Chapter 21

Electromagnetic induction

21.1 Inducing an electric current

21.1.1 Observe and find a pattern

PIVOTAL Lab: *Equipment per group:* whiteboard, markers, a coil with many turns, a bar magnet, and a galvanometer (or a multimeter).

a. Examine the equipment that you have on your desk. The galvanometer registers current through the coil. It needs to be connected to the coil (with no battery). Now that you have connected the galvanometer to the coil, work with your group members to figure out what you can do to make the galvanometer register current through the coil. Once you found one way, look for others so that at the end you can formulate a pattern for the cases in which the current is induced. Describe your experiments and findings with words and sketches.

b. Develop a rule: Devise a preliminary rule that summarizes the condition(s) needed to induce a current in a coil. What are the assumptions that you made?

c. Now that you found your own way to induce electric current in the coil, watch the video with the experiments and compare them to the ones you designed.
[https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-1-1]

21.1.2 Test and revise your idea

PIVOTAL Lab: *Equipment per group:* 2 coils, a battery or variable power supply, a galvanometer, a switch.

Working with your group, connect one coil (coil 1) to a battery/power supply and put the switch in the circuit. Connect the other coil (coil 2) to the galvanometer. Work with your group members to implement the following experiments to test the pattern that you invented in Activity 21.1.1. **Caution! Never connect the galvanometer to the battery or power supply. It will be burned.**

Experiment 1. Use the rule devised in Activity 21.1.1 part **b**. to predict what will happen if you move coil 1 relative to coil 2.

a. Describe the experiments in words and sketches and make the predictions of their outcomes using the rule you invented in Activity 21.1.1.

b. Conduct the experiments and record the outcomes.

c. Make a judgment concerning the rule that you're testing. If necessary, revise your rule to incorporate your new findings. Note that your revised rule should be consistent with *all* the experiments you've conducted up to this point.

Experiment 2. Use your current rule to predict what will happen if you place a coil connected to a galvanometer next to the coil connected to the battery/power supply (so that axis of the coils coincide) and (1) close the switch without moving either coil, then (2) let the current run for a period of time, and then (3) open the switch.

d. Describe the experiments in words and sketches and make the predictions of their outcomes using the rule you invented in Activity 21.1.1.

e. Conduct the experiments and record the outcomes.

f. Make a judgment concerning the rule that you're testing. If necessary, revise your rule to incorporate your new findings. Note that your revised rule should be consistent with *all* the experiments you've conducted up to this point.

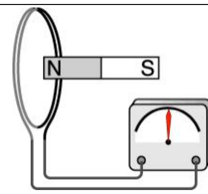
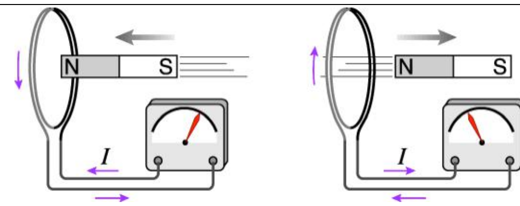
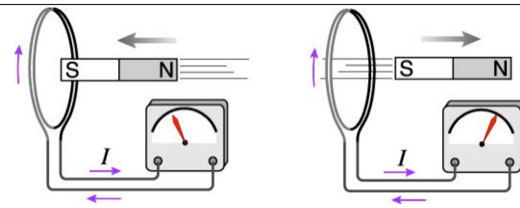
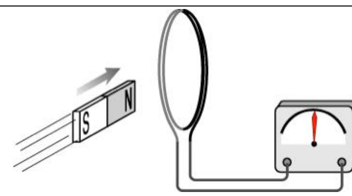
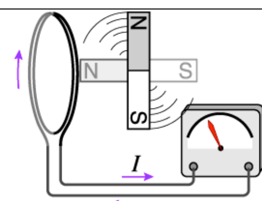
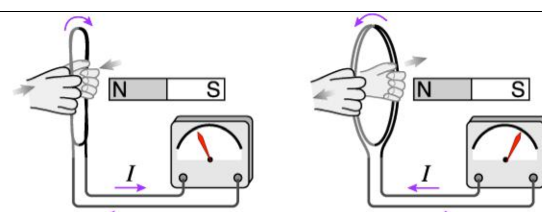
g. Now watch the videos of similar experiments. Can you predict their outcomes using the rule you just tested? [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-21-1-2]

21.1.3 Observe and find a pattern

Class *(alternative to Activities 21.1.1–21.1.3): Equipment per group:* whiteboard, markers.

The table that follows describes six experiments involving a galvanometer, a bar magnet, and a coil.

a. Observe your instructor perform the experiments and record the outcome of each experiment on your whiteboard.

Experiment	**Illustration**
Experiment 1: Hold the magnet motionless in front of the coil, with any orientation.	
Experiment 2: Hold the magnet perpendicular to the coil with the N pole facing the coil. Move the magnet quickly toward the coil. Then pull it away quickly.	
Experiment 3: Repeat experiment 2, but this time with the S pole facing the coil.	
Experiment 4: Align the magnet in the same plane as the coil, and move either pole toward or away from the coil.	
Experiment 5: Hold the magnet in front of the coil and rotate it 90° as shown. (The magnet starts out perpendicular to the coil and ends up parallel to it.)	
Experiment 6: Position the magnet as in experiment 2, but this time grasp the sides of the coil and collapse the coil quickly. Then pull it back open.	

b. Working with your group members, devise a rule that summarizes the conditions that are necessary to induce a current in a coil.

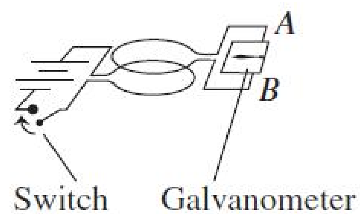
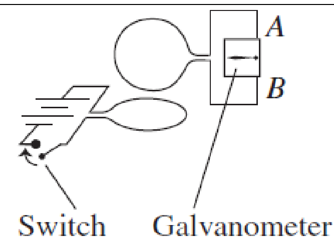
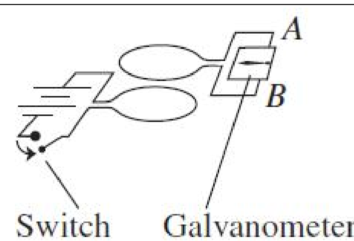
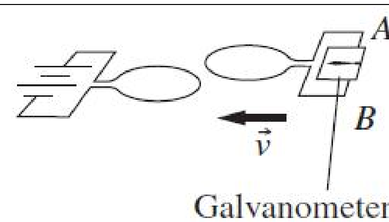
21.1.4 Test your idea

***Class** (alternative to Activities 21.1.1–21.1.3) Equipment (single demo set-up for the class):* 2 coils, one power supply, galvanometer, switch. *Equipment per group:* whiteboard, markers.

Four experiments using a galvanometer, a switch, and a coil are described in the table that follows. Use the rule you devised in Activity 21.1.4 to predict whether there should be an induced current in the coil that is connected to the galvanometer.

a. Working with your group, create a table on your whiteboard: For each experiment predict the outcome based on the rule you devised in Activity 21.1.4. Then record the actual outcome of the experiment next to each prediction.

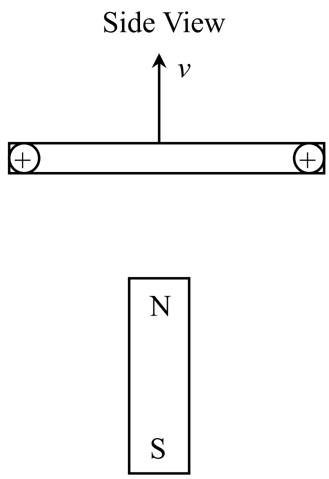
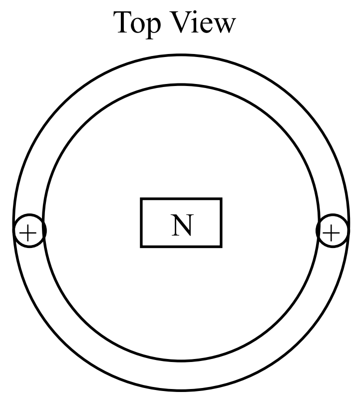
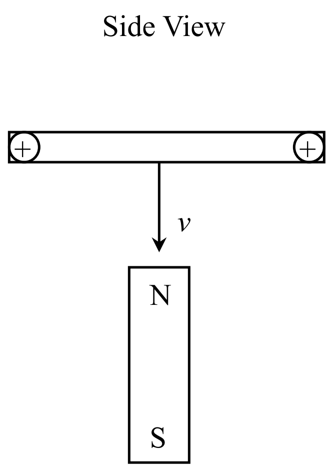
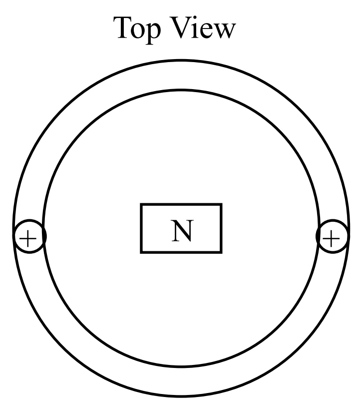
b. Compare the predictions with the actual outcomes. If necessary, revise the rule you developed in Activity 21.1.4.

Experiment	**Illustration**
Experiment 1: The current in the lower coil increases just after the switch is closed.	
Experiment 2: The current in the lower coil increases just after the switch is closed. The coils are perpendicular.	
Experiment 3: The current in the lower coil decreases just after the switch is opened.	
Experiment 4: There is a steady current through the left coil as the right coil moves toward and above the left coil.	

21.1.5 Observe and explain

Class: *Equipment per group:* whiteboard, markers.

In this activity your group will develop a microscopic explanation for the phenomena you've observed in the previous activities. Work with your group on a whiteboard through the steps described below:

	
a. A loop of wire is moving up away from the magnet at a speed *v*. Draw the magnetic field created by the magnet passing through the loop at the instant shown.	**b.** The same loop is moving up, away from the magnet but viewed from above. Draw the force exerted on each of the charges shown in the loop.
	
c. A loop of wire is moving down towards the magnet at a speed *v*. Draw the magnetic field created by the magnet passing through the loop at the instant shown.	**d.** The same loop is moving down, toward the magnet but viewed from above. Draw the force exerted on each of the charges shown in the loop.

e. Discuss with your group members: does this microscopic view explain why a current is induced in the coil?

21.1.6 Reading exercise

Read Section 21.1 in the textbook and answer Review Question 21.1.

21.2 Magnetic flux

21.2.1 Observe and find a pattern

PIVOTAL Lab: *Equipment per group:* whiteboard, markers, coils with different diameters and different numbers of turns, 2-3 bar magnets, a galvanometer (or a multimeter).

By now, your group has figured out how to use a magnet to induce a current in the coil. Your goal for this experiment is to devise a qualitative rule that relates the *magnitude* of induced current to the properties of the magnet, the motion of the magnet, and the properties and the orientation of the coil.

a. Come up with as complete a list as possible of possible factors that might affect the magnitude of the current induced in the coil. Then conduct the experiments to instigate those factors.

b. Briefly describe your experiments using sketches and words.

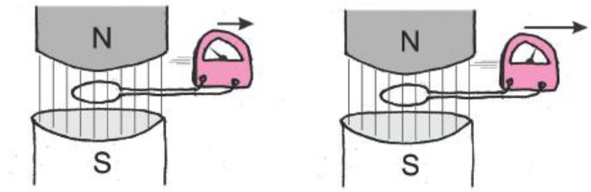
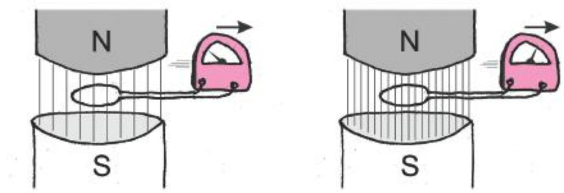
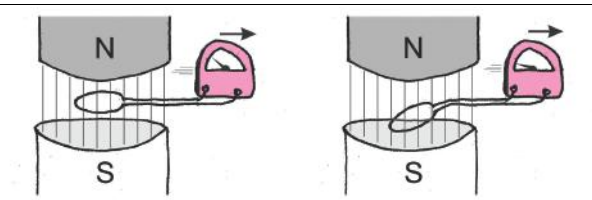
c. Describe the outcomes of your experiments.

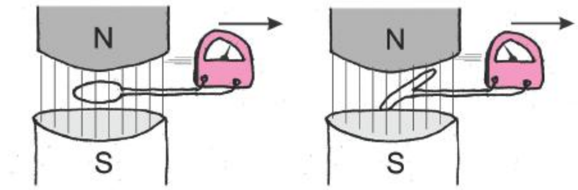
d. Use your experiments and any other information you have to devise qualitative rules (in words) that relate the magnitude of induced current to other factors. Are there any assumptions that must be made for your rule to work?

21.2.2 Observe and find a pattern

Class *(alternative to 21.2.1): Equipment per group:* whiteboard, markers.

The table that follows describes five new experiments using a galvanometer, an electromagnet, and a coil. The outcomes of the experiments are included.

Experiment	**Illustration**	**Outcome**
a. Position a coil so that the $\vec{B}$ field lines are perpendicular to it and move it slowly out of the magnetic field. Repeat the experiment, moving the coil quickly.		The quicker the coil's motion, the larger the induced current.
b. Position the magnet and the coil as in experiment **a**. and move the coil slowly out of the magnetic field. Repeat the experiment using a stronger magnet.		A stronger magnet induces a stronger current in the coil compared to a weaker magnet when the coils move at the same speed with respect to the magnet.
c. Position a magnet perpendicular to the coil and the coil as in experiment **a**. and move the coil slowly out of the magnetic field. Then position the coil so that the plane of the coil makes some other angle with the $\vec{B}$ field lines. Keep the speed the same.		When the $\vec{B}$ field lines are perpendicular to the plane of the moving coil, the strongest current is induced.

Experiment	**Illustration**	**Outcome**
d. Use two identical coils. Fold part of the wire of one coil to make a loop with a smaller area (see the figure). Position each coil and the magnet as in experiment **a**. Move the coils out of the magnetic field at the same speed with respect to the magnet.		A stronger current is induced in the coil with the larger area.

Work with your group members to devise a mathematical expression that relates the *magnitude* of the induced current to various properties of the magnetic field, relative motion of the coil with respect to the magnet, and properties of the coil.

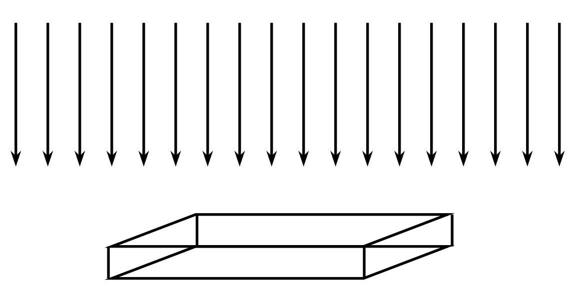
21.2.3 Reason

PIVOTAL Class: *Equipment per group:* whiteboard, markers.

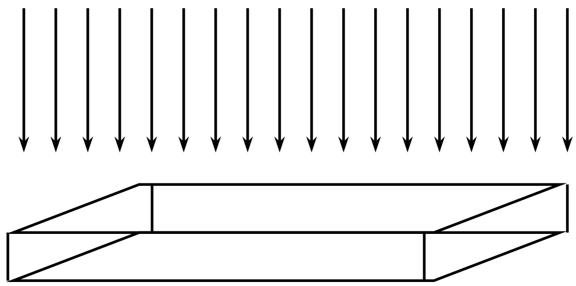
Imagine that rain is falling at a rate of 100 drops per second, per square meter (100 drops/s/m^2).

a. In each of the following three scenarios, work with your group members on a whiteboard to estimate how much rain (in units of drops) you will collect in 1 minute in the box. You should assume the rain falls vertically.

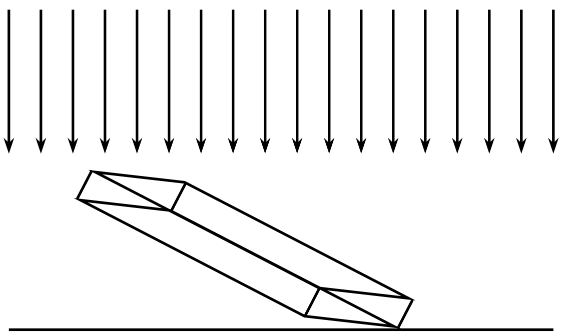
Scenario 1: Box is 2 m wide, 1 m long.



Scenario 2: Box is 3 m wide, 2 m long



Scenario 3: Box is 2 m wide, 1 m long, and tilted 30° above the horizontal. (Ignore any issue of spillage).

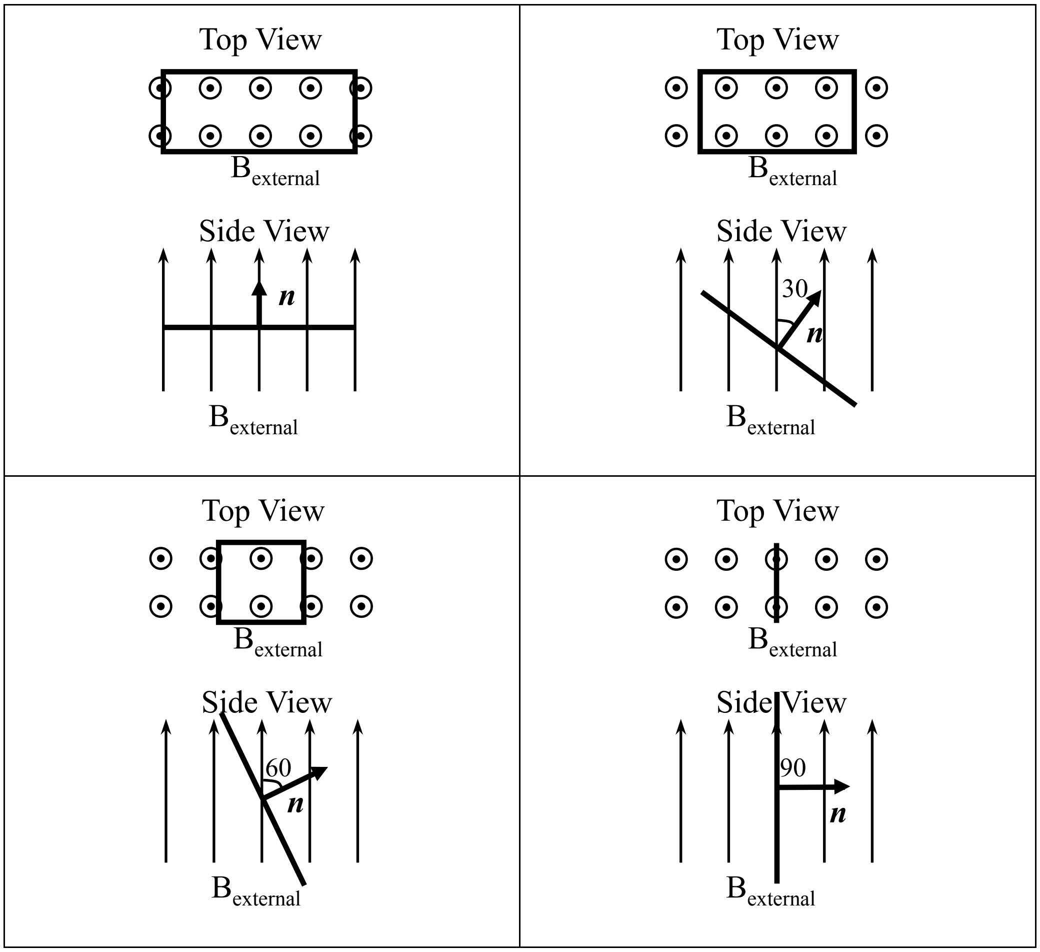


b. Discuss with your group: How would you adjust your answers if the rain was not falling vertically, but, say, at an angle of 60° to the vertical (assume that in the Scenario 3 the rain falls perpendicularly to the box bottom)?

21.2.4 Represent and Reason

PIVOTAL Class: *Equipment per group:* whiteboard, markers.

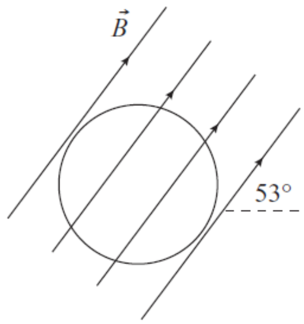
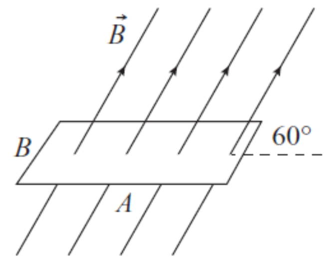
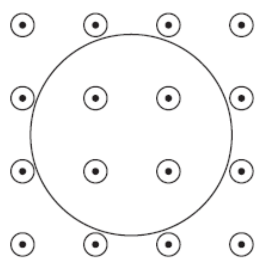
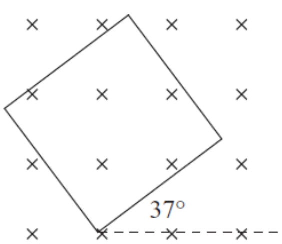
Collaborate with your group to calculate the flux of magnetic field lines passing through the rectangular loop in each of the cases shown below. The loop has dimensions *L* m long by *W* m wide. The magnitude of the $\vec{B}_{\text{external}}$ field is B_{external} (in T). Leave your answer in terms of *L, W,* B_{external} and $\cos\theta$.



21.2.5 Reason

***PIVOTAL* Class:** *Equipment per group:* whiteboard, markers.

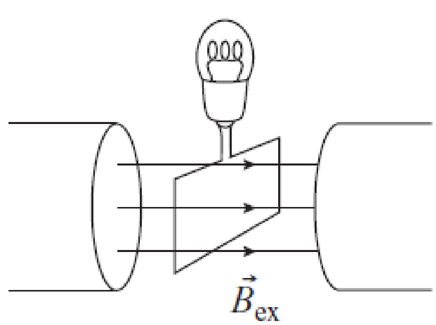
The magnitude of the $\vec{B}$ field in each situation described below is 0.50 T. For each situation in this table, working with your group members, calculate the magnetic flux through the loop.

Situation	**Situation**
Loop and $\vec{B}$ in the plane of the paper. The radius of the circular loop is 5.0 cm. 	Loop perpendicular to the paper and $\vec{B}$ in the plane of the paper. Side A = 0.2 m, side B = 0.1 m. 
Loop in the plane of the paper $\vec{B}$ out of paper. The radius of the circular loop is 5.0 cm. 	Square loop of side A = 0.1 m in the plane of the paper. $\vec{B}$ into the paper. 

21.2.6 Evaluate the solution

Class: *Equipment per group:* whiteboard, markers.

The problem: The magnetic field through the square coil shown in the figure below is at first steady and large (there are many turns in the coil, but only one is shown). The field then decreases to zero in about 1.0 s. A bulb connected to the ends of the coil indicates an induced current in the circuit. When are you most likely to observe light from the bulb?



Proposed solution: A steady light will come from the bulb when the field is steady and large. The brightness of the light will decrease as the field decreases. There is no light when the magnetic field becomes zero.

a. Work with your group members to identify any errors in the proposed solution.

b. Provide a corrected solution if there are errors.

21.2.7 Reading exercise

Read Section 21.2 in the textbook and answer Review Question 21.2.

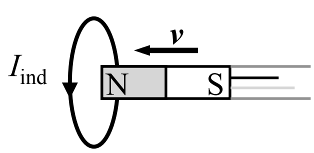
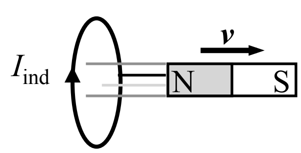
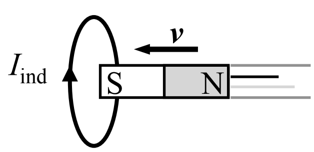
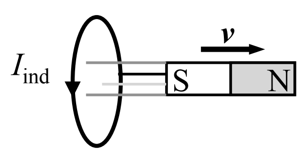
21.3 Direction of the induced current

21.3.1 Observe and find a pattern

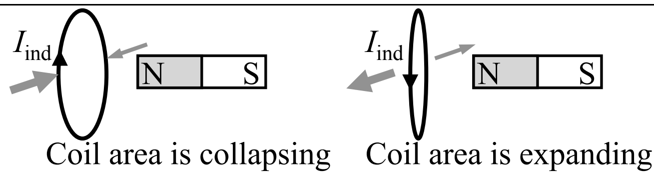
PIVOTAL Class: *Equipment per group:* whiteboard, markers.

The experiments below repeat earlier experiments that used a galvanometer, a bar magnet, and a coil and in which a current was induced. The direction of the induced current is shown in the illustrations.

a. Work with your group members to discuss and analyze the 6 experimental scenarios in the table below. For *each* case, on your whiteboard, draw $\vec{B}_{\text{ext}}$ field vectors through the coil caused by the moving magnet. Indicate whether the external B field vectors through the coil are decreasing or increasing in length. Draw induced magnetic field vectors $\vec{B}_{\text{ind}}$ created by the induced current in the coil.

Experiments:	
	
	

Experiments:

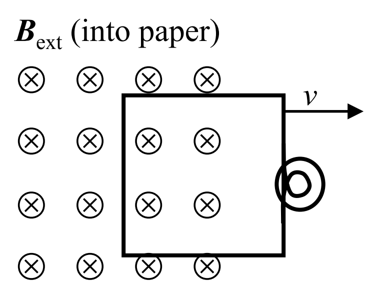


b. Use the data on your whiteboard to devise a rule relating the direction of the induced current in the coil and the change of external magnetic flux through it. *Hints:* (1) Focus on the direction in which $\vec{B}_{ext}$ is changing rather than the direction of $\vec{B}_{ext}$ itself. (2) Compare the direction of the induced magnetic field vectors $\vec{B}_{ind}$ in relation to $\Delta\vec{B}_{ext}$.

c. With your group, formulate a general rule: How does the direction of the induced current in a coil relate to the *change* of external magnetic flux through it?

21.3.2 Practice

PIVOTAL Class: *Equipment per group:* whiteboard, markers.

Work with your group to carefully follow the steps below in the order presented to determine the direction of an induced current using Lenz's rule. In this particular example, you are pulling a coil out of a region with an external magnetic field that points into the paper (the crosses).	

a. Redraw the diagram on your whiteboard. Identify the external magnetic field, $\vec{B}_{ext}$, and decide if the external magnetic flux through the loop is increasing or decreasing as the coil moves.

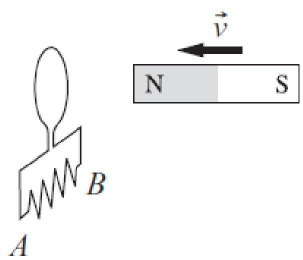
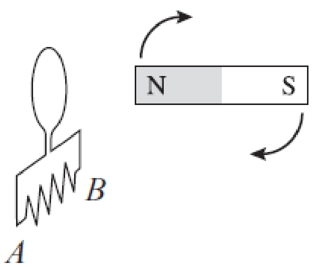
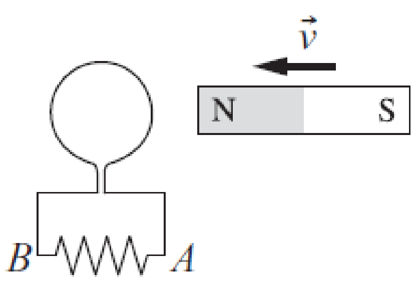
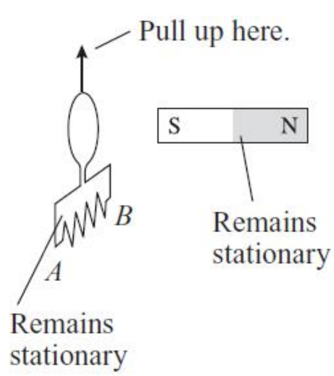
b. Draw the induced magnetic field inside the coil, $\vec{B}_{ind}$, so that it *opposes the change* in external magnetic flux through the loop. Think about how $\vec{B}_{ind}$ can *oppose* an increase or decrease in external magnetic flux.

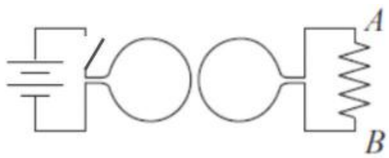
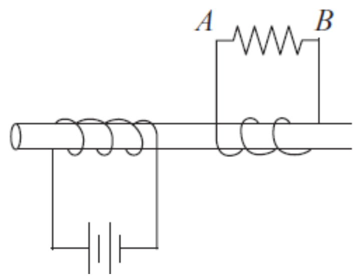
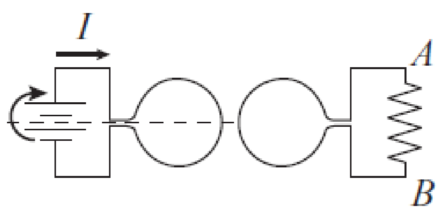
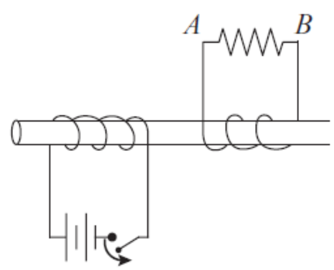
3. Use the right-hand rule for the direction of a magnetic field created by a current to determine the direction of the induced current I_{ind}. I_{ind} must circulate to create $\vec{B}_{ind}$. Curl your fingers in the direction of $\vec{B}_{ind}$ so that your thumb is aligned with one of the wires, and look at the direction of your thumb: That is the direction of I_{ind}. Draw the direction of I_{ind} on your diagram.

21.3.3 Reason

PIVOTAL Class: *Equipment per group:* whiteboard, markers.

For each situation shown in the table that follows, work with your group members to predict whether a current is induced through the resistor attached to the loop. Explain your prediction. If a current is induced, indicate the direction of that induced current. Put your work on a whiteboard and compare with another group.

Experiments	
a. The loop is perpendicular to the page.  	**b.** The loop is perpendicular to the page and the magnet turns 90°. 
c. The loop is in the plane of the page.  	**d.** The loop, perpendicular to the page, is pulled upward so that it collapses. 

Experiments	
e. The switch in the left circuit is closed, and the current increases abruptly. 	**f.** There is a steady current in the left circuit. The rod is made of iron. 
g. The circuit on the left is rotated 90°. 	**h.** The switch in the left circuit is opened, and the current decreases abruptly. The rod is made of iron. 

21.3.4 Real-world application

PIVOTAL ***Class:*** *Equipment (1 class demo):* copper pipe, neodymium magnet. *Equipment per group:* whiteboard, markers.

With your group, observe what happens to the magnet when it is dropped down the pipe. Describe as clearly as possible what you see. Then use your understanding of induction to try and come up with an explanation for why the magnet behaves the way it does. Develop your explanation on a whiteboard and share it with another group. Here are some hints:

a. Think of the copper pipe as many loops of wire that the magnet passes through as it falls.

b. Focus your analysis on two particular points on the pipe: Imagine a loop that the front end of the magnet is moving toward but has not passed through yet. Think about which way the induced current in that loop would circulate. Then think about a loop above the magnet, which the back end of the magnet is exiting. Think about which way the inducted current in that loop would circulate.

c. In what way does a loop of wire with a current through it look like a bar magnet?

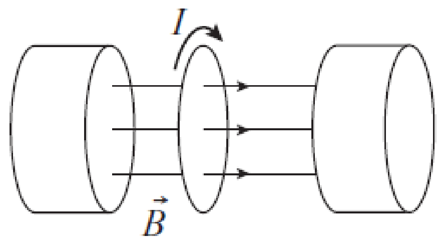
21.3.5 Reading exercise

Read Section 21.3 in the textbook and answer Review Question 21.3.

21.4 Faraday's law of electromagnetic induction

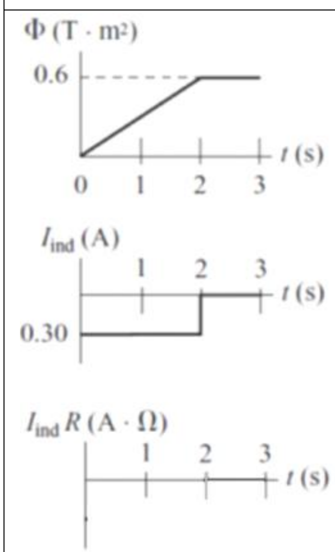
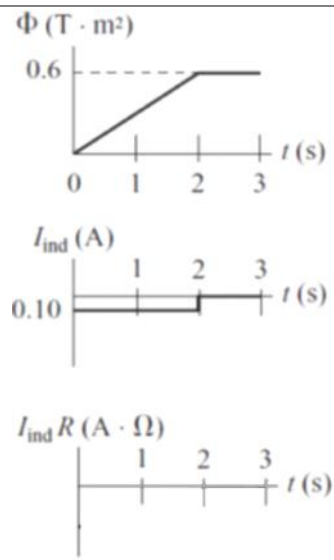
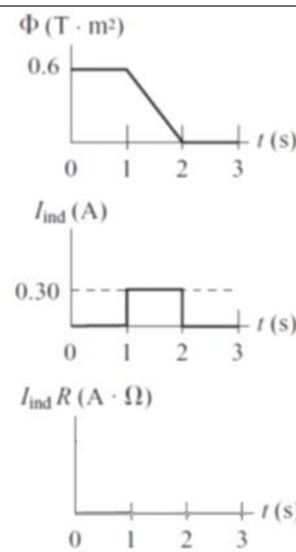
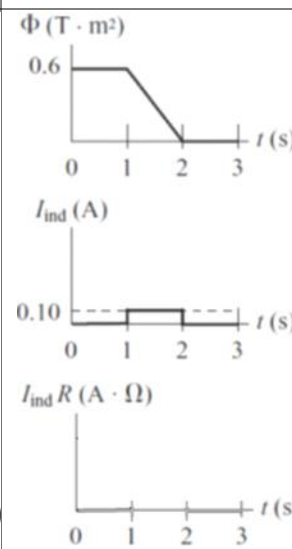
21.4.1 Observe and explain

***PIVOTAL* Class:** *Equipment per group:* whiteboard, markers.



In the table that follows, the results of four experiments are shown in which a changing magnetic field produced by an electromagnet passes through a loop, as illustrated to the right. This changing $\vec{B}$ field causes a changing flux Φ through the loop and an induced current I_{ind} around the loop of resistance R. The product $I_{\text{ind}}R$ is also plotted as a function of time.

a. Collaborating with your group, draw the third graph that shows the product $I_{\text{ind}}R$.

Coil resistance is 1.0 Ω	**Coil resistance is 3.0 Ω**	**Coil resistance is 2.0 Ω**	**Coil resistance is 6.0 Ω**
			

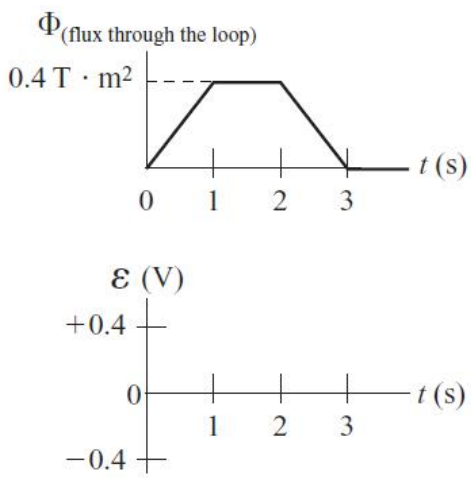
b. Discuss what the meaning of the product $I_{\text{ind}}R$ is and which equivalent quantity this product may represent. Then devise a relationship between $\frac{\Delta\Phi}{\Delta t}$ and that quantity. Do not forget the sign!

21.4.2 Represent and reason

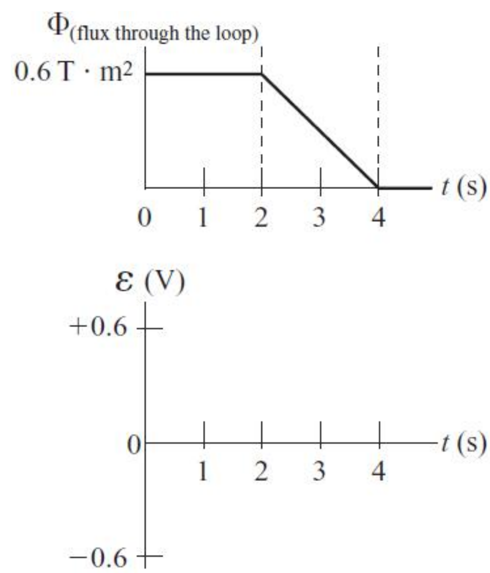
Class: *Equipment per group:* whiteboard, markers.

Four situations are shown in which the external flux through a loop is plotted as a function of time. In the table that follows, draw another graph that shows the induced emf in the loop as a function of time.

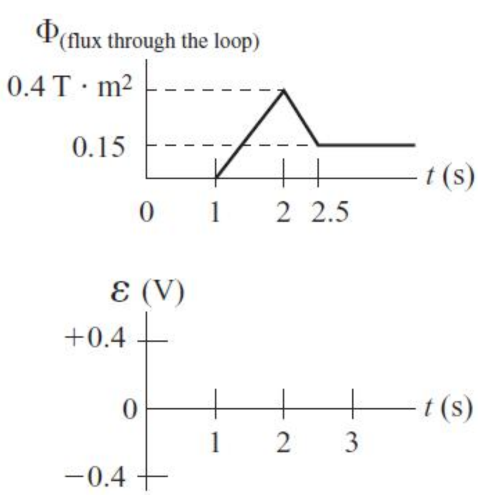
Situation 1



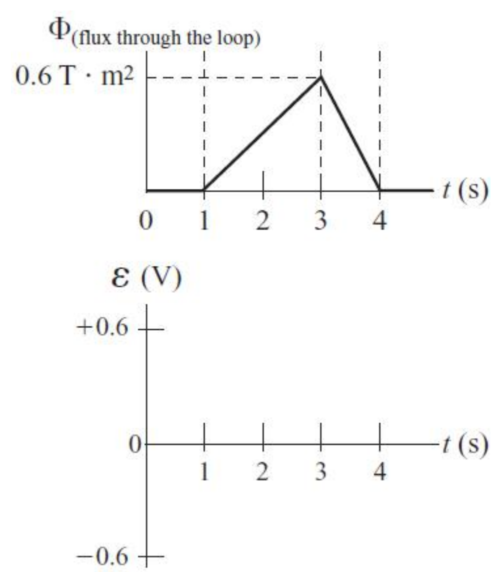
Situation 2



Situation 3



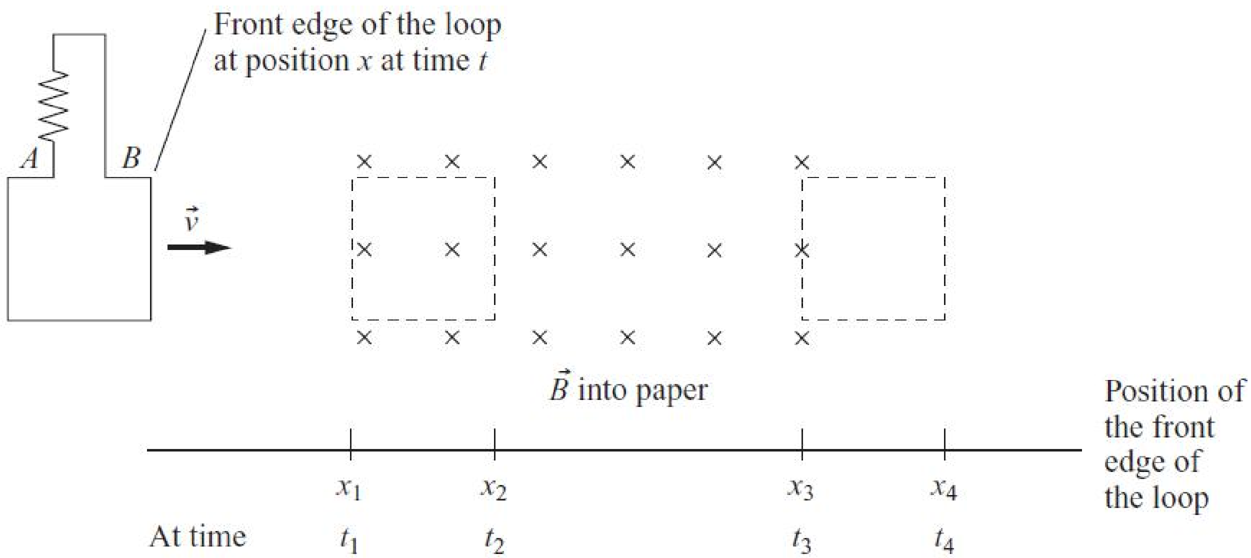
Situation 4



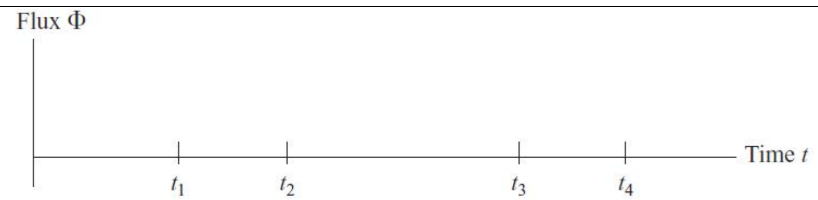
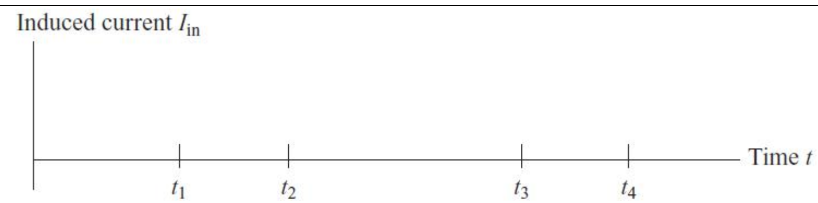
21.4.3 Represent and reason

PIVOTAL Class: *Equipment per group:* whiteboard, markers.

A rectangular loop with a resistor is pulled at constant velocity through a uniform external magnetic field that points into the paper in the regions shown in the illustration with the crosses (×).



Working with your group-mates on a whiteboard, plot graphs of flux and induced current versus time, consistent with the process above.

a. Draw a qualitative flux-versus-time graph for the process (positive in and negative out).	
b. Draw a qualitative induced current-versus-time graph for the process.	

21.4.4 Reading exercise

Read Section 21.4 in the textbook and answer Review Question 21.4.