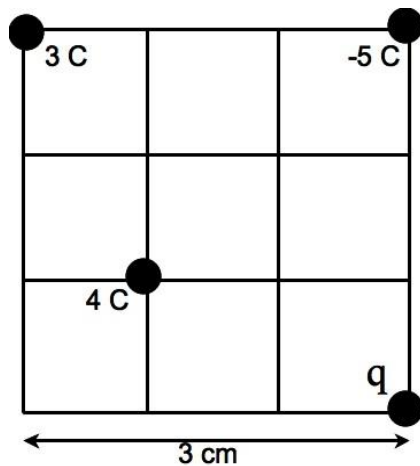
¿ X-3

Calculate the *electric potential* at the location of charge q created by the other three given charges. (Hint: your answer should be a number in SI units.)

¿ X-4

Using your answer from the previous question in a slick way; find the amount of work required to bring charge q from infinity to the position depicted. Write your answer given in terms of the variable q.

The lesson to be learned from the previous questions is that the total potential energy of a system of charges is equal to the work needed to bring **all** the charges together from infinity. This is different from the work done to bring one charge from infinity to where other charges have already been assembled. Therefore, $\Delta U_{total} \neq q\Delta V$. Use these ideas to more fully explain the two equations below.

¿ X-5

Explain the meaning of the equation: $\Delta U_{total} = W_{\substack{assemble \\ system}}$

¿ X-6

Explain the meaning of the equation: $q \cdot \Delta V = W_{\substack{on\ test\ charge\ q \\ by\ inital\ system}}$