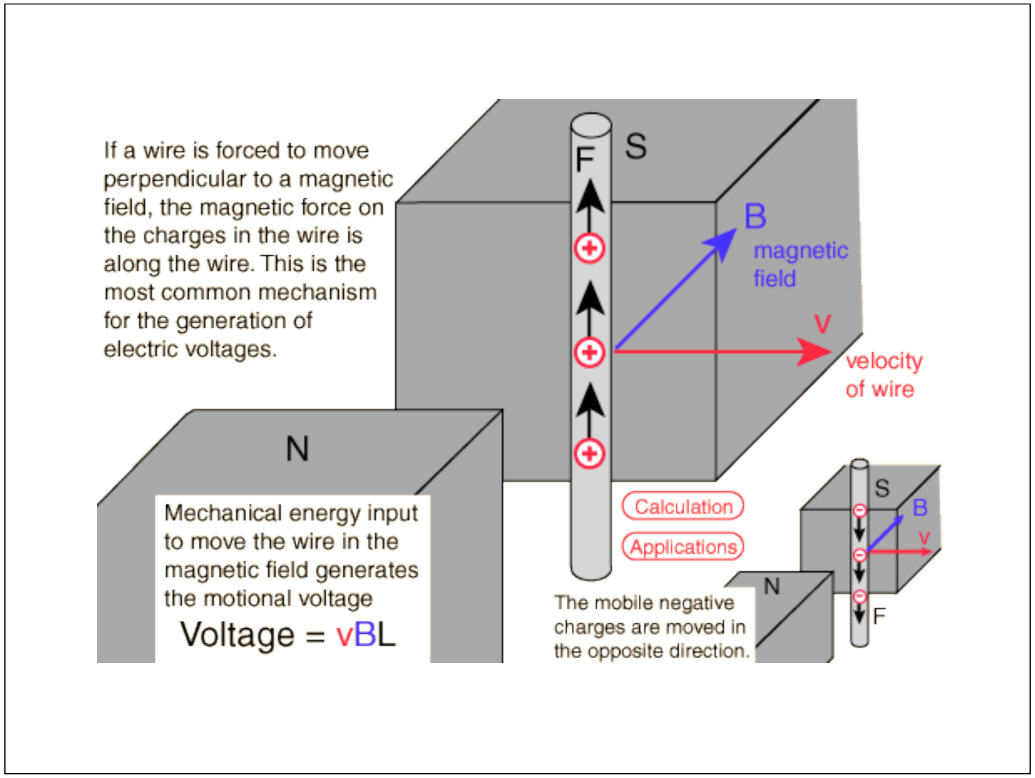
20.2 Lenz's Law

Motional emf

Lenz's law

Applications of Faraday's Law

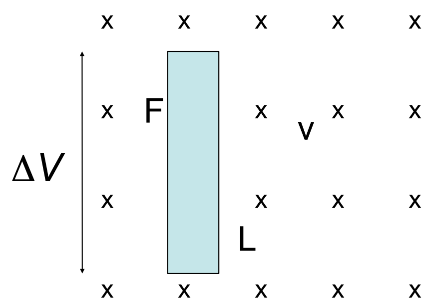
Demo show the eddy current effect of dropping a magnet in a conducting tube



If a wire is forced to move perpendicular to a magnetic field, the magnetic force on the charges in the wire is along the wire. This is the most common mechanism for the generation of electric voltages.
F
S
B
magnetic field
v
velocity of wire
N
Mechanical energy input to move the wire in the magnetic field generates the motional voltage
Voltage = vBL
Calculation
Applications
S
B
v
N
F
The mobile negative charges are moved in the opposite direction.

Motional emf

A voltage is produced by a conductor moving in a magnetic field



B into the page

Charges in the conductor experience a force upward

$$F = qvB$$

The work done in moving a charge from bottom to top

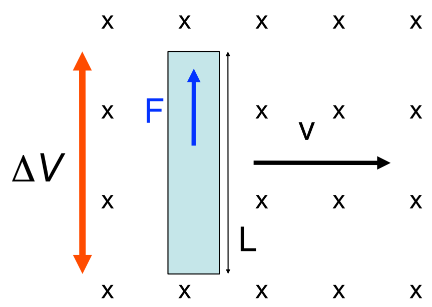
$$W = FL = qvBL$$

The potential difference is

$$\Delta V = \frac{W}{q} = vBL$$

Motional emf

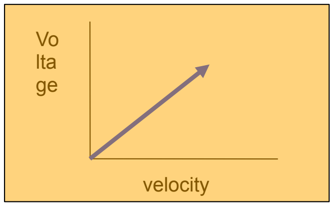
A voltage is produced by a conductor moving in a magnetic field



B into the page

Charges in the conductor experience a force upward

$$F = qvB$$



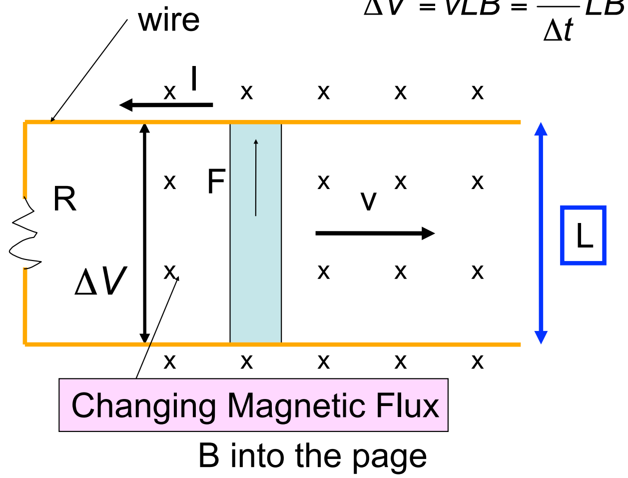
$$W = FL = qvBL$$

The potential difference is

$$\Delta V = \frac{W}{q} = vBL$$

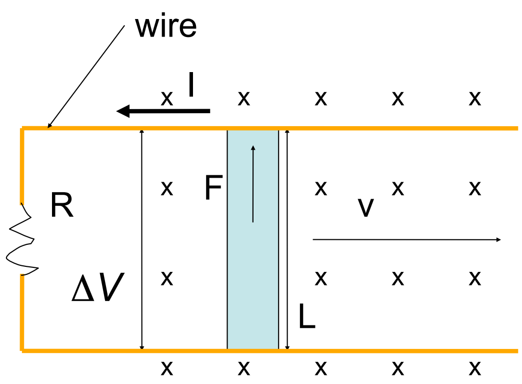
The potential difference can drive a current through a circuit
The emf arises from changing flux due to changing area according to Faraday's Law

$$\Delta V = vLB = \frac{\Delta x}{\Delta t}LB = \frac{\Delta AB}{\Delta t} = \frac{\Delta \Phi_B}{\Delta t} = |\varepsilon|$$



$$I = \frac{|\varepsilon|}{R} = \frac{BLv}{R}$$

18. R= 6.0 Ω and L=1.2 m and B=2.5 T. a) What speed should the bar be moving to generate a current of 0.50A in the resistor? b) How much power is dissipated in R? c) Where does the power come from?



B into the page

a)

$$I = \frac{\varepsilon}{R} = \frac{BLv}{R}$$

$$v = \frac{IR}{BL} = \frac{0.5(6.0)}{2.5(1.2)}$$

$$v = 1.0 m/s$$

b)

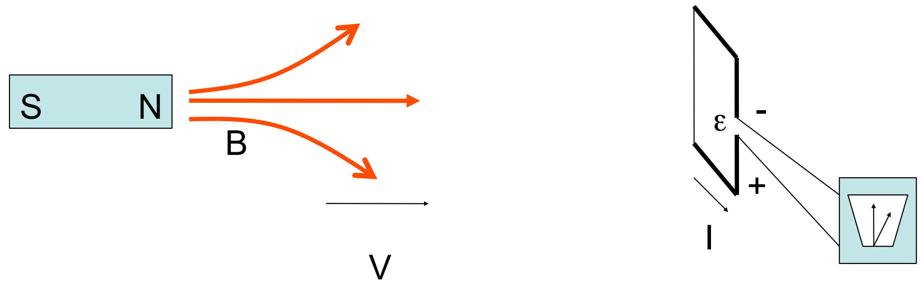
$$P = I^2 R = (0.5)^2 (6.0)$$

$$P = 1.5 W$$

c) Work is done by the force moving the bar

Lenz's Law
determines the direction of current flow.

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$



Lenz's Law
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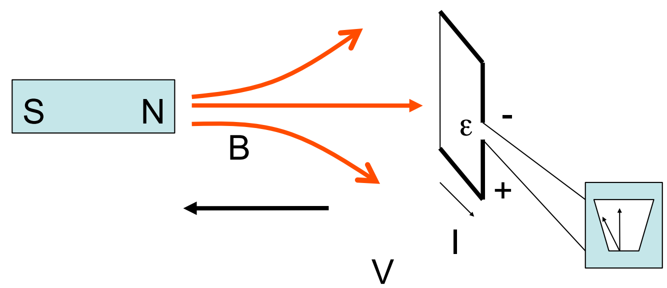
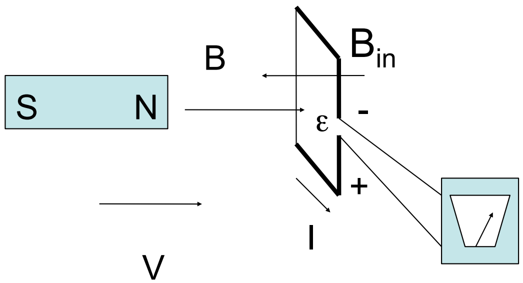
$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$



Lenz's Law

The polarity of the induced emf is such that it induces a current whose magnetic field opposes the change in magnetic flux through the loop. i.e. the current flows to maintain the original flux through the loop.



B increasing in loop

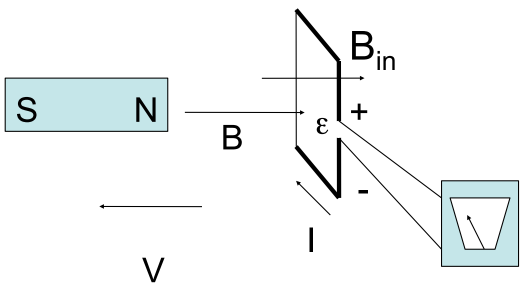
B_{in} acts to oppose the change in flux

Current direction that produces B_{in} is as shown (right hand rule)

Emf has the polarity shown. ε drives current in external circuit.

Now reverse the motion of the magnet

The current reverses direction



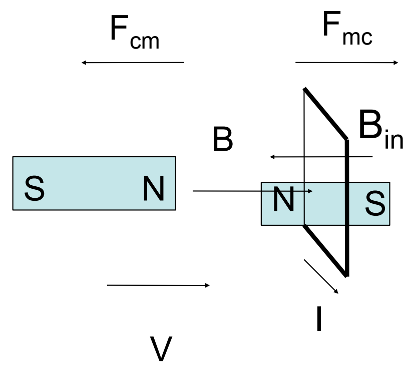
B decreasing in loop

B_{in} acts to oppose the change in flux

Current direction that produces Bin is as shown (right hand rule)

Emf has the polarity shown.

Lenz's Law and Reaction Forces



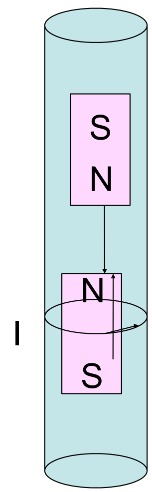
A force is exerted by the magnet on loop to produce the current

A force must be exerted by the current on the magnet to oppose the change

The current flowing in the direction shown induces a magnetic dipole in the current loop that creates a force in the opposite direction

Example. Eddy currents

A magnet is dropped down a cylindrical conductor. Currents are induced in the conductor to oppose the movement of the magnet



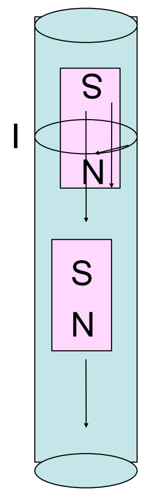
B increasing

B_{in} Induced magnetic field

creates magnetic dipole that opposes the movement of magnet

Example. Eddy currents

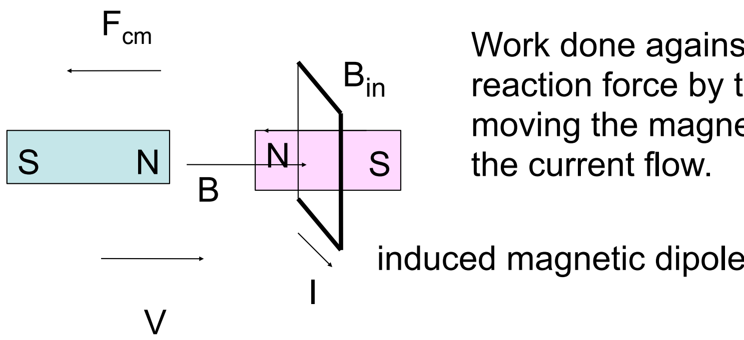
What about the region behind the magnet?



B_{in} creates magnetic dipole that opposes the movement of magnet

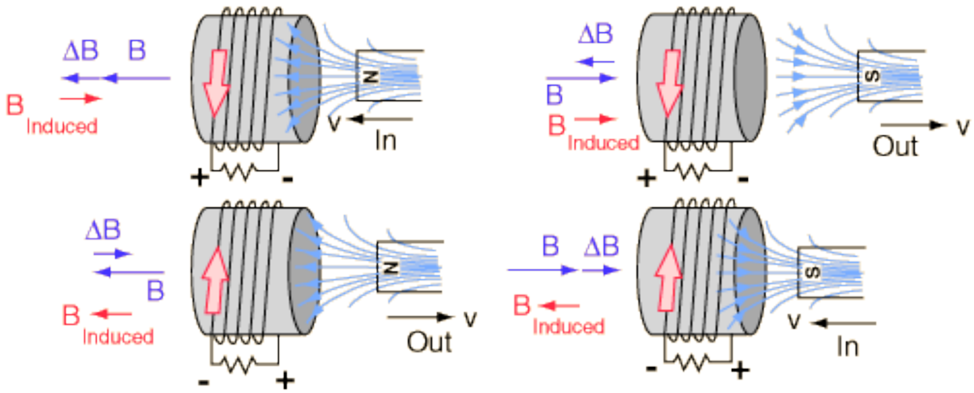
B decreasing

Work

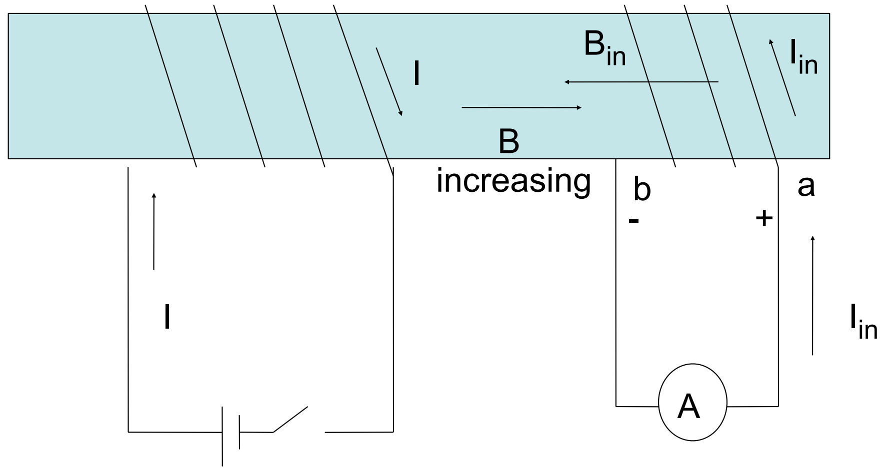


Work done against the reaction force by the force moving the magnet drives the current flow.

4 cases:


ΔB
B
B
Induced
N
v
In
+
-
ΔB
B
B
Induced
S
Out
v
+
-
ΔB
B
B
Induced
N
Out
v
-
+
B
ΔB
B
Induced
S
v
In
-
+

Two coils are connected by an iron core. Is the emf from a to b positive or negative when the switch is closed?



current flows from b to a

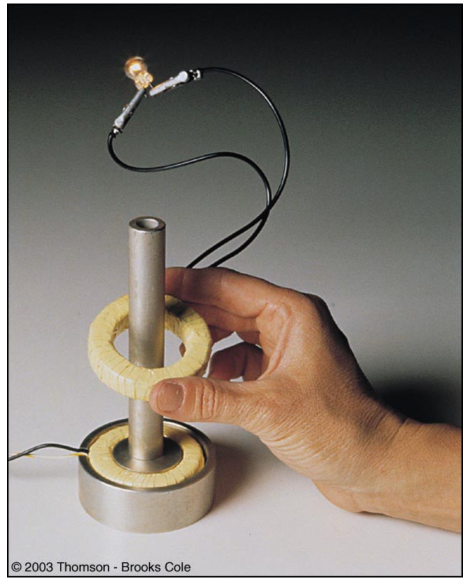
I_{ab} is negative therefore ε_{ab} is negative

Electromagnetic Induction

Alternating induced voltage

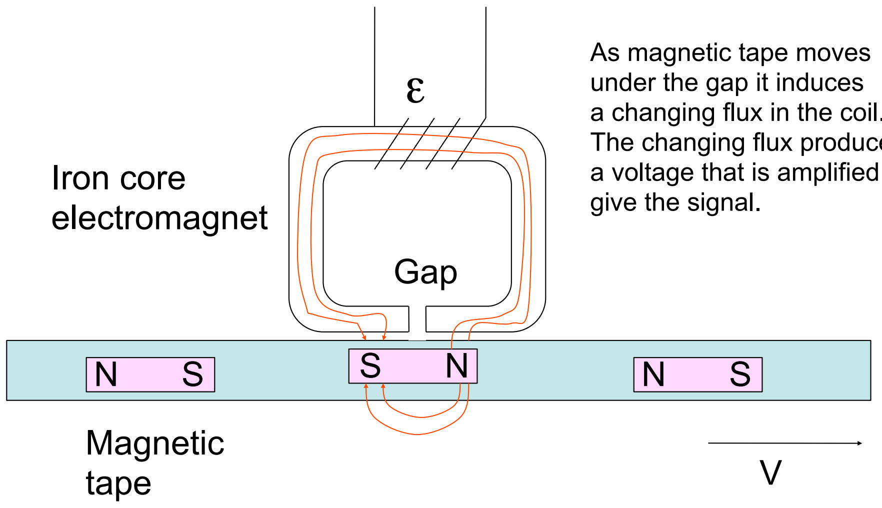
Alternating magnetic field

Alternating current (varies with time)



Energy transfer through space

Application of Faraday's Law
Generation of voltage by a tape recorder



As magnetic tape moves under the gap it induces a changing flux in the coil. The changing flux produces a voltage that is amplified to give the signal.

20.3 Electrical Generator

Electrical Generators

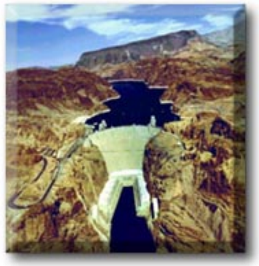
Self-induction

Demo

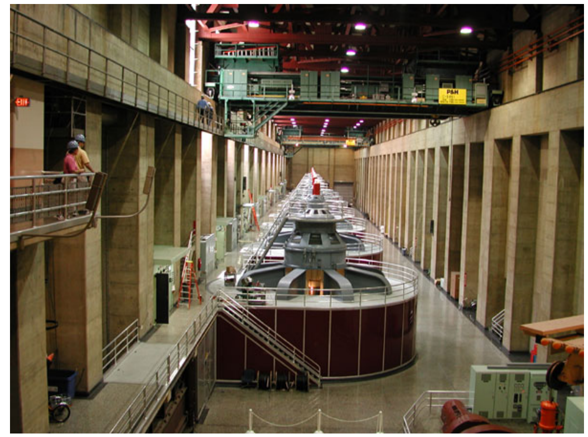
Electrical generator- show that the motor can be used as a generator. first start the motor then switch it to the generator mode the light bulb should go on (turn down the lights_

Magnetic induction use the iron core inductor to levitate a ring. show that the ring does not levitate if it is cut. then show that a light bulb can be lit using magnetic induction. Energy transfer through space. Electro magnetic energy.

Hoover Dam



Electrical generators



Electrical Generator

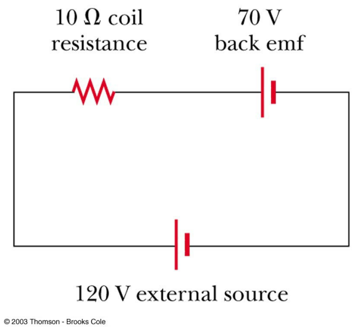
Uses mechanical work to generate electrical current

Changing flux through a rotating coil produces emf
Faraday's Law

Alternating current is produced

Direct current can be produced using a commutator.

Back emf in motor



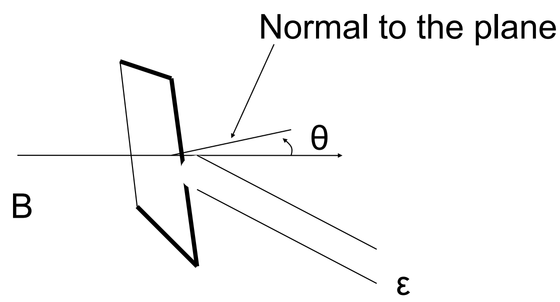
When a motor is turning it generates a emf that opposes the current flow -Back emf.
The Back emf is less when starting the motor or when it is under heavy load (not turning fast). Under these conditions large currents flow – the motor has the chance of burning out.

• Wednesday 12/2

- Final Exam (40% of grade) on Monday December 7th 1130a-230pm in York 2622
- You can bring ***two*** 8.5x11” pages, front and back, of notes
- Calculators may be used
- multiple choice like quizzes, only longer by about 2-3x more questions...
- Covers ALL of 1B: Ch15 - 21, inclusive

- Bring your own Scantron forms and pencils
- Final Review Problem Session: Tomorrow Night

Flux through a rotating loop in a B field



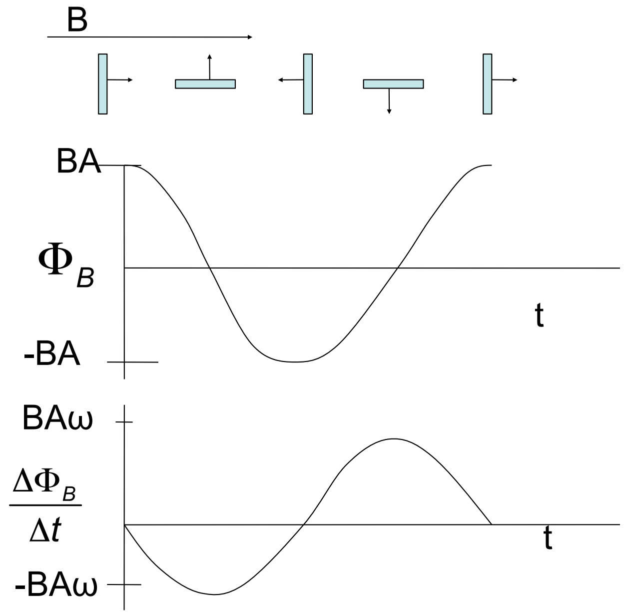
The flux through the loop

$$\Phi_B = BA\cos\theta$$

$$\theta = \omega t$$

ω = angular velocity (radians/s)

Relation between Φ_B and $\frac{\Delta\Phi_B}{\Delta t}$



$$\Phi_B = BA\cos\omega t$$

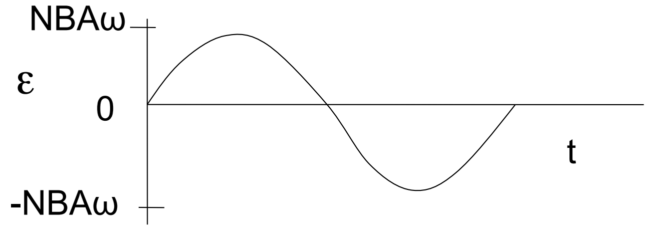
$$\frac{\Delta\Phi_B}{\Delta t} = -BA\omega\sin\omega t$$

proportional to ω

The emf generated by a loop of N turns rotating at constant angular velocity ω is

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$\varepsilon = NBA\omega \sin\omega t$$



35. In a model ac generator, a 500 turn rectangular coil 8.0 cmx 20 cm rotates at 120 rev/min in a uniform magnetic field of 0.60 T. a) What is the maximum emf induced in the coil?

$$\varepsilon = NBA\omega \sin\omega t$$

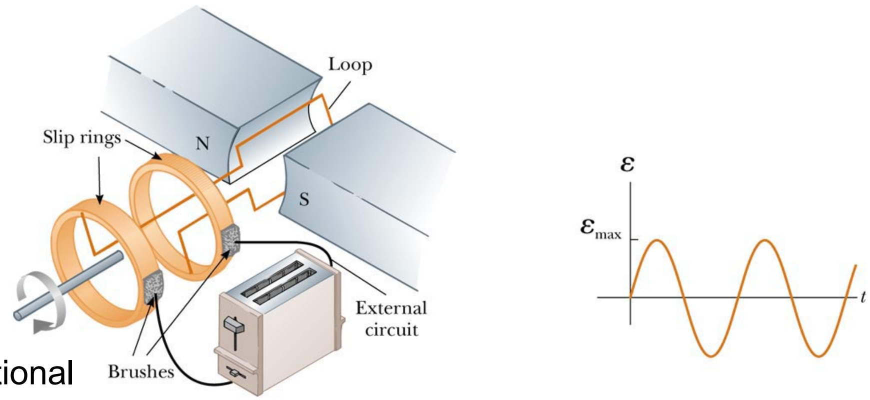
The maximum value of ε

$$\varepsilon_{max} = NBA\omega$$

$$\varepsilon_{max} = (500)(0.6)(0.08x0.2)\frac{(120x2\pi)}{60} = 60V$$

Electrical Generator

Alternating Current (AC) generator



Rotational

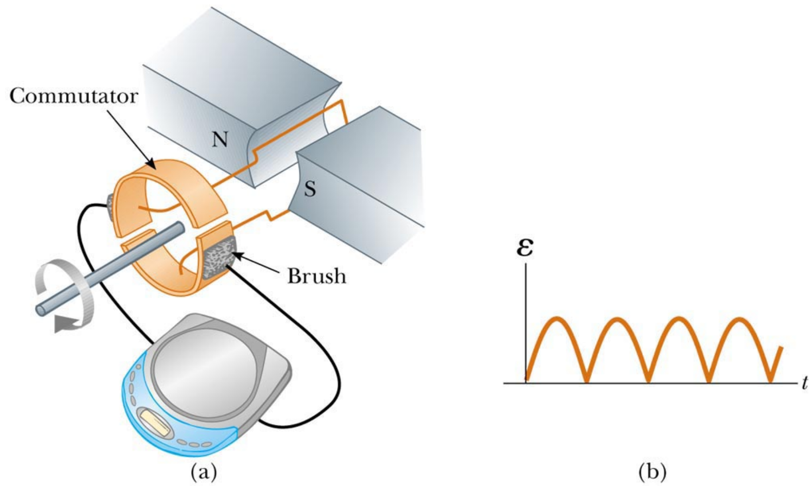
Work

(a)

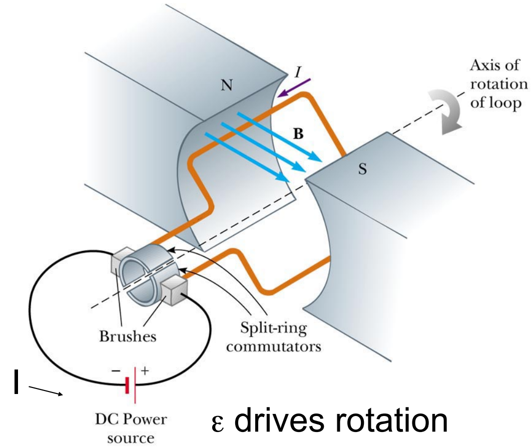
)mson - Brooks Cole

(b)

Direct Current (DC) generator

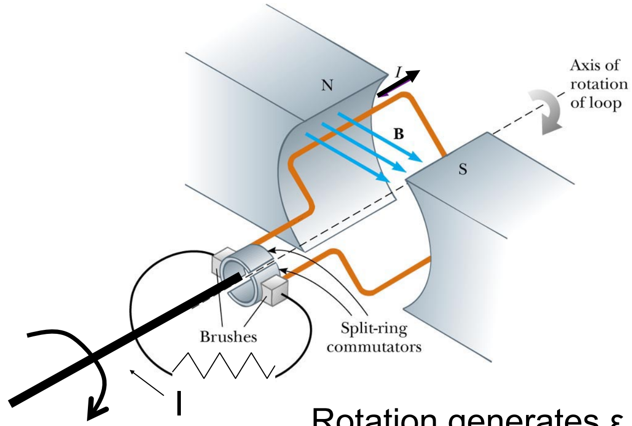


A generator is motor acting in reverse



ε drives rotation

DC motor



Rotation generates ε

DC generator

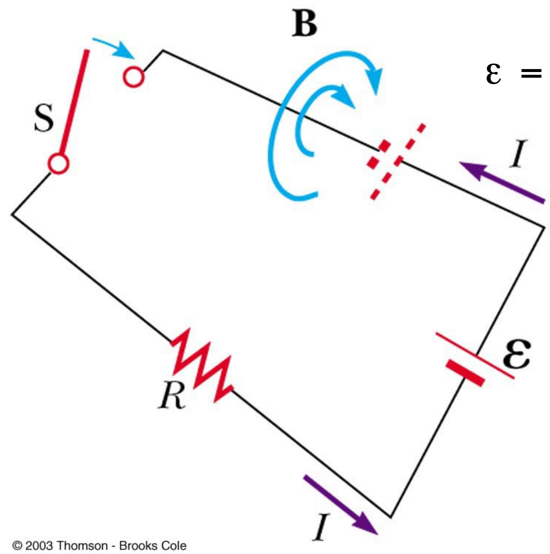
Self-Inductance

- a property of a circuit carrying a current
- a voltage is induced that opposes the change in current
- used to make devices called inductors

Self- inductance of a circuit

a reverse emf is produce by the changing current

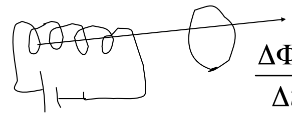
$$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$$



Self Inductance of a coil

A changing magnetic field in a coil produces an emf in another coil

$$\frac{\Delta I}{\Delta t}$$



ε

$$\frac{\Delta \Phi_B}{\Delta t}$$

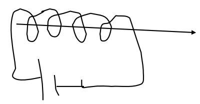
Inductance

However changing fields in a coil due to changing the current in the coil itself also produce an emf in coil a.

$$\frac{\Delta \Phi_B}{\Delta t}$$

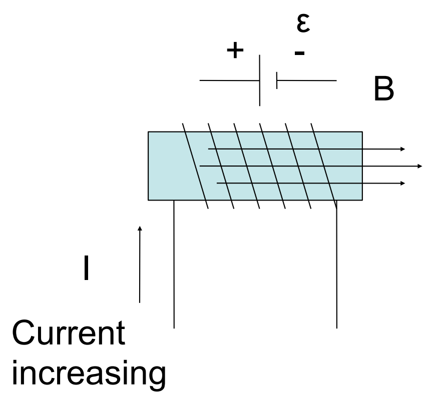
ε

$$\frac{\Delta I}{\Delta t}$$



Self-Inductance

Self-inductance of a coil



B increases, $\frac{\Delta B}{\Delta t}$

changes magnetic flux in the coil,

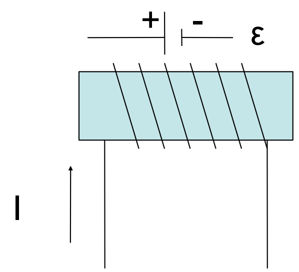
$$\frac{\Delta \Phi_B}{\Delta t} = \frac{A \Delta B}{\Delta t}$$

Produces emf in coil

$$\varepsilon = -N\frac{\Delta \Phi_B}{\Delta t} = -N\frac{A \Delta B}{\Delta t}$$

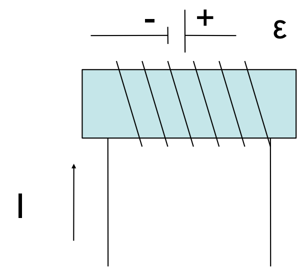
The direction of the induced emf opposes the change in current.

A changing current in a coil induces an emf that opposes the change



I increasing

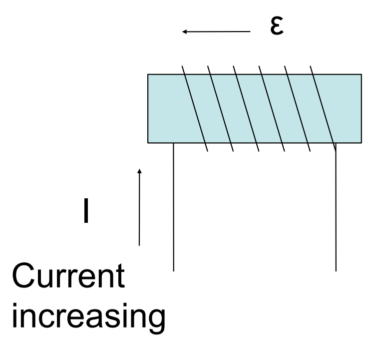
induced emf
opposes I



I decreasing

induced emf
supports I

Inductance L is a measure of the self-induced emf



The self-induced emf is

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

but $\frac{\Delta\Phi_B}{\Delta t} \propto \frac{\Delta I}{\Delta t}$

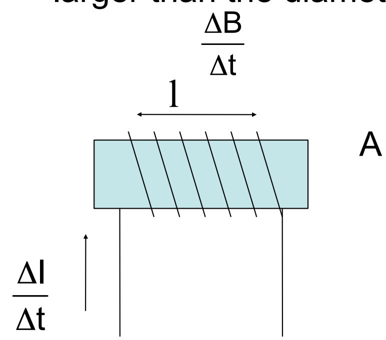
proportionality constant is L

$$\varepsilon = -L\frac{\Delta I}{\Delta t}$$

L is a property of the coil, Units of L , Henry (H) $\frac{Vs}{A}$

Inductance of a solenoid with N turns and length ℓ ,

wound around an air core (assume the length is much larger than the diameter).



$$\Phi_B = BA = \mu_o \frac{N}{\ell} IA$$

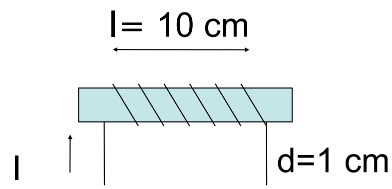
$$\frac{\Delta\Phi_B}{\Delta t} = \mu_o \frac{N}{\ell} \frac{\Delta I}{\Delta t} A$$

$$\varepsilon = -N \frac{\Delta\Phi_B}{\Delta t} = -\mu_o \frac{N^2}{\ell} A \frac{\Delta I}{\Delta t} = -L \frac{\Delta I}{\Delta t}$$

$$L = \mu_o \frac{N^2}{\ell} A$$

inductance proportional to N squared x area/length

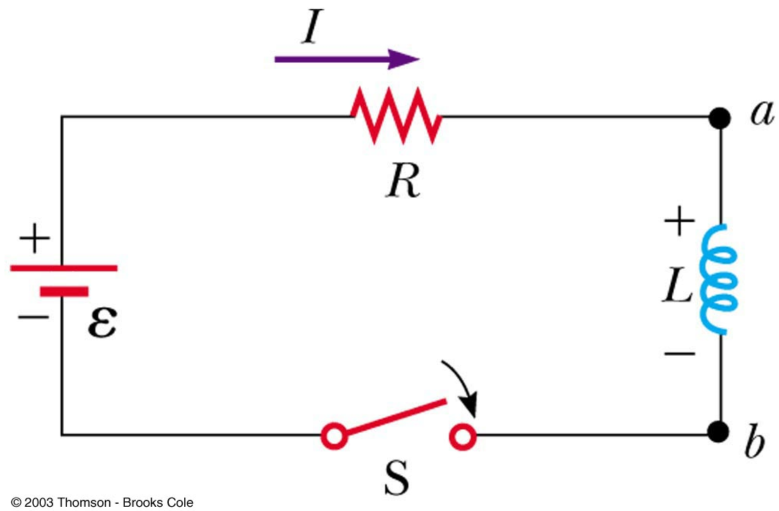
An air wound solenoid of 100 turns has a length of 10 cm and a diameter of 1 cm. Find the inductance of the coil.



$$L = \mu_o \frac{N^2}{\ell} A = \mu_o \frac{N^2}{\ell} \pi \frac{d^2}{4}$$

$$L = \frac{4\pi 10^{-7} (100)^2 \pi (0.01)^2}{0.1(4)} = 1.0x10^{-5} H$$

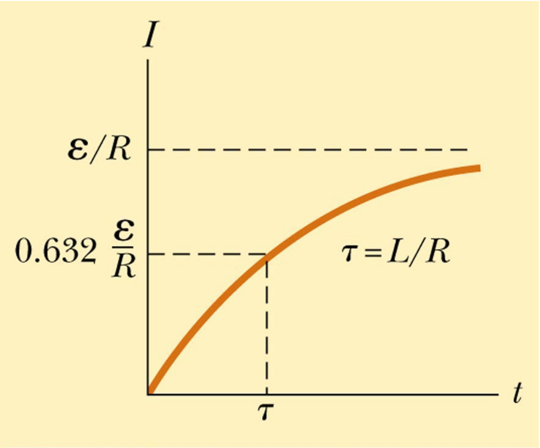
RL circuit



The inductor prevents the rapid buildup of current

$$\varepsilon = -L\frac{\Delta I}{\Delta t}$$

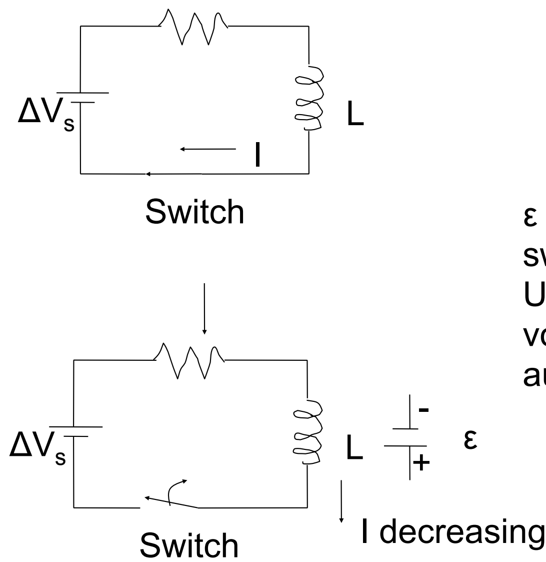
But at long time does not reduce the current, $\frac{\Delta I}{\Delta t} = 0$ at t=∞



$$I = I_o(1 - e^{-\frac{t}{\tau}})$$

$$\tau = \frac{L}{R}$$

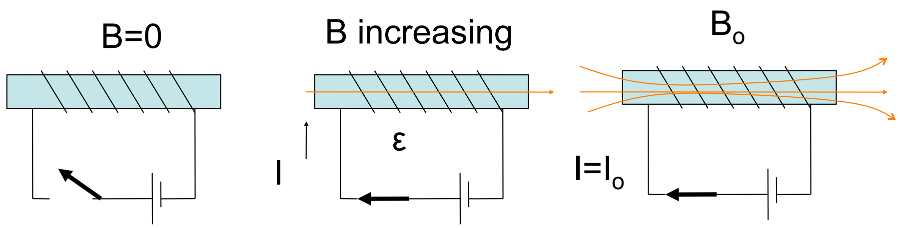
Spark generation



$$\varepsilon = -L\frac{\Delta I}{\Delta t}$$

ε is very high (1000 V) if switch is opened quickly. Used to generate high voltage in spark plugs in automobile ignition

Energy is stored in a magnetic field of an inductor.



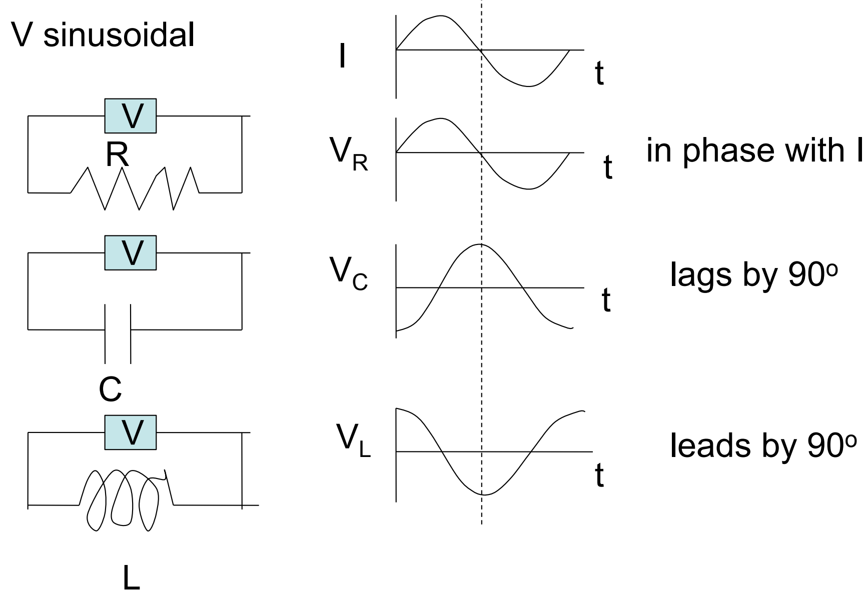
Work is done against ε to produce the B field.

This produces a change in the PE of the inductor

$$PE_L = \frac{1}{2}LI^2$$

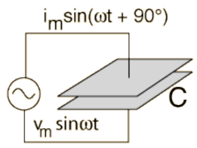
This stored PE can be used to do work

Response to a sinusoidal voltage



different phase shift between current and voltage

Capacitive Reactance, X_c



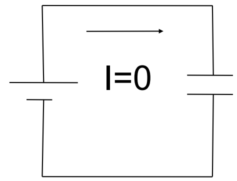
$$X_C = \frac{1}{\omega C}$$

$$\Delta V_C = X_C I$$

$$X_c = \frac{1}{\omega C}$$

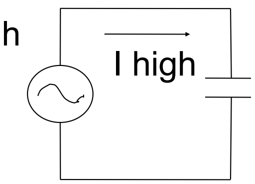
X_C is higher at low frequency. The capacitor block current at long time. because more charge accumulates.

f=0
DC



X_C= infinity

f=high



X_C = low

X_c has units of Ohms

A 10 microfarad capacitor is in an ac circuit with a voltage source with RMS voltage of 10 V. a) Find the current for a frequency of 100 Hz. b) Find the current for a frequency of 1000 Hz.

a)

$$\Delta V_C = X_C I$$

$$I = \frac{\Delta V_C}{X_C} = \frac{\Delta V_C (2\pi f C)}{1}$$

$$I = 10(2\pi)(100)(10^{-5}) = 6.3x10^{-2} A$$

b) The frequency is 10 x higher, the current is 10 x higher

$I=10x6.3x10^{-2}$

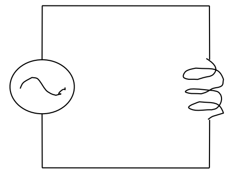
$=6.3x10^{-1}A$

Inductive reactance, X_L

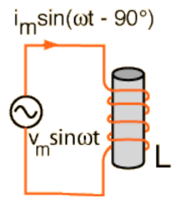
$\Delta V_L = X_L I$

$$I = \frac{\Delta V_L}{X_L}$$

$$X_L = \omega L$$



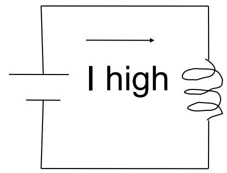
An inductor has higher back emf when $\Delta I/\Delta t$ is greater, i.e. at high frequency. Inductive reactance higher at high frequency.



$$X_L = \omega L$$

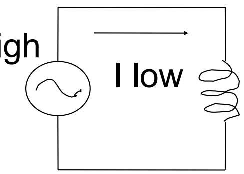
$$X_L = 2\pi f L \qquad I = \frac{\Delta V_L}{X_L}$$

f=0



$X_L = 0$

f high



$X_L =$ high

Inductive reactance is higher at high frequency

A inductor with L= 10^{-5} H is driven by a 10 V ac source.
a) Find the current at f=100 Hz.
b) Find the current at f=1000Hz

a)

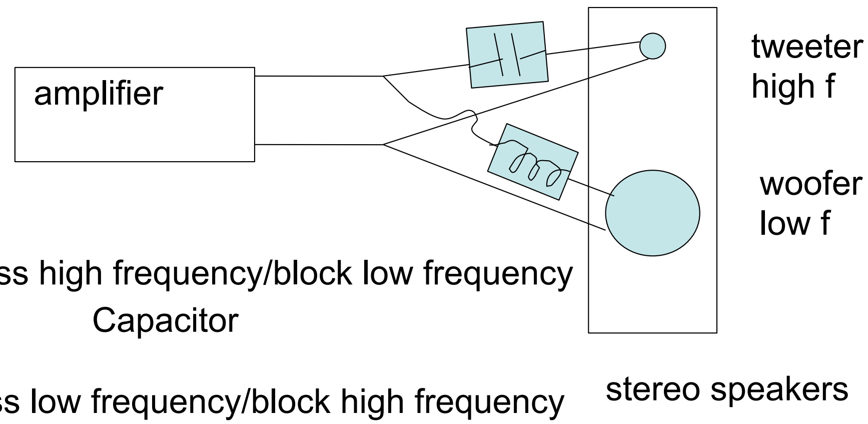
$$I_{RMS} = \frac{\Delta V_{L,RMS}}{X_L} = \frac{\Delta V_{L,RMS}}{2\pi fL}$$

$$I = \frac{10}{2\pi(100)(10^{-5})} = 1.6x10^3 A$$

b) the frequency is 10x greater
the current is inversely proportional to f
the current is 10x lower

$I=1.6x10^3/10=1.6x10^2A$

Application.
High pass and low pass filters.



pass high frequency/block low frequency

Capacitor

pass low frequency/block high frequency

Inductor

• Friday 12/4

•Final Exam (40% of grade) on Monday December 7th 1130a-230pm in York 2622

•You can bring ***two*** 8.5x11" pages, front and back, of notes

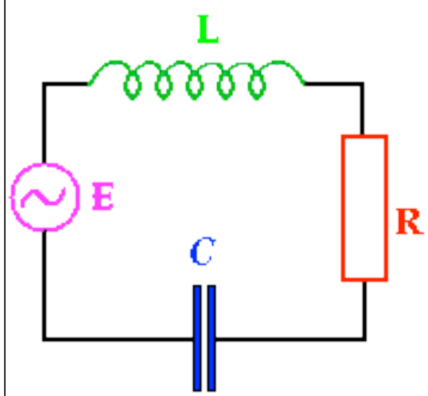
•Calculators may be used

• multiple choice like quizzes, only longer by about 2-3x more questions...

•Covers ALL of 1B: Ch15 - 21, inclusive

- Bring your own Scantron forms and pencils
- Final Review Problem Session: Tomorrow Night

RLC circuit



Currents and voltages are sinusoidal

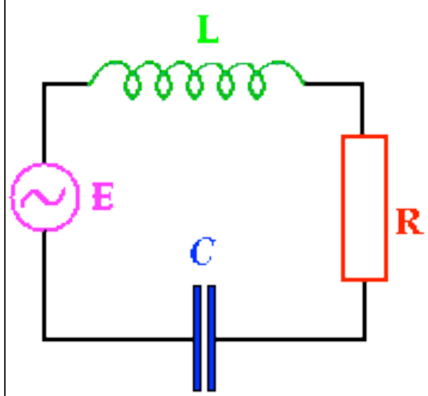
Charge and discharge of capacitor

Power only dissipated in R

At resonance frequency maximum energy stored in electric and magnetic fields.

This circuit can be used to pick out selected frequencies. e.g. in a radio receiver.

Voltages



Voltage across R ,L , C are sinusoidal

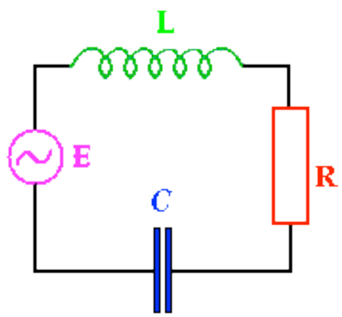
But with different phase relative to the current, and relative to each other

The sum of voltage

$$\Delta V_s = \Delta V_R + \Delta V_L + \Delta V_C$$

But at any time the voltages are not maximum across R, L and C but differ because of phase shifts.

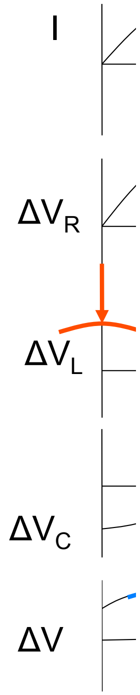
Sum of Voltages



$I = I_{max} \sin\omega t$

$\Delta V = \Delta V_R + \Delta V_L + \Delta V_C$

$\Delta V = \Delta V_{max} \sin(\omega t + \Phi_i)$



Impedance, Z

$$\Delta V = \sqrt{(\Delta V_L - \Delta V_C)^2 + \Delta V_R{}^2}$$

$$\Delta V = \sqrt{(IX_L - IX_C)^2 + I^2R^2}$$

$$\Delta V = I\sqrt{(X_L - X_C)^2 + R^2}$$

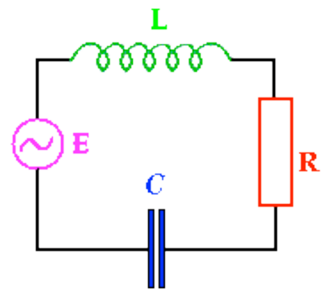
$$\Delta V = IZ$$

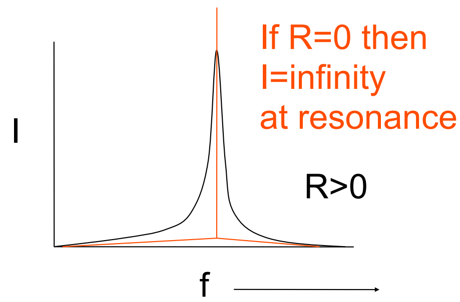
Like Ohm's Law

$$Z = \sqrt{(X_L - X_C)^2 + R^2}$$

L, C and R contribute to Z, Impedance.

Resonance





$$Z = \sqrt{(X_L - X_C)^2 + R^2}$$

When $X_L = X_C$
then $X_L - X_C = 0$
Z becomes a minimum
I becomes maximum

resonance frequency

$$X_C = X_L$$

$$\frac{1}{2\pi f_o C} = 2\pi f_o L$$

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

f

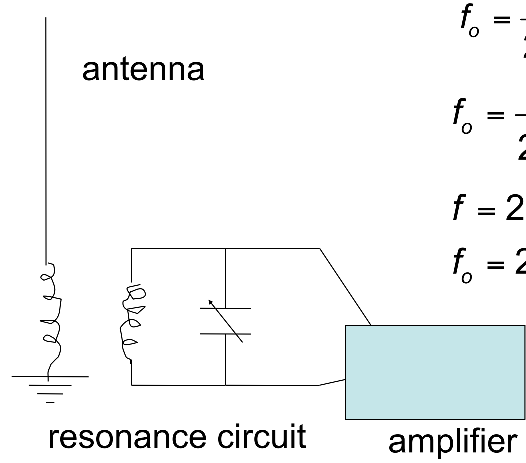
34. A resonance circuit in a radio receiver is tuned to a certain station when the inductor has a value of 0.20 mH and the capacitor has a value of 30 pF. Find the frequency of the station.

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

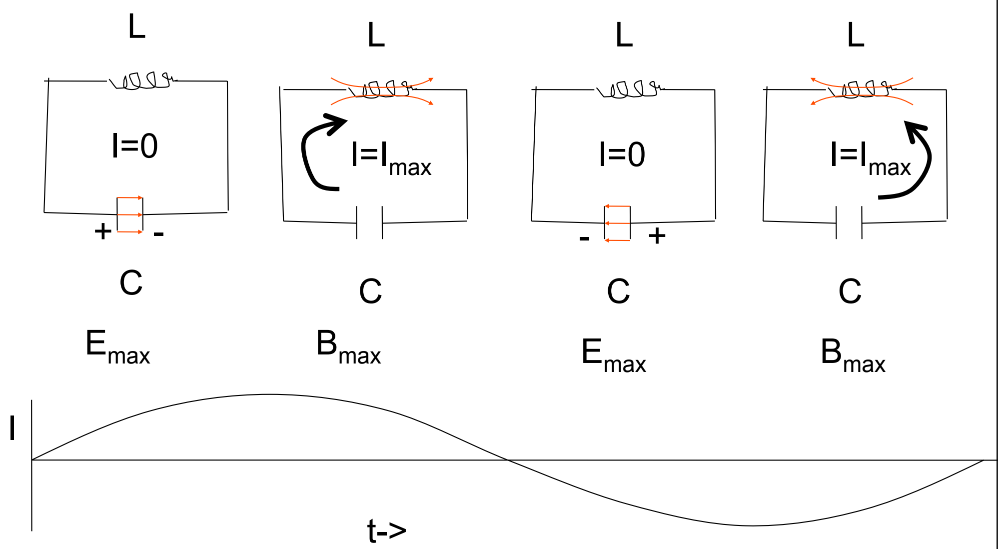
$$f_o = \frac{1}{2\pi\sqrt{0.2x10^{-3}(30x10^{-12})}}$$

$$f = 2.05x10^{6}Hz$$

$$f_o = 2.05MHz$$



For LC circuit (R->0) at resonance
Energy oscillates between Electric and Magnetic Fields



21 Electromagnetic Radiation

Maxwell's prediction

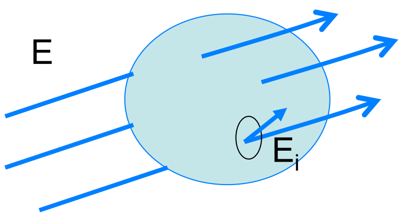
properties of electromagnetic waves

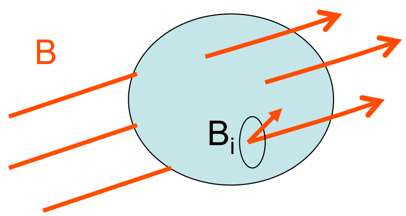
James Clerk Maxwell

- Electricity and magnetism were originally thought to be unrelated
- in 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena

Electric and Magnetic Field Relations in Free Space

closed surface





Gauss's Law

$$\sum_{surface} E_i \Delta\ell_i = \frac{q}{\varepsilon_o} = 0$$

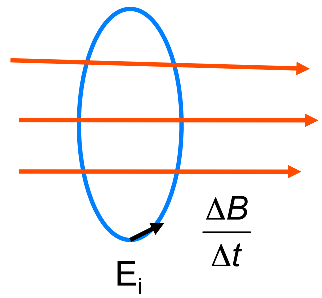
q=0

Gauss's Law for Magnetism

$$\sum_{surface} B_i \, \Delta A_i = 0$$

no magnetic monopoles

closed loop



$$\varepsilon = \sum_{loop} E_i \Delta \ell_i = -\frac{A \Delta B}{\Delta t}$$

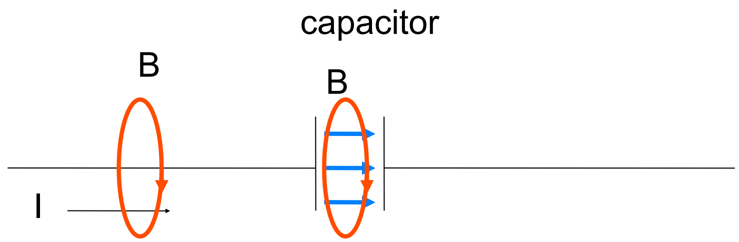
Faraday's Law

Changing B field generates an E field

Does a changing E field produce a B field?

Maxwell discovered that it does.

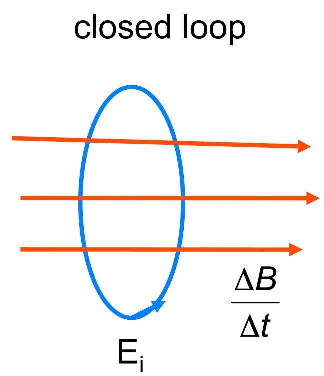
Consider a current flowing into a capacitor. The current changes the charge on the capacitor. Changing the E field across the capacitor. The changing E field results in a displacement current.

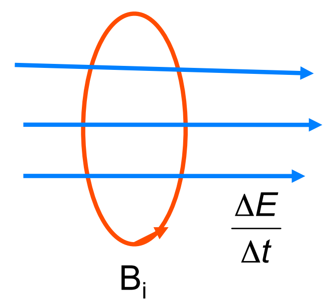


$$\frac{\Delta E}{\Delta t}$$

Displacement current

$$i_d = \varepsilon_o \frac{\Delta \Phi_E}{\Delta t} = \varepsilon_o \frac{A \Delta E}{\Delta t}$$





$$\varepsilon = \sum E_i \Delta\ell_i = -\frac{A\Delta B}{\Delta t}$$

Faraday's Law

Changing B field generates an E field

$$\sum B_i \Delta\ell_i = \mu_o I_d = \mu_o \varepsilon_o \frac{A\Delta E}{\Delta t}$$

Ampere's Law in free space

Changing E field generates a B field

Maxwell's relations

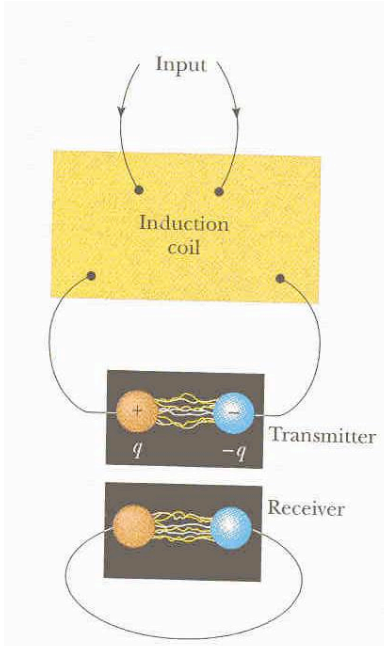
Gauss' Law in Free space– Electric flux through a surface is zero in the absence of charge

Gauss' Law for magnetism - Magnetic lines form closed loops (no magnetic monopoles)

Faraday's Law - A changing magnetic field produces an electric field.

Ampere's Law in Free space - A changing electric field is equivalent to a current. Thus, a changing electric field produces a magnetic field.

Using the equations relating these ideas (Maxwell's equations) Maxwell predicted the existence of electromagnetic radiation.



Heinrich Hertz,
German Physicist 1857-1894

Showed that electromagnetic waves could be produced
and detected.

Electromagnetic radiation

- Electric and magnetic fields radiate as waves from an accelerating charge
- The waves propagate at the speed of light
- The waves propagate in a vacuum.
- Carries energy and momentum

Maxwell predicted the speed of light

Maxwell's equations predicted the speed of light to be determined by fundamental constants.

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

$$c = \frac{1}{\sqrt{4\pi x 10^{-7}(8.85419 x 10^{-12})}}$$

$$c = 2.99792 x 10^{8}\, m/s$$

Experimental value

$c_{exp.}$ = 2.99792458x10^8 m/s

exact agreement

Speed of light is a universal constant.

3.00×10^8 m/s

approximately 1 ft per nanosecond (10^{-9} s)

The time for light to travel halfway around the earth

2×10^8 m is about 0.7 s

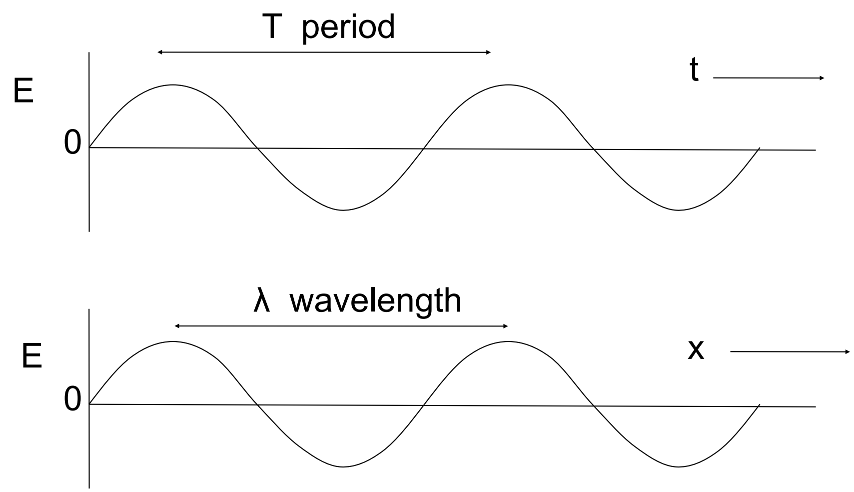
A radar system determines the distance from an approaching airplane by the round trip time of a radar pulse. If a plane is 10 km away how long does the radar pulse take to return to the radar.

radar

$$t = \frac{2d}{c} = \frac{2(10x10^3)}{3x10^8} = 6.7x10^{-5}s$$

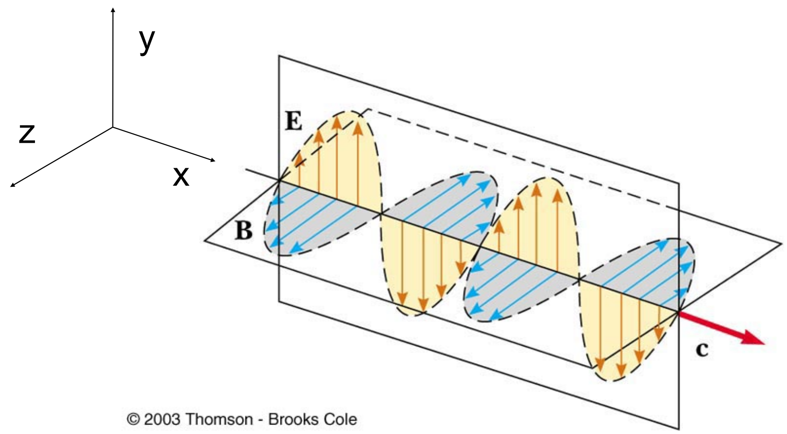
$67\mu s$

Electromagnetic Waves



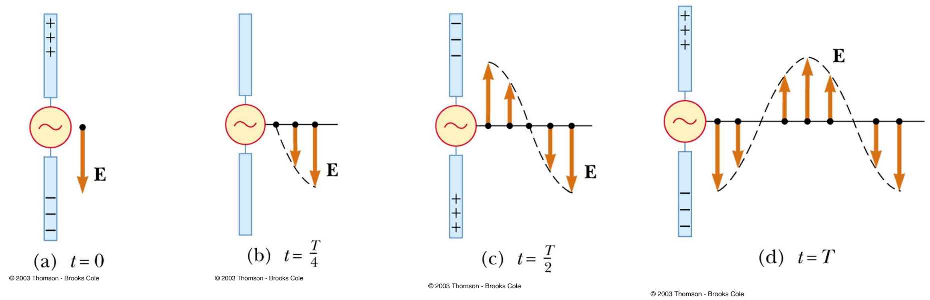
$$f = \frac{1}{T} \qquad c = \lambda f$$

Electromagnetic plane wave
E and B fields perpendicular to each other and to the direction of propagation, in phase



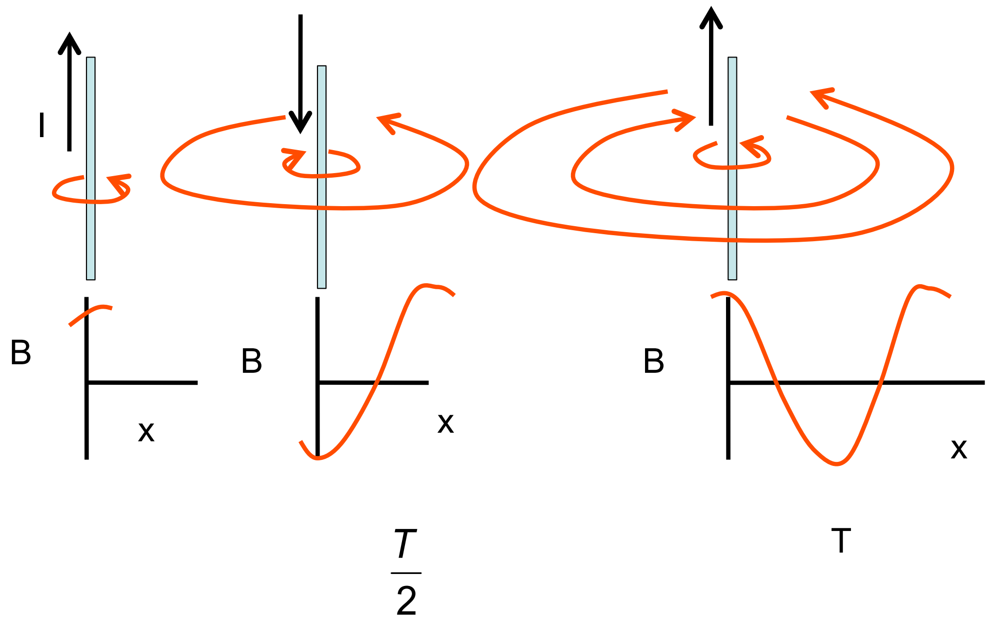
Represention the E and B fields at one point in time for different values of x in the direction of propagation

Production of electromagnetic waves by electric fields in a dipole antenna



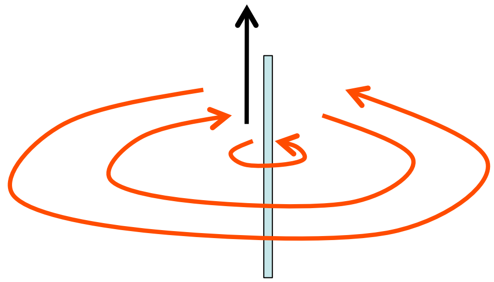
The E field due to accelerating charges on the antenna propagates at the speed of light.

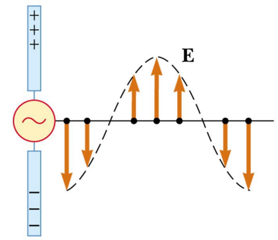
Production of magnetic fields by dipole antenna



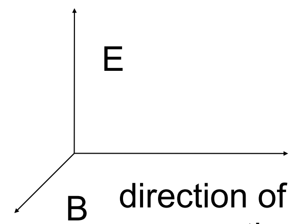
At long distances from the antenna- plane wave

E field perpendicular to B field





(d) $t = T$



Some properties of electromagnetic radiation

Speed of light $c=2.99\times10^{8}$ m/s

Electric and magnetic fields both present in fixed ratio

$$\frac{E}{B} = c$$

Energy is carried by both E field and B field
The average power / area carried by the E field and B field are equal.

$$\frac{Power}{area} = \frac{B_{max}^2 c}{2\mu_o} = \frac{E_{max}^2}{2\mu_o c} = \frac{E_{max} B_{max}}{2\mu_o}$$

A radio transmitter has a range of 50 km and a power output of 1.0 kW. What is the max E field at the edge of the range if the signal is transmitted uniformly over a hemisphere?

$$\frac{power}{area} = \frac{p}{2\pi R^2} = \frac{E_{\max}^2}{2\mu_o c}$$

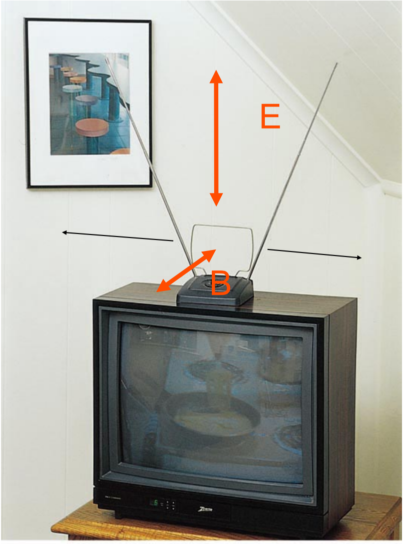
$$E_{\max} = \sqrt{\frac{p\mu_o c}{\pi R^2}} = \sqrt{\frac{(1000)(4\pi x10^{-7})(3x10^8)}{\pi(50x10^3)^2}} = 7x10^{-3} V/m$$

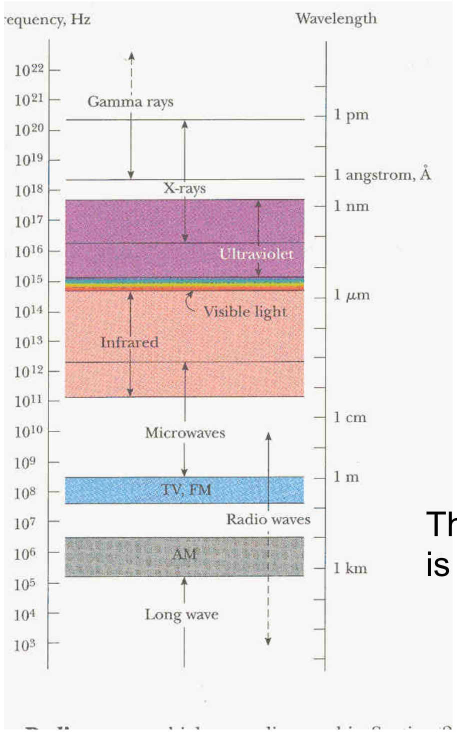
Antennas
Dipole antenna detects the E field
Loop antenna detects the B field

What is the direction of the E fields and B fields?

What is the direction to the TV station?

The direction of propagation is perpendicular to E and B
The station is to the left or right





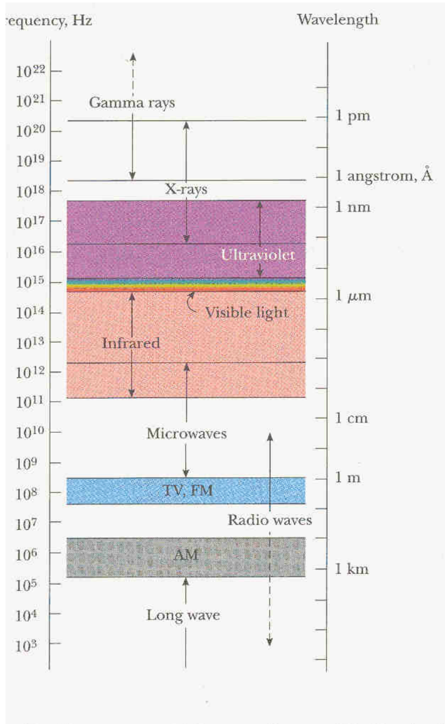
Electromagnetic radiation

$$\lambda = \frac{c}{f}$$

Find the wavelength of EM waves from a fm radio station f=100MHz

$$\lambda = \frac{c}{f} = \frac{3x10^8}{100x10^6} = 3.0m$$

The size of the optimal antenna is about ¼ wavelength

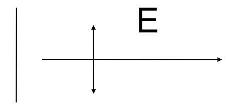


Electromagnetic radiation

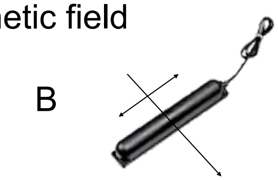
$$\lambda = \frac{c}{f}$$

Radio f=100kHz-100 MHz
λ= 1km-1m

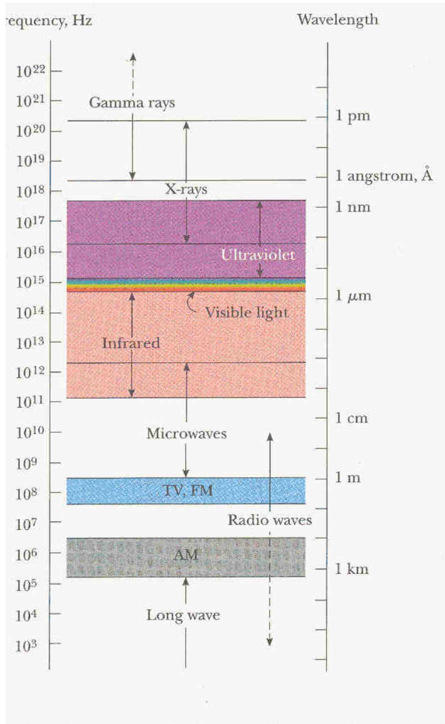
dipole antenna-detect electric field



ferrite core antenna- detect magnetic field



Electromagnetic radiation

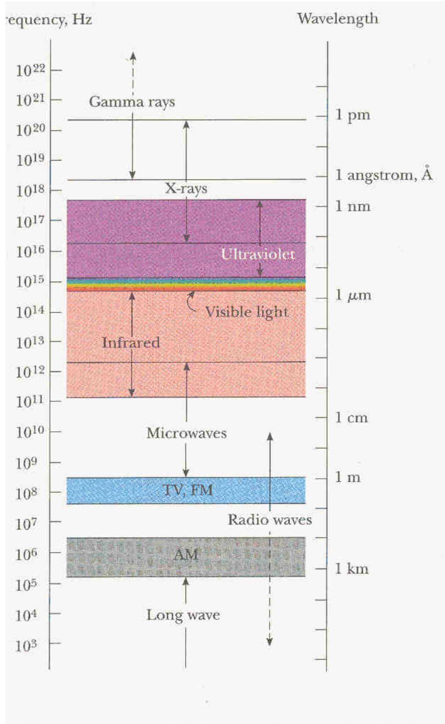


$$\lambda = \frac{c}{f}$$

microwaves, cell phones
f~1-10 GHz
λ~ 1-10 cm

dipole antenna

length =λ/4



Electromagnetic radiation

visible light
f~10^{15} Hz
λ~ 400-700 nm

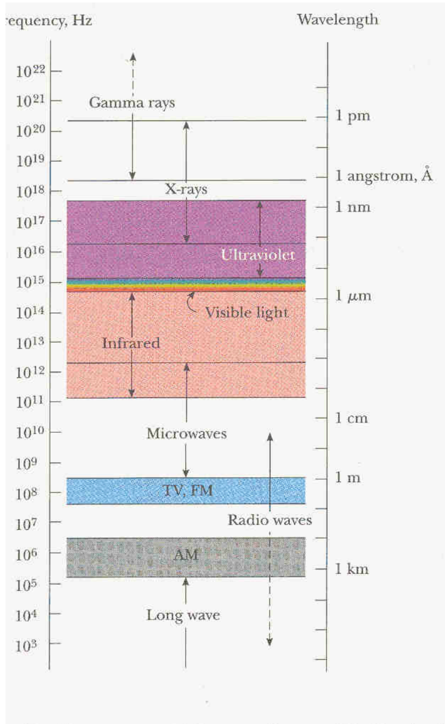
stained glass, gold particles
with diameter ~100 nm
scatter specific colors of light

Red Laser

visible light λ~650 nm

oscillations due to excited electrons losing energy
in going from excited high energy states.

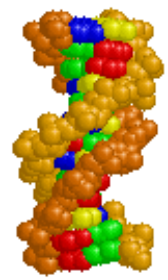
Diffraction effects occur when light passes through
Periodic structures with same length scale as the
wavelength



Electromagnetic radiation

x-rays
f~10^{19} Hz
λ~0.1 nm

X-ray diffraction
x-rays scatter from atoms
give information about
spatial dimensions ~0.1 nm



Summary

Electric Fields -produced by charges and changing magnetic fields

Magnetic Fields -produced by moving charges and changing electric fields

Electromagnetic radiation- results from changing electric and magnetic fields- Carries energy and momentum through space.