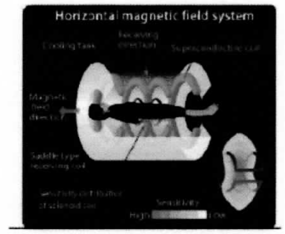
Announcements 4/6/10

Short PS 10 due next Tuesday; I know some of you have multiple tests this week, please don't hesitate to ask for extra time if you need it. Also no lab warmup for next week.

Graded homework and self-tests available outside my office after class

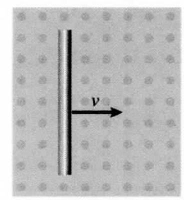
Problems and questions for class 4/6/10



What is the direction of the current in the solenoid?

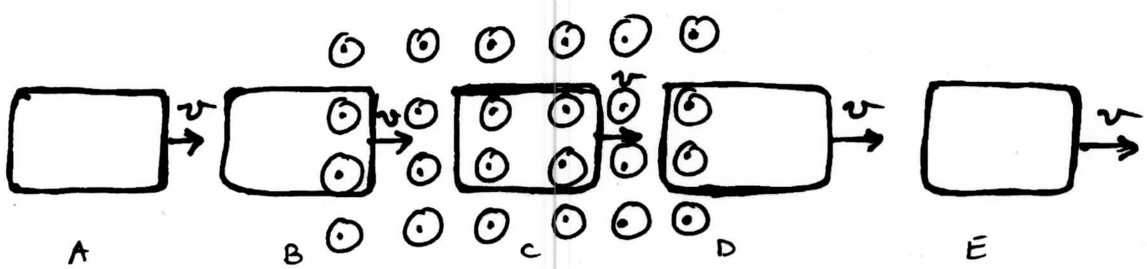
If the solenoid produces a field of 10 T and is 2 m long and 0.5 m in diameter with 5000 turns, what is the current in the solenoid?

Consider a metal bar moving to the right through a uniform magnetic field pointing out of the page. Which way do the electrons in the bar move?

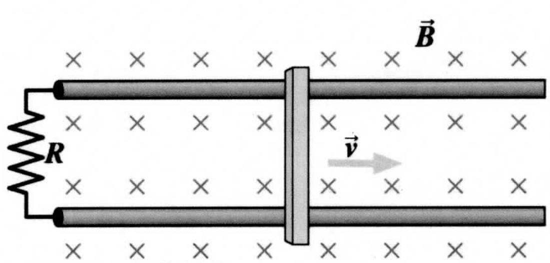


$\vec{B}$-field
(out of page)

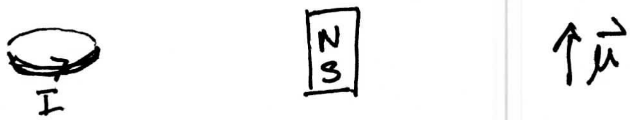
A rectangular conducting loop passes through a region of uniform magnetic field. Give the direction of the current (clockwise or counterclockwise) flowing around the loop at each of the five lettered instants shown.



A pair of parallel conducting rails a distance l apart are connected by a resistor R at the left. A conducting bar can slide across the rails with negligible friction while keeping electrical contact. The whole system is in a uniform magnetic field B as shown. You pull the bar at constant velocity v to the right. (a) What is the direction of the current in the resistor? (b) At what rate do you do work in pulling the bar?



Key ideas from last time



Current loop = bar magnet = magnetic dipole

Magnetic dipole moment of current loop: $\vec{\mu} = NI\vec{A}_{loop}$

Direction of $\vec{\mu}, \vec{A}_{loop}$ = direction of $\vec{B}_{loop}$ on axis of loop

In external magnetic field, magnetic dipoles feel torque that rotates them to align with $\vec{B}_{ext}$: $\quad \vec{\tau} = \vec{\mu} \times \vec{B}_{ext}$

- compass needles
- magnetic sensing/navigation in animals

Potential energy change rotating a dipole through $\vec{B}_{ext}$:

$$\Delta U = -\mu B_{ext}\left(\cos\theta_{final} - \cos\theta_{initial}\right)$$

J.J.
4/6/2010

1. Magnetic materials
2. Solenoids
3. Electromagnetic induction
    1. Observation: current flows in response to change in magnetic flux Φ_B

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

    2. Explanation: if conductor is moving through $\vec{B}$ get $q\vec{v}\times\vec{B}$ force on mobile charges

Can't matter whether conductor moves or magnet moves!

What are these "elementary magnets"? What gives atoms and molecules a magnetic dipole moment?

e^-, p^+, nuclei have $\vec{\mu}$ due to their spin:

$$\vec{\mu} = \gamma \vec{S}$$

γ: "gyromagnetic ratio" — just a proportionality constant

Spin = intrinsic angular momentum — behaves exactly as if particle was a ball of charge spinning around its axis (though it isn't — origin of spin is mysterious

Both protons & electrons are "spin $\frac{1}{2}$" particles meaning there are two quantum states for spin, "up" & "down" and magnitude is $\pm\frac{1}{2}\hbar$ ($\hbar$ = unit of spin)

Without $\vec{B}$, spin states have same energy, but in $\vec{B}$ energies are different
(show energy calc)

Save for later

Show Maitland figs: if apply very strong $\vec{B}$, (many T) can create enough of an energy difference that $\Delta U = 2\mu B$ is large enough to matter

We'll talk more about NMR later

Then apply a radio wave with the right energy for flipping the spins → radio wave absorbed
— other energies are not absorbed

Simplest way to use: identify molecules by how their own internal B changes the

What makes some materials magnetic but most not?

$\vec{\mu}$ of atom = total $\vec{\mu}$ of all nuclei & electrons

Turns out that γ is much bigger for electrons than nuclei so most of the magnetic dipole moment of atoms and molecules comes from electrons

~~Pauli exclusion principle:~~ Generally in an atom or molecule, electrons exist in pairs with opposite spins
- even if atom has odd # of electrons, when it forms bonds w/other atoms, those odd electrons tend to pair off w/opp spin → net spin of zero

So it's <u>rare</u> to have materials w/ unpaired electrons: most materials are not magnetic

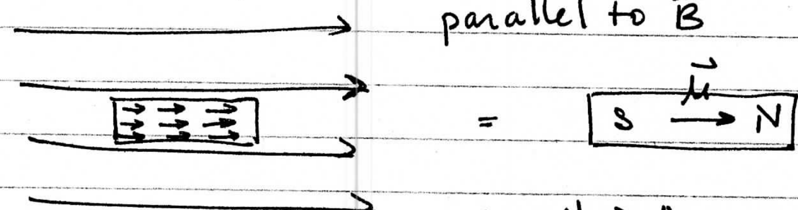
But: a material with unpaired e^- will be a magnetic material. Two kinds of magnetic materials:

<u>Ferromagnetic</u>: iron and a few others

unpaired spins → net $\vec{\mu}$ in material

Show field demonstrator w/ 2 rect. magnets

place in $\vec{B}$: spins rotate to follow $\vec{B}$ ⇒ net $\vec{\mu}$ parallel to $\vec{B}$



say it is "magnetized"

In addition there is a sort of "locking" mechanism that keeps the spins aligned even after the $\vec{B}$ is removed — stays magnetized until something disrupts alignment (heat, dropping magnet)

<u>Paramagnetic</u>: other species w/unpaired e^- but no locking mechanism — these magnetize in $\vec{B}$ but demagnetize when $\vec{B}$ is removed.

Solenoids: way to make strong uniform $\vec{B}$

One final idea before we leave loops of current: best way to make a uniform $\vec{B}$ is with a long stack of many loops

~~Figure~~: Highly uniform field inside, not much $\vec{B}$ outside

Bring a slinky

Why? show Wolfson Fig 26.34

Magnitude of $B = \mu_0 n I$ everywhere inside
← # turns / length

Direction: field on axis of each coil

What if you want a magnetic field of 10 T for MRI?

[Example 26.10 gives quant]

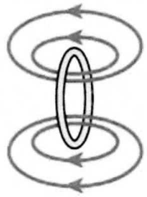
2 m long coil
5000 turns
how much current needed?

$$B = \mu_0 n I \implies I = \frac{B}{\mu_0 n} = \frac{10.0\ T}{(1.26\times10^{-6}\ N/A^2) = \left(\frac{5000\ turns}{2\ m}\right)}$$

$$\boxed{I = 3.2\ kA}$$ wow!

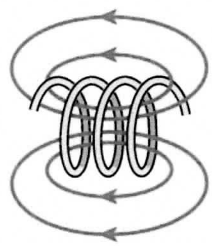
Use superconducting solenoids → don't require a lot of power, don't create a lot of heat

Solenoid figure

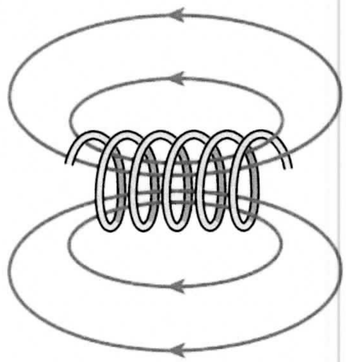


(a)

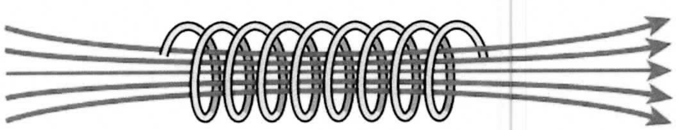
Total $\vec{B}$ field = sum of $\vec{B}$ of each loop



(b)



(c)



(d)

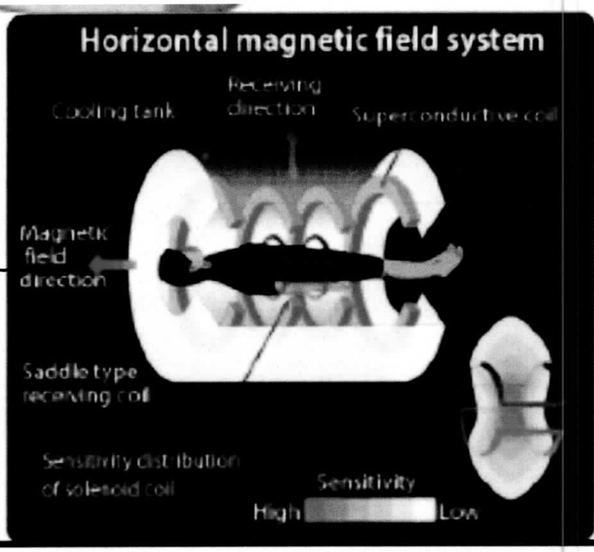
loops outside of $\vec{B}$ get bigger → farther apart → field lines far apart ↔ weak field

$B = \mu_0 I n$

# of turns/length

What is the direction of the current in the solenoid?

$\leftarrow B$



(close to you)

1. up in the front part of the coil
2. down in the front part of the coil

If the solenoid produces a field of 10 T and is 2 m long and 0.5 m in diameter with 5000 turns, what is the current in the solenoid?

$$B = \mu_0 I n \Rightarrow I = \frac{B}{\mu_0 n} \qquad n = \frac{5000 \text{ turns}}{2 \text{ m}}$$

$$\Rightarrow I = 3200 \text{ A}$$

Electromagnetic induction

Demo: rolling and dropping magnets
When you try to move a magnet near a conductor, get some surprising effects!

Demo: ~~[illegible]~~
put galvanometer (current meter) on document camera
display current reading while holding magnet near solenoid:
NO CURRENT w/stationary magnet
CURRENT if coil moves <u>or</u> if magnet moves

How much current depends on: how strong a magnet you use
how fast magnet moves
<u>Direction</u> of current depends on:
which end of magnet is closer to solenoid
whether magnet & solenoid are getting closer together or farther apart?

Draw summary on board like Amy's slide 1

Hypothesis: a changing $\vec{B}$ somehow creates a current ~~[illegible]~~
If so: must also get current if turn $\vec{B}$ on or off – which we do!
make checklist on board

How does this work?

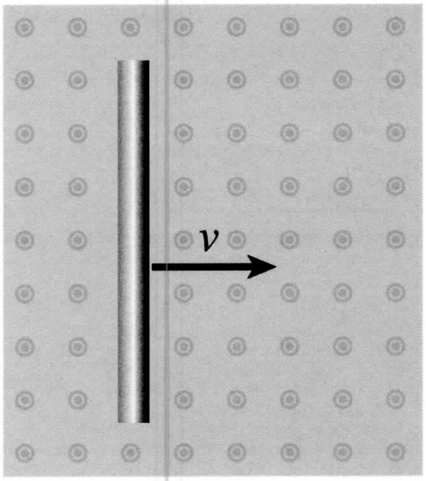
Observation:
~~induced emf~~ <u>amount of current induced in a loop is proportional to rate of change of magnetic flux through the loop</u>

show quilting hoop

What is magnetic flux? $\Phi_B \equiv \vec{B} \cdot \vec{A}$ for constant $\vec{B}$ and <u>the area bounded by the loop</u>
basically: remember how we draw field lines more densely to represent a strong field, less densely to represent a weak field
– flux is like counting up the number of field lines that pass through the loop

Consider a metallic bar moving to the right with velocity v through a uniform magnetic field pointing out of the paper.

$\vec{F} = q\vec{v} \times \vec{B}$



$\vec{B}$-field
(out of page)

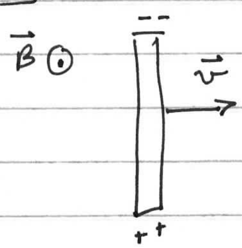
The electrons in the bar move

1. to the top.
2. to the bottom.
3. in another direction.

Why does this happen?

Consider pulling a conducting bar through $\vec{B}_{ext}$

$\boxed{\text{CT}}$ Which way do e^- move? up: $q\vec{v}\times\vec{B}$ points up

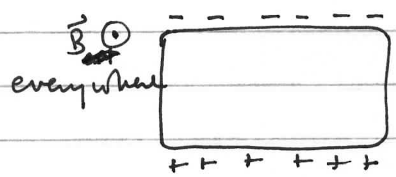


Magnetic force creates a battery:

charge separates until $\vec{F}_E + \vec{F}_B = 0$

i.e. $qE = qvB$ and opposite

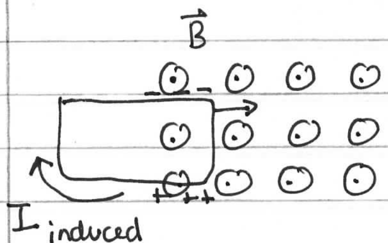
Pull rectangular loop in field: similarly polarizes



No current

No change in flux of $\vec{B}_{existing}$ through loop

What if instead loop is partway in $\vec{B}$?



end in $\vec{B}$ acts like a battery – drives current around!

current is a result of the motion – there was no current until we moved the loop

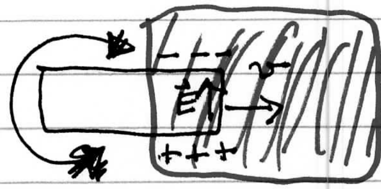
There is a changing flux through the loop!

$\boxed{\text{CT}}$ Moving loop through $\vec{B}_{ext}$: when do you get current and which way?

CW when entering, CCW when leaving

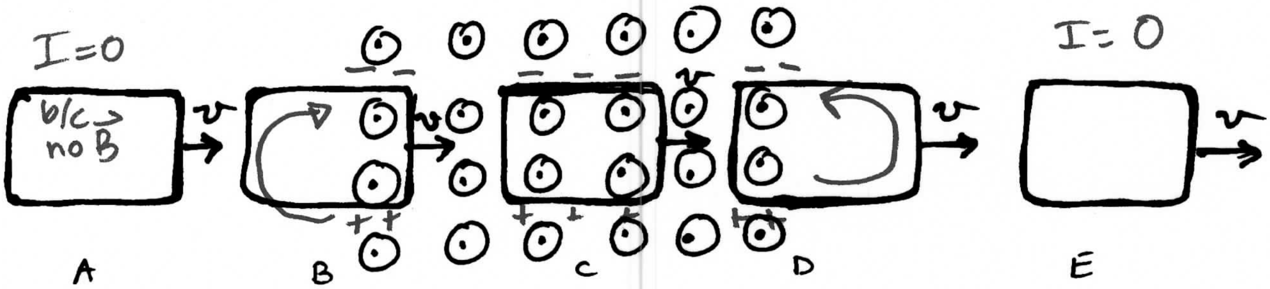
no current when fully in

$\vec{B}$



battery @ end in $\vec{B}$
causes charge to circulate

A rectangular conducting loop passes through a region of uniform magnetic field. Which of the following correctly describes the direction of the currents flowing around the loop at the five locations shown? (CW = clockwise, CCW = counterclockwise)



	A	B	C	D	E
1.	CW	CW	CCW	CCW	CCW
2.	0	CW	0	CCW	0
3.	0	CW	0	CW	0
4.	0	CCW	0	CW	0
5.	0	CCW	0	CCW	0
6.	CCW	CCW	CW	CW	CW

How much current? Which direction?

Observed relationship:

$$\mathcal{E}_{ind} = -\frac{d\Phi_B}{dt}$$

induced emf: the ~~battery~~ current is driven by the "battery" of the motion, except it's spread all the way around

$$\mathcal{E}_{ind} = I_{ind} R_{loop}$$

We'll ~~focus on~~ start by finding induced emfs, then current from $\mathcal{E}$

Always find abs. value of emf:

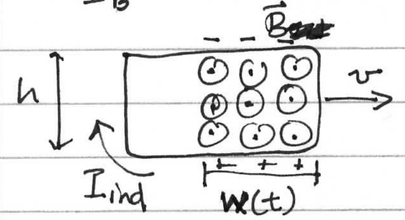
$$|\mathcal{E}| = \left| -\frac{d\Phi_B}{dt} \right|$$

and then ~~we~~ we'll figure out the direction from the physics – a principle called Lenz's Law that we'll learn shortly

Example: Calculate current in moving loop

For moving loop: think of dividing loop's area into area that contains $\vec{B}$ and area that doesn't

$\Phi_B = \vec{B} \circ \vec{A}(t)$ where $A(t)$ = area in which there is $\vec{B}$



$\Phi_B = BA(t)$ b/c $\vec{B}$ and $\vec{A}$ are parallel (angle between $\vec{B}$ and $\vec{A} = 0°$

$= B\underbrace{hw(t)}_{\text{area with } \vec{B}}$ $\qquad BA\cos\theta = BA\cos 0° = BA$)

~~How fast~~ $\quad \frac{d\Phi_B}{dt} = \frac{d}{dt}(B h w(t)) = Bh\frac{dw(t)}{dt}$

B, h: constant $\quad w(t)$: changing

If t=0 is when edge of loop reached edge of $\vec{B}$, then

$w(t) = vt$

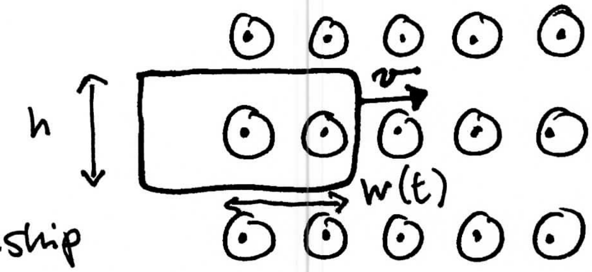
$$\Rightarrow \frac{d\Phi_B}{dt} = Bhv = |\mathcal{E}|$$

(and if loop has resistance R,

$$I_{ind} = \frac{|\mathcal{E}|}{R} = \frac{Bhv}{R}$$

~~Ex~~

A conducting loop moves into a limited region of constant magnetic field as shown. Find the induced current in the loop.



Observed relationship

$$\mathcal{E}_{ind} = -\frac{d\Phi_B}{dt}$$ ← flux of external $\vec{B}$ through loop

induced current comes from $I_{ind} = \frac{\mathcal{E}_{ind}}{R}$

More practical:

$$|\mathcal{E}_{ind}| = \left| -\frac{d\Phi_B}{dt} \right|$$

What is $\frac{d\Phi_B}{dt}$ for this loop?

$$\Phi_B = \vec{B} \cdot \vec{A}(t)$$ ← amount of loop area that has field going through it

$$= BA(t) \quad \text{b/c } \vec{B} \parallel \vec{A}(t) \text{ so } \cos 0° = 1$$

Right end of loop enters $\vec{B}$ at time $t=0$

$$w(t) = vt \implies A(t) = hw(t) = hvt$$

$$\Phi_B = Bhvt \implies \frac{d\Phi_B}{dt} = Bhv$$

$$I_{ind} = \frac{|\mathcal{E}_{ind}|}{R} = \frac{|d\Phi_B/dt|}{R} = \frac{Bhv}{R}$$

What is the direction of the induced current?

When loop is entering $\vec{B}$, Φ_B is increasing

Notice direction of magnetic field of induced current $\vec{B}_{ind}$

$\boxed{\text{inside the loop,}}$ $\vec{B}_{ind}$ is into page — opposite $\vec{B}$

* $\vec{B}_{ind}$ partially offsets flux of $\vec{B}$ increasing inside loop *

When loop is leaving: ~~?~~ current goes opposite way

→ induced current ⇒ $\vec{B}_{ind}$ out of page

* $\vec{B}_{ind}$ partially offsets decreasing flux of $\vec{B}$ inside loop *

Lenz's Law

induced current flows in direction to oppose the change that created it

typically means that the flux of $\vec{B}_{ind}$ through loop partially offsets the change in flux of the original $\vec{B}$

KEEP CAREFUL TRACK of $\vec{B}_{ind}$ vs. original/external $\vec{B}$

$\vec{B}_{ind}$ = mag field of induced current

$\vec{B}$ = original field that has $\frac{d\Phi_B}{dt}$ through loop

$\boxed{CT}$ Moving loop toward wire: I induced ccw

(1) Identify direction of $\vec{B}$ inside loop: in this case it's $\vec{B}_{wire}$

(2) Identify whether Φ_B is increasing or decreasing

(3) Induced current's $\vec{B}_{ind}$ partially offsets $\frac{d\Phi_B}{dt}$

Lenz's Law:

Really about energy conservation: if induced current resists change it dissipates energy.

$\boxed{CT}$ Force on moving loop: repulsive: $\vec{F} = I\vec{L} \times \vec{B}$ forces