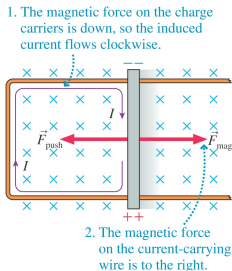
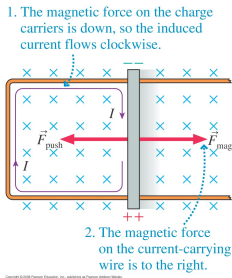


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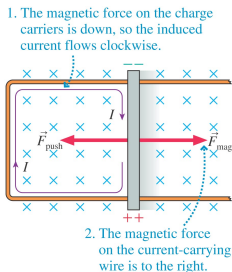
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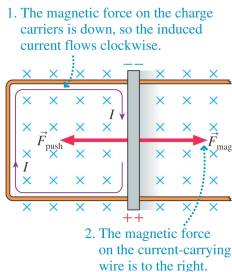
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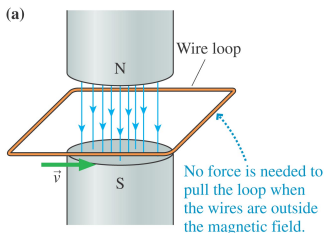
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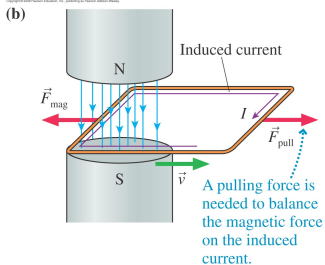


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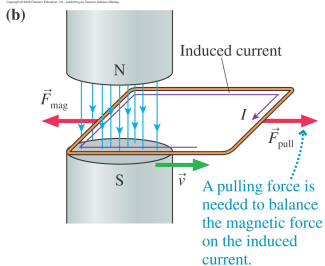
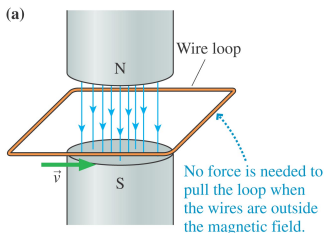
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- In the top left figure there is no magnetic force on the wire as no magnetic field goes through the copper.

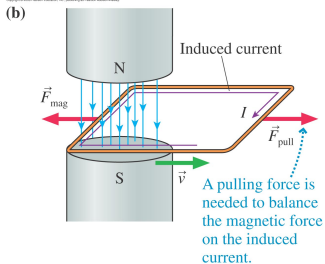
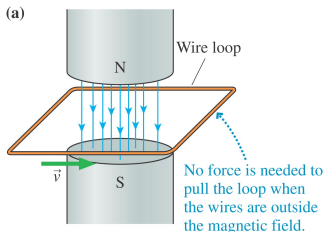


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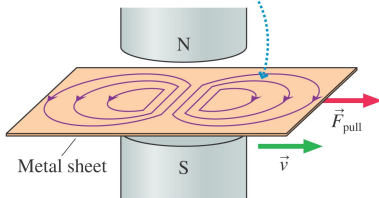
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- The induced current then generates a magnetic force which opposes the motion. So, to get the wire out of the field, you may have to pull pretty hard.

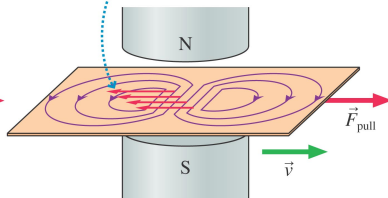
# Eddy Currents

- (a) Eddy currents are induced when a metal sheet is pulled through a magnetic field.



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- (b) The magnetic force on the eddy currents is opposite in direction to  $\vec{v}$ .



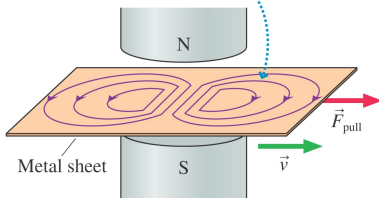
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- If you drag a sheet of metal through a magnet then a current is induced but there is no wire to define their path.

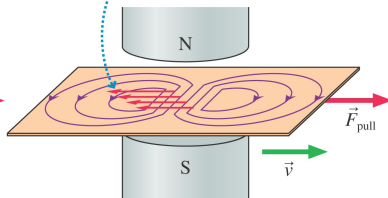


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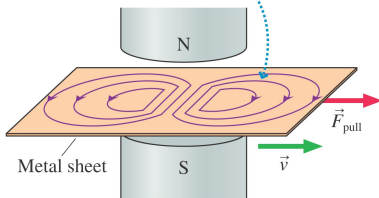
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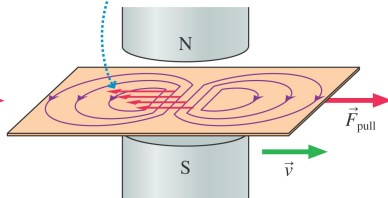
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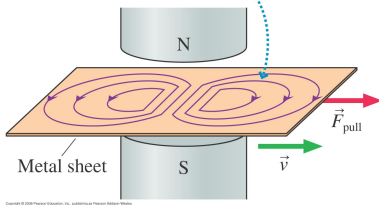
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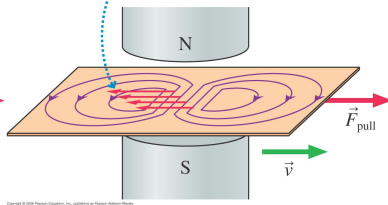
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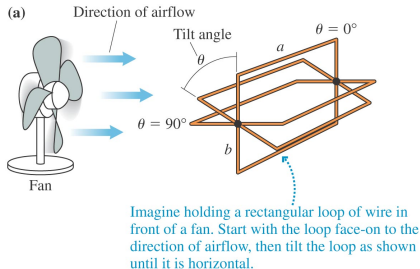


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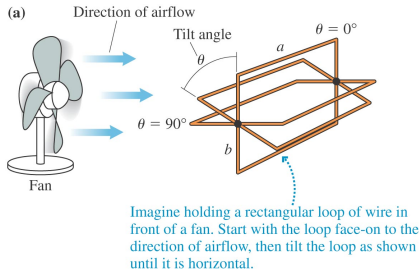
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- Whirlpools of current form called **eddy currents**.
- Again, a magnetic force is produced which opposes the motion. So, it is difficult to push a sheet of metal through a magnetic field.
- This is undesirable if you wish to pull some metal quickly through a field but very desirable if you want to use magnetic braking.

# Magnetic Flux (34.3)



- We have already seen the concept of flux with electric fields and Gauss' Law.

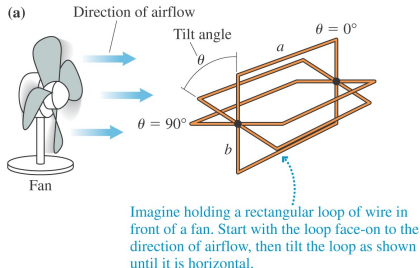
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# Magnetic Flux (34.3)



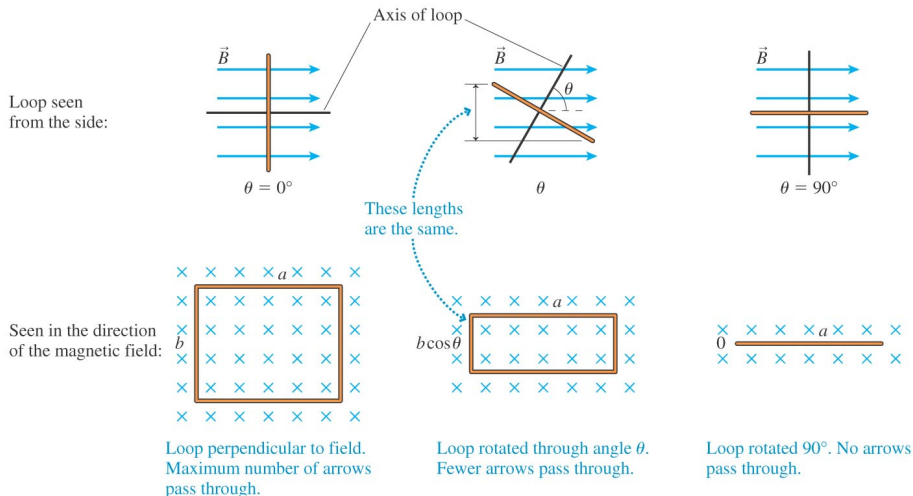
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- We have already seen the concept of flux with electric fields and Gauss' Law.
- It is also possible to define flux of a magnetic field in the same way.
- Again we picture magnetic field lines like airflow through the loop of current. The effective area of the loop is

$$A_{\text{eff}} = ab \cos \theta = A \cos \theta$$

So, no air flows through at  $90^\circ$  and maximum flow is at  $0^\circ$ .

# Magnetic Flux (34.3)



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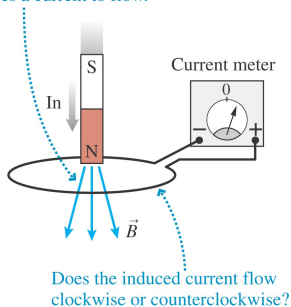
$$\Phi_m = AB \cos \theta$$

- Now, if we define an area vector  $\vec{A}$  perpendicular to the loop and of magnitude  $A$ , we can write this as

$$\Phi_m = \vec{A} \cdot \vec{B}$$

# Lenz's Law (34.4)

A bar magnet pushed into a loop increases the flux through the loop and induces a current to flow.



- Pushing a bar magnet into a loop induces a current in the loop.

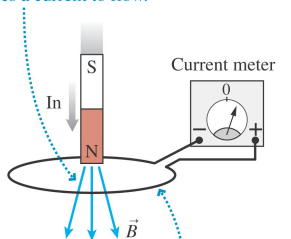
## Lenz's Law

There is an induced current in a closed conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the **change** in flux.

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# Lenz's Law (34.4)

A bar magnet pushed into a loop increases the flux through the loop and induces a current to flow.



Does the induced current flow clockwise or counterclockwise?

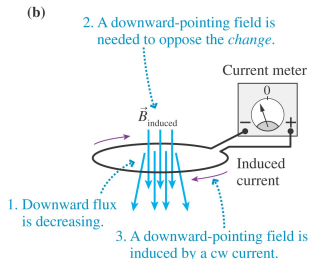
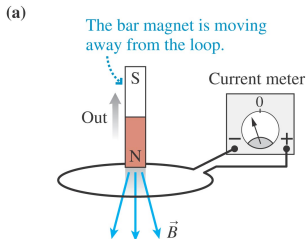
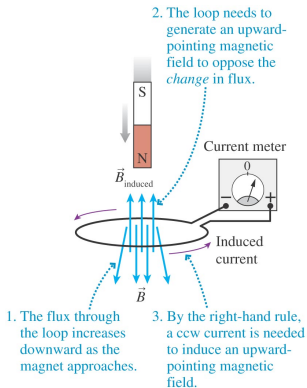
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- Pushing a bar magnet into a loop induces a current in the loop.
- Pulling it back out induces a current in the opposite direction.

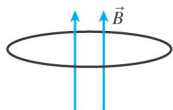
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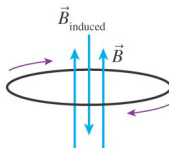
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No induced current

**$\vec{B}$  up and steady**

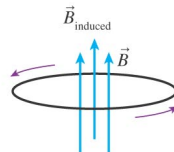
- No change in flux
- No induced field
- No induced current



Induced current

**$\vec{B}$  up and increasing**

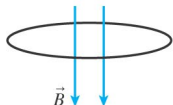
- Change in flux  $\uparrow$
- Induced field  $\downarrow$
- Induced current cw



Induced current

**$\vec{B}$  up and decreasing**

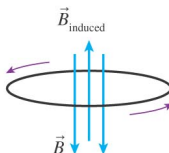
- Change in flux  $\downarrow$
- Induced field  $\uparrow$
- Induced current ccw



No induced current

**$\vec{B}$  down and steady**

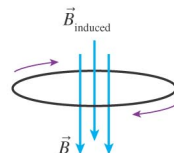
- No change in flux
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Induced current

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Induced current

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# Faraday's Law (34.5)

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# Faraday's Law (34.5)

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- We have understood that a current is induced in a wire dragged through a magnetic field through understanding the forces on the charges on the wire. We have also seen that a changing magnetic field induces a current (but have not yet seen why).
- In either case, there must be an **induced emf**  $\mathcal{E}$ . The current induced is (Ohm's Law):

$$I_{\text{induced}} = \frac{\mathcal{E}}{R}$$

(in the direction given by Lenz's Law)



# Faraday's Law

- So, it is the induced emf which determines the current.

This is a new law of physics!

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## Faraday's Law

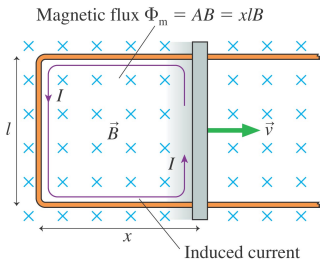
An emf  $\mathcal{E}$  is induced around a closed loop if the magnetic flux through the loop changes. The magnitude of the emf is

$$\mathcal{E} = \left| \frac{d\Phi_m}{dt} \right|$$

and the direction of the emf is given by Lenz's Law.

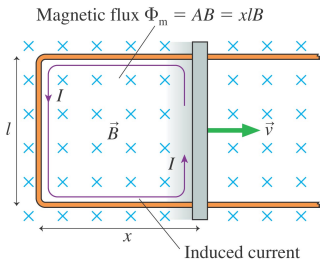
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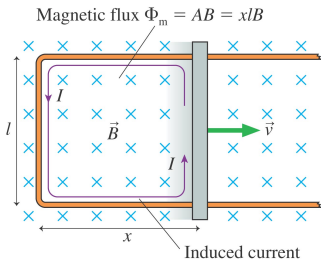
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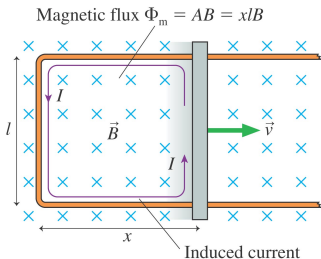
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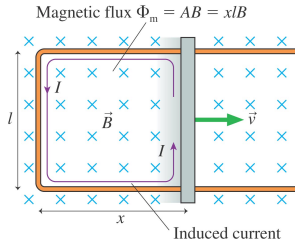


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- Consider the example on the left: a wire moving on a U-shaped rail.

- The field is perpendicular to the loop, so the flux is  $\Phi = AB$  where  $A$  is the area of the loop.
- As the wire slides the enclosed area changes. If  $x$  is the distance from the end of the loop to the wire then  $A = xL$  and the flux is

$$\Phi_m = AB = xLB$$

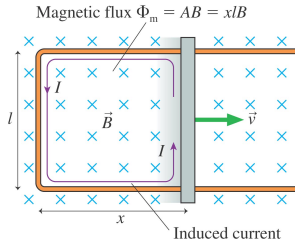
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- The flux through the loop increases as the wire moves, so

$$\mathcal{E} = \left| \frac{d\Phi_m}{dt} \right| = \frac{d}{dt}(x l B) =$$

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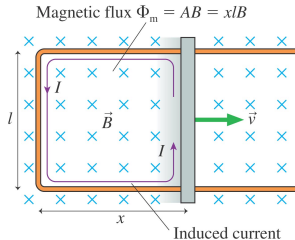


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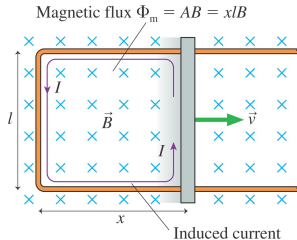
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# Faraday's Law



- The flux through the loop increases as the wire moves, so

$$\mathcal{E} = \left| \frac{d\Phi_m}{dt} \right| = \frac{d}{dt}(xLB) = \frac{dx}{dt}LB = vLB$$

- Now we can calculate the induced current as

$$I = \frac{\mathcal{E}}{R} = \frac{vLB}{R}$$

The same expression we got before!

# What Does Faraday's Law Tell Us?

- If we write Faraday's Law as

$$\mathcal{E} = \left| \frac{d\Phi_m}{dt} \right| = \left| \vec{B} \cdot \frac{d\vec{A}}{dt} + \vec{A} \cdot \frac{d\vec{B}}{dt} \right|$$

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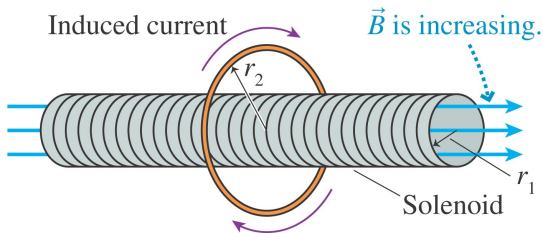
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- Each term represents a fundamentally different way to change the flux and induce an emf
  - 1 The loop can expand or rotate
  - 2 The magnetic field can change
- We need a physical model to understand that second part.

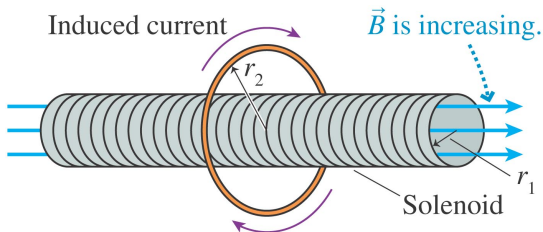
# A Funny Example



- We know that an ideal solenoid has magnetic field inside but no field outside.



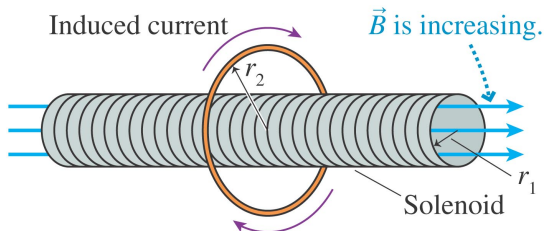
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- So, if we change the magnetic field in this solenoid does a current get induced in the loop of wire?

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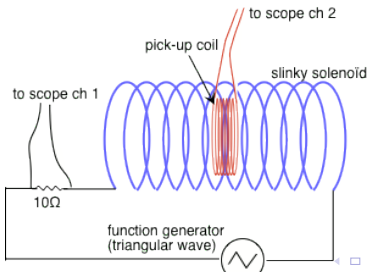
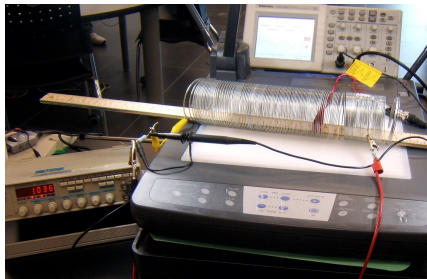


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- We know that an ideal solenoid has magnetic field inside but no field outside.
- So, if we change the magnetic field in this solenoid does a current get induced in the loop of wire?
- Yes! But what is the physical mechanism which can explain this? How does the loop of wire “know” that the magnetic flux has changed???

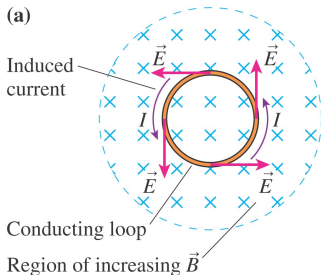
# Induction in a Solenoid, an experiment

Here's the experiment set up on a Document Presenter:



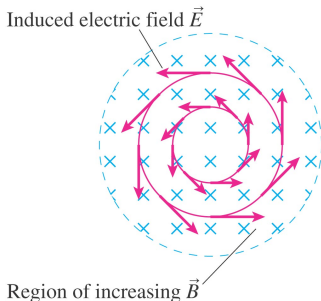
# Induced Fields (34.6)

(a)



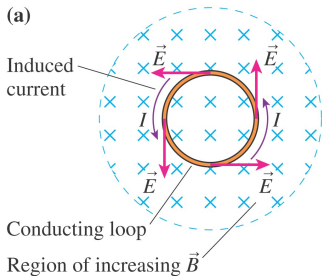
- In the figure there is a changing magnetic field. Somehow it must be causing an electric field in the wire in order to induce the current.

(b)

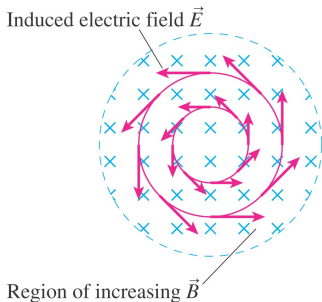


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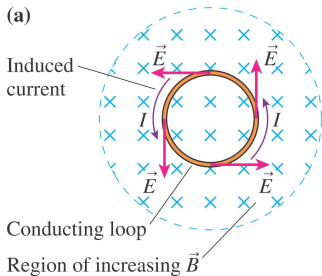
(b)



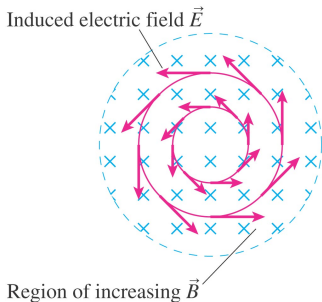
- In the figure there is a changing magnetic field. Somehow it must be causing an electric field in the wire in order to induce the current.
- The **induced electric field** must be tangent to the wire and is the physical mechanism that makes the current flow.

# Induced Fields (34.6)

(a)



(b)

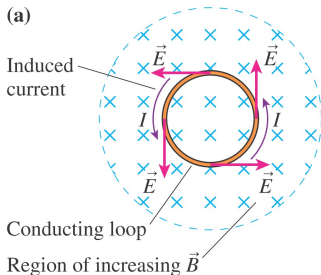


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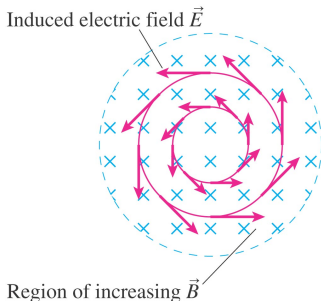
Region of increasing  $\vec{B}$

# Induced Fields (34.6)

(a)



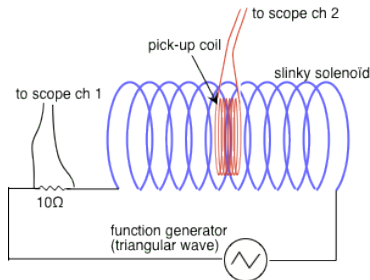
(b)



- In the figure there is a changing magnetic field. Somehow it must be causing an electric field in the wire in order to induce the current.
- The **induced electric field** must be tangent to the wire and is the physical mechanism that makes the current flow.
- Even if the loop of wire is not there, the electric field is still induced.
- This strange induced field does not come from charges. It is a **non-Coulomb electric field**. Yet another sign that an electric field is not just a mathematical concept, it is a real, physical “thing”.

# Induction in a Solenoid, an experiment

- Passing a current through a solenoid creates a magnetic field.
- If the current is varying in time then the changing magnetic flux can induce an EMF in a loop of wire inside the solenoid.

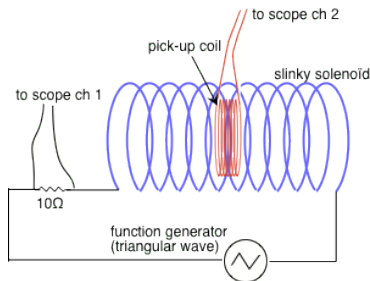




# Induction in a Solenoid, an experiment

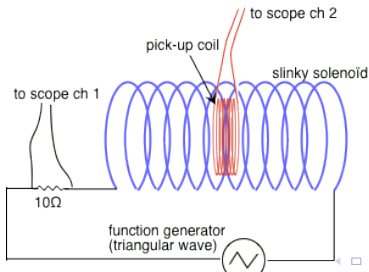
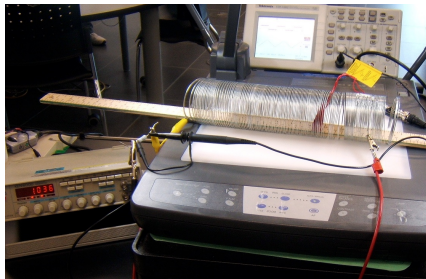
In this experiment we will use the following setup:

- A slinky is the solenoid.
- A  $10\text{-}\Omega$  resistor in series allows current to be measured.
- The pick-up coil is made of 10 loops of ordinary hook-up wire.
- The oscilloscope monitors the current in the slinky on Channel 1 and the induced EMF in the pick-up coil on Channel 2.
- A function generator provides a triangular-shaped voltage-vs-time waveform to the slinky-resistor combo.

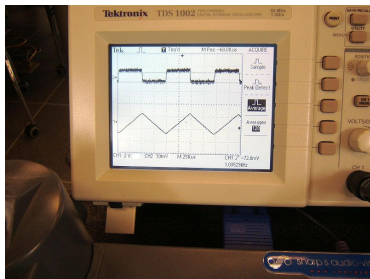


# Induction in a Solenoid, setup

Here's the experiment set up on a Document Presenter:



# Induction in a Solenoid, data



We want to predict the induced EMF,  $\mathcal{E}$ . Here are the data:

- $n = 440$  turns/m : Number of turns/metre of slinky
- $A_p = 1.08 \times 10^{-3} \text{ m}^2 \pm 8\%$  : Area inside pick-up coil
- $N_p = 10$  : Number of turns in pickup coil
- $\Delta V = 3.28 \pm 0.05 \text{ V}$  : P-P voltage change across  $10\text{-}\Omega$  resistor
- $\Delta t = 483 \mu\text{s}$  : Time for  $\Delta V$  is 1/2 period, ( $f = 1.035 \text{ kHz}$ )

Find  $\mathcal{E}$  during the rising half cycle.

# Induction in a Solenoid, calculations

Find  $\mathcal{E}$  during the rising half cycle.

The peak-to-peak change in  $B$  in the solenoid is  $\Delta B$ :

$$\Delta B = \mu_0 n \Delta I = \mu_0 n \Delta V / R$$

$$= (4\pi \times 10^{-7} \text{ T m/ A})(440 \text{ m}^{-1})(3.28 \text{ V}/10 \Omega) = 1.81 \times 10^{-4} \text{ T } (\pm 10\%)$$

$$\mathcal{E} = N_p \frac{d\Phi_B}{dt} = N_p \frac{A_p \Delta B}{\Delta t}$$

$$= (10) \frac{(1.08 \times 10^{-3} \text{ m}^2)(1.81 \times 10^{-4} \text{ T})}{483 \mu\text{s}} = 4.05 \text{ mV } (\pm 20\%)$$

On the scope we see that the voltage across the pick-up coil changes from about  $-4 \text{ mV}$  to  $+4 \text{ mV}$ , which is within experimental error of our calculation.