Basic Physics 2 Lecture Module

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Basic Physics 2
Lecture Module

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General Electricity & Magnetism

General Electricity & Magnetism

- General Electricity
- General magnetism
- Electricity & magnetism relationship
- Direct current & alternating current
- Conductor & isolator
- Superconductivity
- EMF: Batteries

Electric Charge

- Charge is an intrinsic property of matter, it comes in two opposite senses, positive and negative. Like charges repel, opposite charges attract.
- There is a smallest unit of charge, e, which is $e = 1.602\times10^{-19}$ C. Charge can only come in units of e, so charge is quantized. The unit of charge is the Coulomb.
- Charge is conserved. Charge can be destroyed only in pairs (+e and –e can annihilate each other). Otherwise, it can only be moved from place to place.
- Mobile charges we will usually deal with are electrons, which can be removed from an atom to make positive charge, or added to an atom to make negative charge. A positively charged atom or molecule can also be mobile.
- Materials can be either conductors or insulators. Conductors and insulators can both be charged by adding charge, but charge can also be induced.
- Spherical conductors act as if all of the charge on their surface were concentrated at their centers.

General Electricity

- The collection or flow of electrons in the form of an electric charge.
- As electrons collect on an object, it becomes negatively charged. As electrons leave an object it attains a positive charges. Charges interact with each other.
- Surrounding every charge is an electric field. Through the electric field, a charge is able to push or pull on another charge.
- Static electricity is stationary or collects on the surface of an object, whereas current electricity is flowing very rapidly through a conductor.
- The flow of electricity in current electricity has electrical pressure or voltage. Electric charges flow from an area of high voltage to an area of low voltage.

Magnetism

- Magnetism is the properties and interactions of magnets.
- The earliest magnets were found naturally in the mineral *magnetite* which is abundant the rock-type *lodestone*. These magnets were used by the ancient peoples as compasses to guide sailing vessels.
- Magnets produce magnetic forces and have magnetic field lines. Magnets have two ends or poles, called north and south poles. At the poles of a magnet, the magnetic field lines are closer together.
- Magnetic substances like iron, cobalt, and nickel are composed of small areas where the groups of atoms are aligned like the poles of a magnet. These regions are called domains. All of the domains of a magnetic substance tend to align themselves in the same direction when placed in a magnetic field. These domains are typically composed of billions of atoms.
- The nickel iron core of the earth gives the earth a magnetic field much like a bar magnet.

Electricity & Magnetism Relationship

- When an electric current passes through a wire a magnetic field is formed. When electric current flows through a wire, a magnetic field forms around the wire. The direction of the magnetic field depends on the direction of the current in the wire.
- When an electric current is passed through a coil of wire wrapped around a metal core, a very strong magnetic field is produced. This is called an electromagnet.
- A galvanometer is an electromagnet that interacts with a permanent magnet. The stronger the electric current passing through the electromagnet, the more is interacts with the permanent magnet.
- Moving a loop of wire through a magnetic field produces an electric current, this is electromagnetic induction.
- A generator is used to convert mechanical energy into electrical energy by electromagnetic induction, whereas an electric motor is a device which changes electrical energy into mechanical energy.

Direct & Alternating Current

- Direct current is electrical current which comes from a battery which supplies a constant flow of electricity in one direction.
- Alternating current is electrical current which comes from a generator. As the electromagnet is rotated in the permanent magnet the direction of the current *alternates* once for every revolution.
- The DC source is a battery, current flows in one direction.
- The AC source is the generator and the current alternates once for each revolution.

Conductor & Insulator

- A conductor is a material which allows an electric current to pass. Metals are good conductors of electricity.
- An insulator is a material which does not allow an electric current to pass. Nonmetals are good conductors of electricity. Plastic, glass, wood, and rubber are good insulators.
- Both insulators and conductors can be charged, the difference is that:
  - On an insulator charges are not able to move from place to place. If you charge an insulator, you are typically depositing (or removing) charges only from the surface, and they will stay where you put them.
  - On a conductor, charges can freely move. If you try to place charge on a conductor, it will quickly spread over the entire conductor.

Superconductivity

- In normal materials, there is always some resistance, even if low, to current flow. This seems to make sense—start current flowing in a loop (using a battery, say), and if you remove the battery the current will eventually slow and stop.

- Remarkably, at very low temperatures (~4 K) some conductors lose all resistance. Such materials are said to be superconductors. In such a material, once you start current flowing, it will continue to flow "forever," like some sort of perpetual motion machine.

- Nowadays, "high-temperature" superconductors have been discovered that work at up to 150 K, which is high enough to be interesting for technological applications such as giant magnets that take no power, perhaps for levitating trains and so on.

EMF: Batteries

- A battery is a source of charge, but also a source of voltage (potential difference). We describe a battery's ability to create a charge flow (a current) as an electromotive force (EMF).
- Other sources of EMF are, for example, an electric generator, solar cells, fuel cells, etc.
- Batteries are composed of a chemical substance which can generate voltage which can be used in a circuit. There are two kinds of batteries: dry cell and wet cell batteries.
- The zinc container of the dry cell contains a moist chemical paste surrounding a carbon rod suspended in the middle.
- A wet cell contains two connected plates made of different metals or metal compounds in a conducting solution. Most car batteries have a series of six cells, each containing lead and lead oxide in a sulfuric acid solution.

How Do Batteries Work?

- A battery is a source of charge, but also a source of voltage (potential difference).
- We earlier saw that there is a relationship between energy, charge, and voltage $U = qV$.
- Thus, a battery is a source of energy. We describe a battery's ability to create a charge flow (a current) as an *electromotive force*, or emf.
- We need a symbol for emf, and we will use an E, but it needs to be distinguishable from electric field, so we will use a script $\mathscr{E}$.
- The unit of emf is just the volt (V).
- Other sources of emf are, for example, an electric generator, solar cells, fuel cells, etc.
- Here is a case where two emf sources are connected in opposing directions. The direction of i indicates that $\mathscr{E}_a > \mathscr{E}_b$. In fact, emf a charges emf b.

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Basic Electric & Ohm's Law

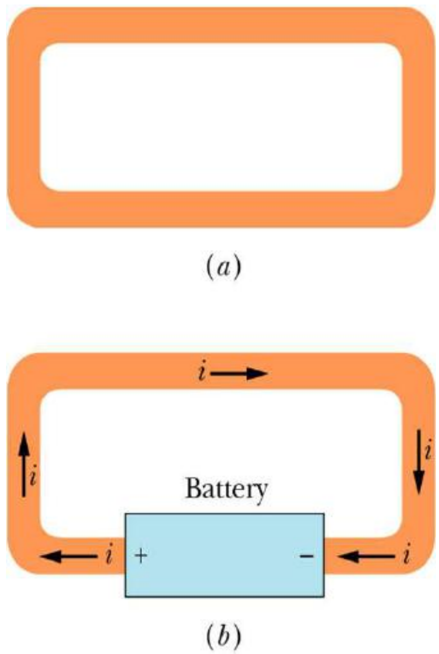
Basic Electric, Ohm Law

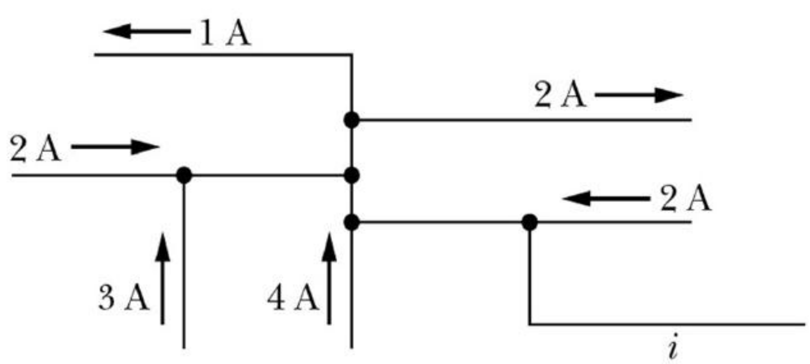
- Current
- Resistance
- Resistivity & conductivity
- Ohm’s law
- Electric circuits
- Electrical power & energy

Current

- Current is the flow of electrical charge, i.e. amount of charge per second moving through a wire, $i = dq/dt$.
- It is a scalar, not a vector, but it has a direction—positive in the direction of flow of positive charge carriers.
- Any way that you can get charges to move will create a current, but a typical way is to attach a battery to a wire *loop*.
- Charges will flow from the + terminal to the – terminal (again, it is really electrons that flow in the opposite direction, but current is defined as the direction of positive charge carriers).

Units: ampere
1 A = 1 C/s



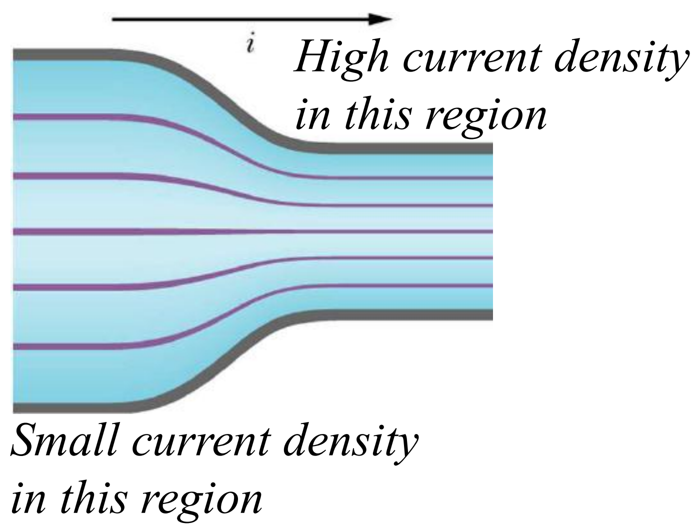


Current Density

- When we care only about the total current i in a conductor, we do not have to worry about its shape.
- However, sometimes we want to look in more detail at the current flow inside the conductor. Similar to what we did with Gauss' Law (electric flux through a surface), we can consider the flow of charge through a surface. To do this, we consider (charge per unit time) per unit area, i.e. current per unit area, or *current density*. The units are amps/square meter (A/m^2).
- Current density is a vector (since it has a flow magnitude and direction). We use the symbol . The relationship between current and current density is

$$\vec{J}$$

$$i = \int \vec{J} \cdot d\vec{A}$$



Electrical Resistance

- What is Resistance (R) is the opposition to the flow of an electric current, causing the electrical energy to be converted to thermal energy or light.

- The metal which makes up a light bulb filament or stovetop eye has a high electrical resistance. This causes light and heat to be given off.

- The unit for measuring resistance is the ohm (Ω). The resistance of short thick piece of wire is less than the resistance of a long, thin piece of wire.

Resistance

- Resistance is defined to be $R = \dfrac{V}{i}$.

  That is, we apply a voltage *V*, and ask how much current *i* results. This is called Ohm's Law.

- If we apply the voltage to a conducting wire, the current will be very large so R is small.

- If we apply the voltage to a less conducting material, such as glass, the current will be tiny so R is very large.

- The unit of resistance is the ohm, W. (Greek letter omega.)

- 1 ohm = 1 W = 1 volt per ampere = 1 V/A

Resistivity and Conductivity

- Rather than consider the overall resistance of an object, we can discuss the property of a material to resist the flow of electric current.
- This is called the *resistivity*. The text uses (re-uses) the symbol *r* for resistivity. Note that this IS NOT related to the charge density, which we discussed earlier.
- The resistivity is related not to potential difference *V* and current *i*, but to electric field *E* and current density *J*.

$$\rho = \frac{E}{J}$$

Definition of resistivity

Units V/m over A/m^2 = Vm/A = ohm-meter = Ω m

(*a*)

(*b*)

Note that the ability for current to flow in a material depends not only on the material, but on the electrical connection to it.

Note use (re-use) of σ for conductivity. NOT surface charge density.

$$\sigma = \frac{1}{\rho}$$

Definition of conductivity

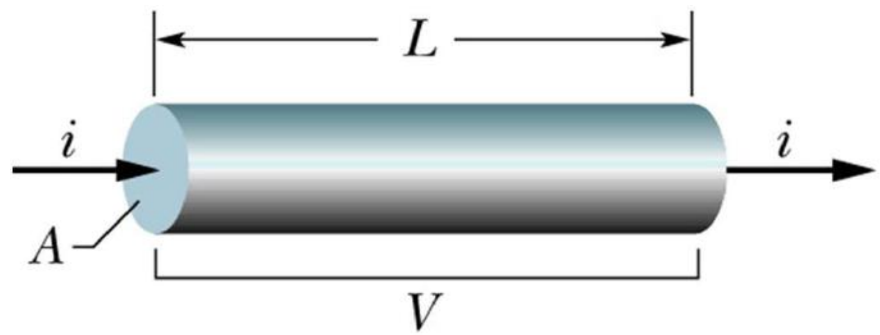
More on Resistivity

- Since resistivity has units of ohm-meter, you might think that you can just divide by the length of a material to find its resistance in ohms.

$$R = \rho / L?$$

since $E = V / L$ and $J = i / A$

resistivity is $\rho = \frac{E}{J} = \frac{V/L}{i/A} = RA/L$



$$R = \rho \frac{L}{A}$$

Resistance from resistivity

$$\rho - \rho_0 = \rho_0 \alpha (T - T_0)$$

Dependence on temperature: you can imagine that a higher temperature of a material causes greater thermal agitation, and impedes the orderly flow of electricity. We consider a temperature coefficient a:

Ohm's Law

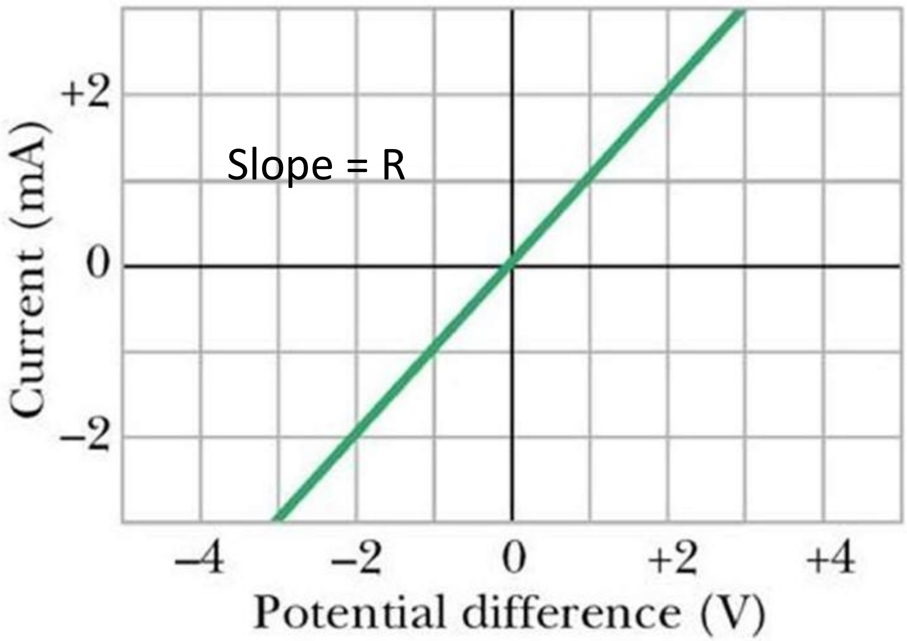
- Ohm's law is an assertion that the current through a device is always directly proportional to the potential difference applied to the device.

- Resistance, R, (units, ohms, Ω) is the proportionality between voltage V applied, and current, i.

$$R = \frac{V}{i}$$

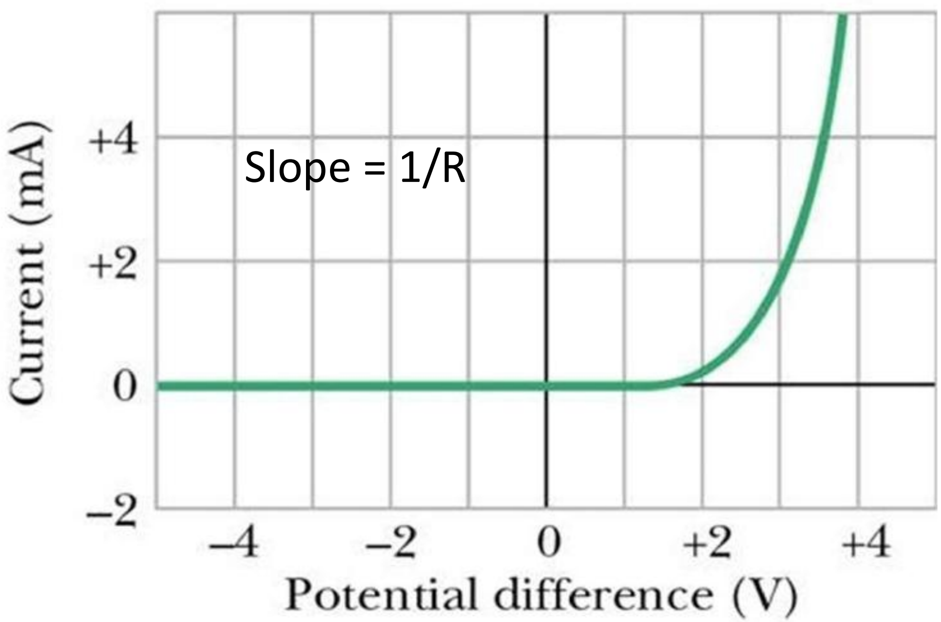
- A conducting device obeys Ohm's law when the resistance of the device is independent of the magnitude and polarity of the applied potential difference. A conducting material obeys Ohm's law when the resistivity of the material is independent of the magnitude and direction of the applied electric field.

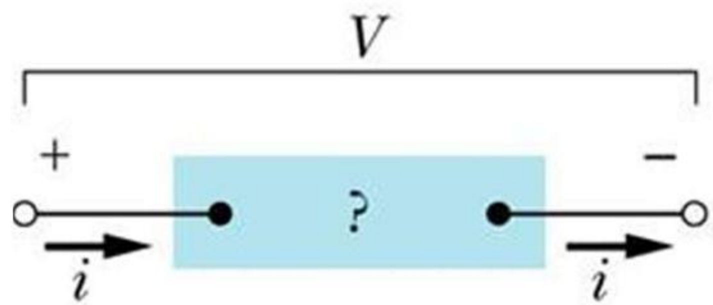
- Ohm's Law states that R is a constant. It is not always a constant, but if not, the device does not obey Ohm's Law.



Does not obey Ohm’s Law

R=1000 Ω





Electric Circuits

- Circuits typically contain a voltage source, a wire conductor, and one or more devices which use the electrical energy.
- A series circuit is one which provides a single pathway for the current to flow. If the circuit breaks, all devices using the circuit will fail. A parallel circuit has multiple pathways for the current to flow. If the circuit is broken the current may pass through other pathways and other devices will continue to work.
- A closed circuit is one in which the pathway of the electrical current is complete and unbroken. An open circuit is one in which the pathway of the electrical current is broken. A switch is a device in the circuit in which the circuit can be closed (turned on) or open (turned off).
- Most household wiring is logically designed with a combination of parallel circuits. Electrical energy enters the home usually at a breaker box or fuse box and distributes the electricity through multiple circuits. A breaker box or fuse box is a safety feature which will open

Electrical Power & Energy

- Electrical Power is the product of the current (I) and the voltage (v). The unit for electrical power is the same as that for mechanical power in the previous module – the watt (W)

$$\text{power} = \text{current} \times \text{voltage difference}$$
$$P\,(\text{watts}) = I\,(\text{amperes}) \times V\,(\text{volts})$$

- Electrical energy is a measure of the amount of power used and the time of use. Electrical energy is the product of the power and the time.

$$\text{energy} = \text{power} \times \text{time}$$
$$E\,(\text{kWh}) = P\,(\text{kW}) \times t\,(\text{h})$$

- Recall that power is energy per unit time, $P = \frac{dU}{dt}$ (watts).
- Recall also that for an arrangement of charge, *dq*, there is an associated potential energy *dU = dqV*.
- Thus,

$$P = \frac{dq}{dt}V = iV$$

Rate of electrical energy transfer

Units: $1\ \mathrm{VA} = (1\ \mathrm{J/C})(1\ \mathrm{C/s}) = 1\ \mathrm{J/s} = 1\ \mathrm{W}$

- In a resistor that obeys Ohm's Law, we can use the relation between *R* and *i*, or *R* and *V*, to obtain two equivalent expressions:

$$P = i^2 R \qquad P = \frac{V^2}{R}$$

Resistive dissipation

- In this case, the power is dissipated as heat in the resistor.

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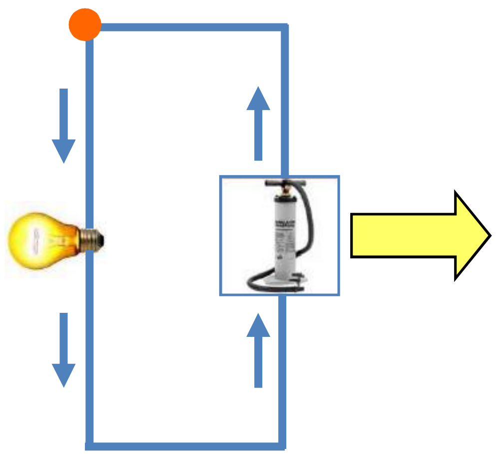
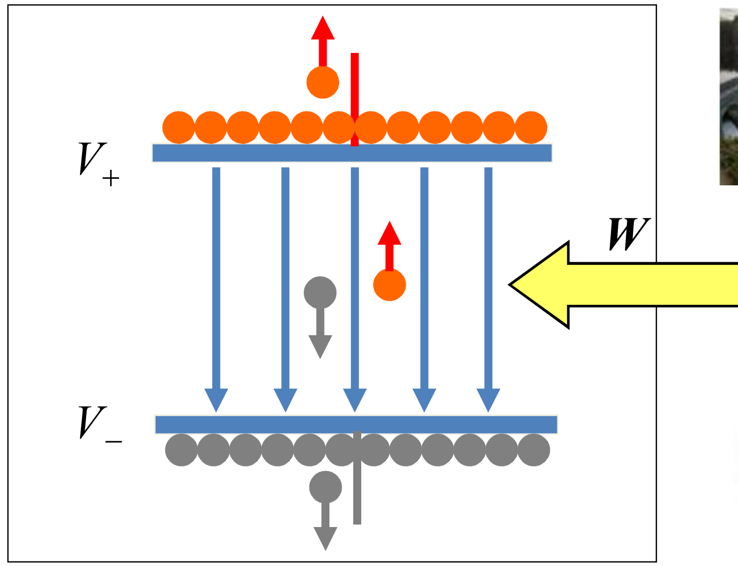
Circuits

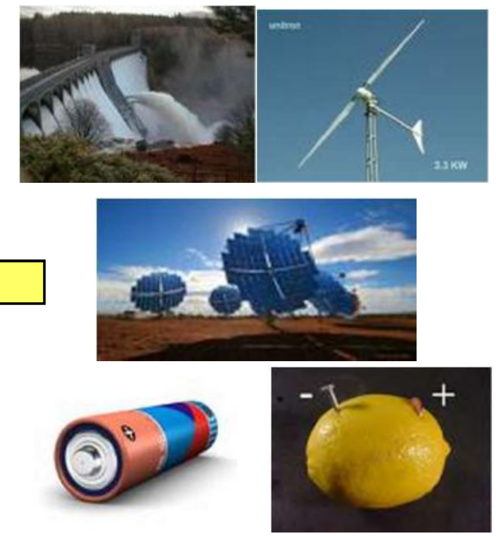
Circuits

- EMF
- Kirchoff's rules
- Single loop circuit
- Resistance in series
- Resistance in parallel
- Multi loop circuit
- RC circuit

Emf Devices





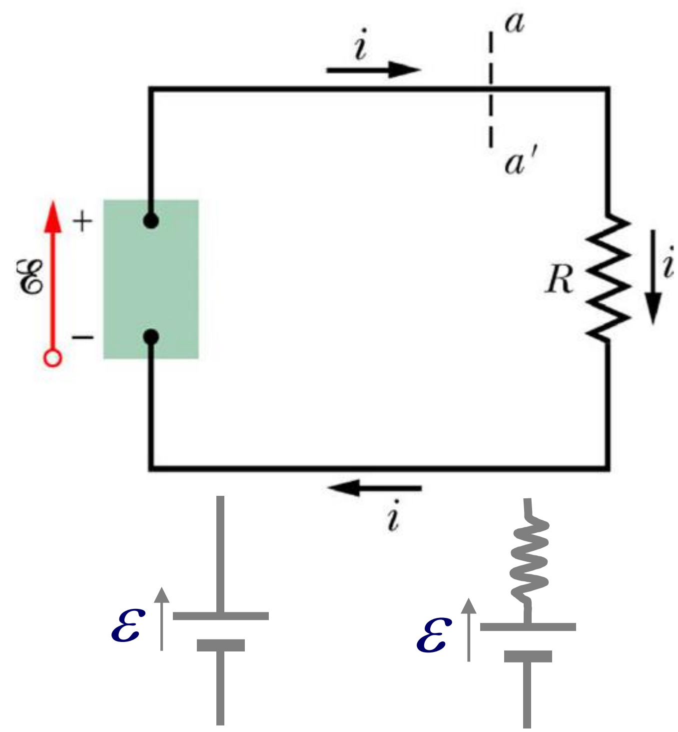


- The term emf comes from the outdated phrase electromovitive force.
- emf devices include battery, electric generator, solar cell, fuel cell,……
- emf devices are sources of charge, but also sources of voltage (potential difference).
- emf devices must do work to pump charges from lower to higher terminals.
- Source of emf devices: chemical, solar, mechanical, thermal-electric energy.

Emf $\mathcal{E}$

- We need a symbol  for emf, and we will use a script to $\mathcal{E}$ represent emf. $\mathcal{E}$ is the potential difference between terminals of an emf device.
- The SI unit for emf is Volt (V).
- We earlier saw that there is a relationship between energy, charge, and voltage $dqV = dW$
- So, $$\varepsilon = \frac{dW}{dq}$$
- Power $dW = \varepsilon dq = \varepsilon i dt = P dt$

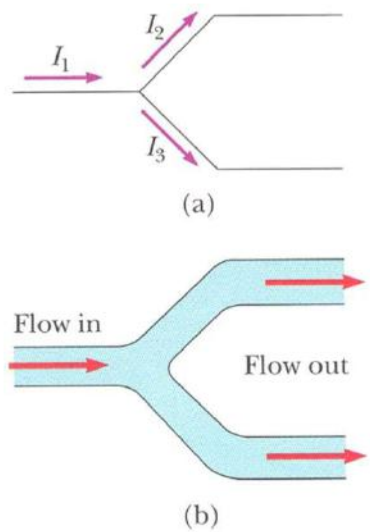
$$P = \varepsilon i$$



Ideal emf device:
$V = \mathcal{E}$
(open or close loop)

Real emf device:
$V = \mathcal{E}$ *(open loop)*
$V < \mathcal{E}$ *(close loop)*

Kirchhoff's Rules

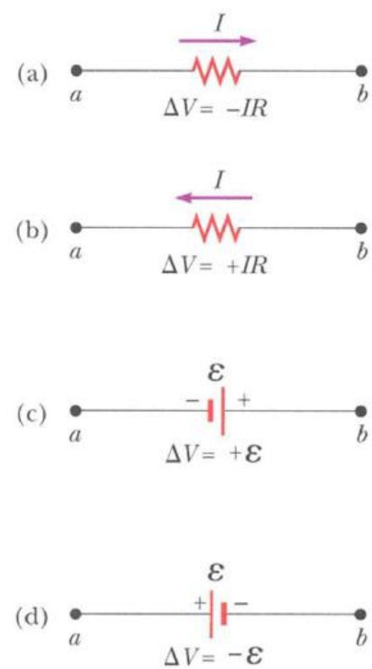


- Junction Rule: At any junction, the sum of the currents must equal zero:

$$\sum_{junction} i = 0$$

- Loop Rule: The sum of the potential differences across all elements around any closed circuit loop must be zero:

$$\sum_{closedloop} \Delta V = 0$$



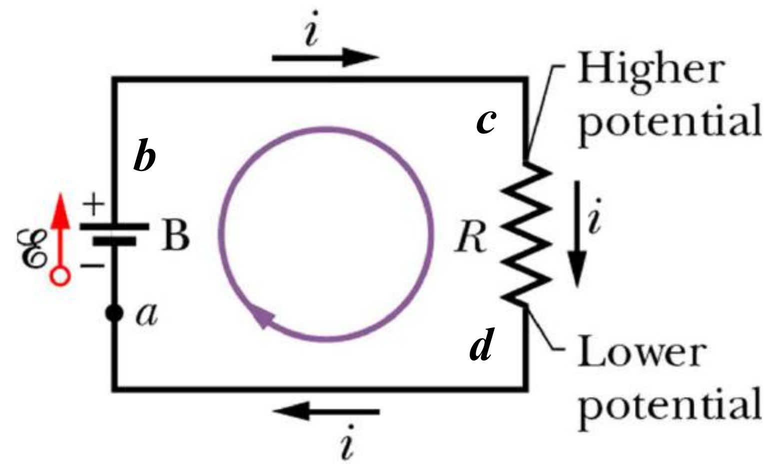
- For a move through a resistance in the direction of current, the change in potential is –iR; in the opposite direction it is +iR.
- For a move through an ideal emf device in the direction of the emf arrow, the change in potential is +ε; in the opposite direction it is - ε.

A Single-Loop Circuit

- Travel clockwise from a:

$$\Delta V_{ba} = V_b - V_a = \varepsilon$$
$$\Delta V_{cb} = V_c - V_b = 0$$
$$\Delta V_{dc} = V_d - V_c = -iR$$
$$\Delta V_{ad} = V_a - V_d = 0$$
$$\sum_{closedloop} \Delta V = \varepsilon + 0 - iR + 0 = 0$$

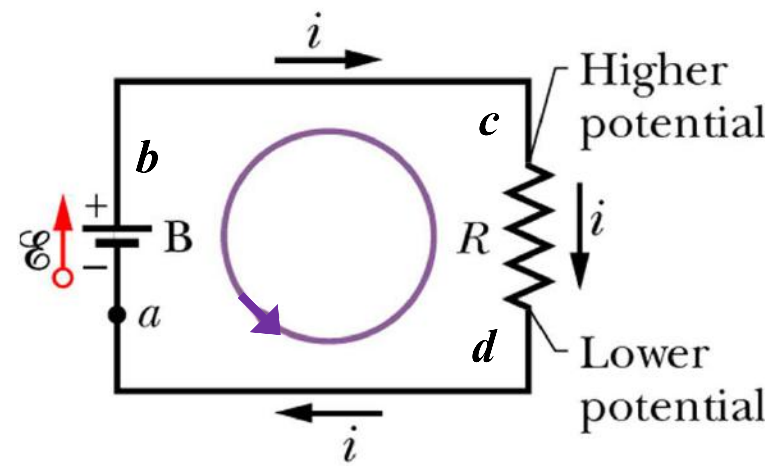
$$\varepsilon - iR = 0$$
$$i = \frac{\varepsilon}{R}$$



- Travel counterclockwise from a:

$$\Delta V_{da} = V_d - V_a = 0$$
$$\Delta V_{cd} = V_c - V_d = iR$$
$$\Delta V_{bc} = V_b - V_c = 0$$
$$\Delta V_{ab} = V_a - V_b = -\varepsilon$$
$$\sum_{closedloop} \Delta V = 0 + iR + 0 - \varepsilon = 0$$

$$iR - \varepsilon = 0$$
$$i = \frac{\varepsilon}{R}$$



Resistance in Series

- Junction Rule: When a potential difference V is applied across resistances connected in series, the resistances have identical currents i:

$$i = i_1 = i_2 = i_3$$

- Loop Rule: The sum of the potential differences across resistances is equal to the applied potential difference V:

$$\varepsilon - iR_1 - iR_2 - iR_3 = 0$$

$$i = \frac{\varepsilon}{R_1 + R_2 + R_3}$$

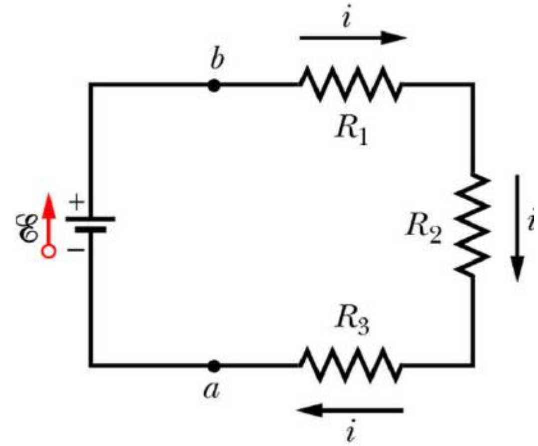
$$\varepsilon - iR_{eq} = 0$$

$$i = \frac{\varepsilon}{R_{eq}}$$

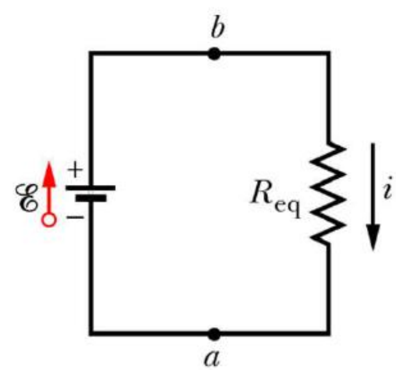
$$R_{eq} = R_1 + R_2 + R_3$$

- The equivalent resistance of a series combination of resistors is the numerical sum of the individual resistances and is always greater than any individual resistance.

$$R_{eq} = \sum_{i=1}^{n} R_i$$



(a)

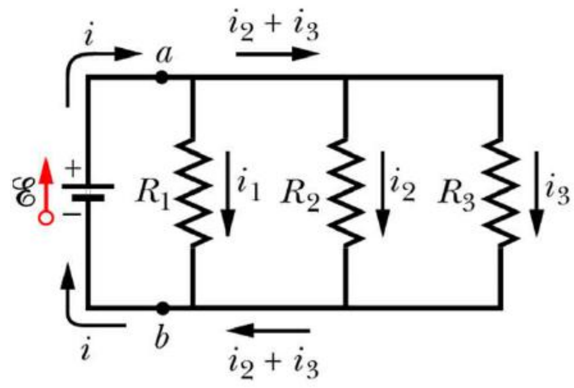


(b)

Resistances in Parallel

- When a potential difference V is applied across resistances connected in parallel, the resistances all have that same potential difference V.

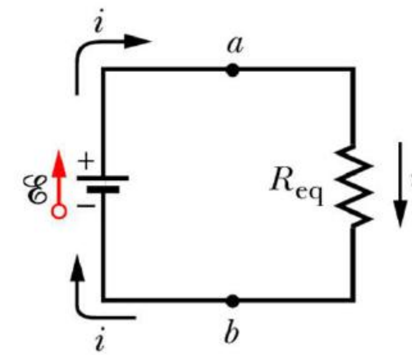
$$V = V_1 = V_2 = V_3$$



(a) Junction Rule:

$$i_1 = \frac{V}{R_1}, i_2 = \frac{V}{R_2}, i_3 = \frac{V}{R_3}$$

$$i = i_1 + i_2 + i_3 = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$



(b) Loop Rule:

$$V - iR_{eq} = 0$$

$$i = \frac{V}{R_{eq}}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

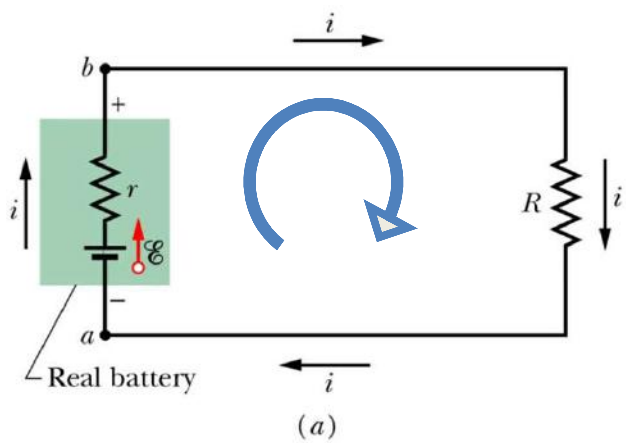
- The inverse of the equivalent resistance of two or more resistors in a parallel combination is the sum of the inverse of the individual resistances. Furthermore, the equivalent resistance is always less than the smallest resistance in the group.

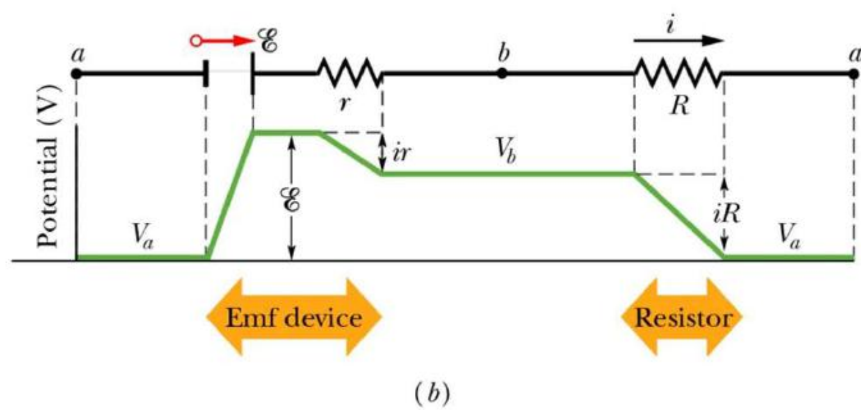
$$\frac{1}{R_{eq}} = \sum_{i=1}^{n} \frac{1}{R_i}$$

Real Battery

- Real battery has internal resistance to the internal movement of charge.
- Current: $\varepsilon - ir - iR = 0$ $\quad$ $i = \dfrac{\varepsilon}{R+r}$
- Potential difference:

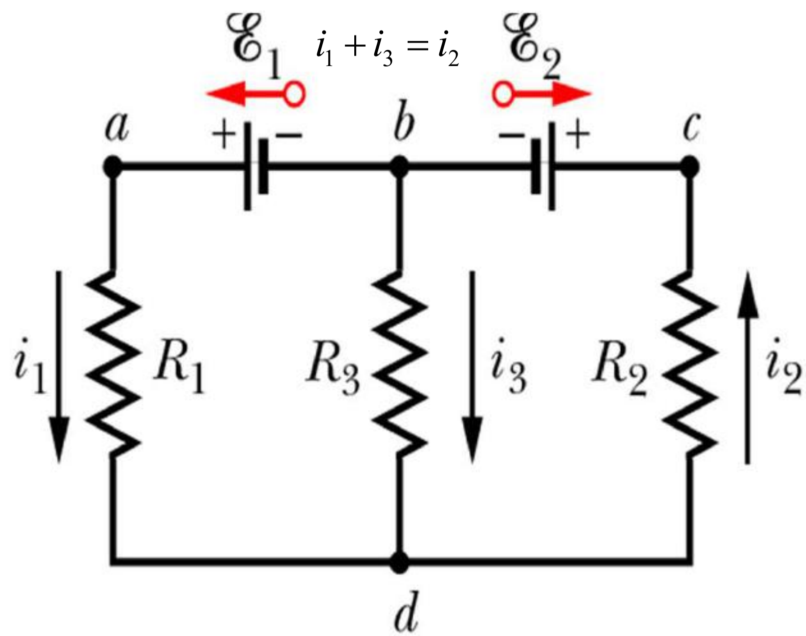
  clockwise: $V_a + \varepsilon - ir = V_b$ $\quad$ $V_b - V_a = \varepsilon - ir = \varepsilon - \dfrac{\varepsilon}{R+r} r = \dfrac{\varepsilon}{R+r} R$
- Power $\quad$ $P = iV = i(\varepsilon - ir) = i\varepsilon - i^2 r$





Multiloop Circuits

- Determine junctions, branches and loops.
- Label arbitrarily the currents for each branch. Assign same current to all element in series in a branch.
- The directions of the currents are assumed arbitrarily; negative current result means opposite direction.
- Junction rule: $$i_1 + i_3 = i_2$$



- You can use the junction rule as often as you need. In general, the number of times you can use the junction rule is one fewer than the number of junction points in the circuit.

Multiloop Circuits II

- Determine loop and choose moving direction arbitrarily.
- When following the assumed current direction, ir is negative and voltage drops; Reverse when going against the assumed current; Emf is positive when traversed from – to +, negative otherwise.
- Loop rule:

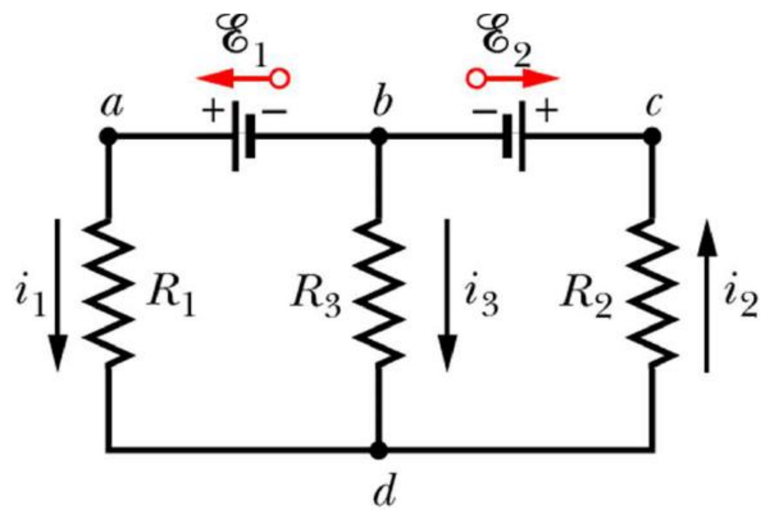
  badb: *left-hand loop in counterclockwise*

$$\varepsilon_1 - i_1 R_1 + i_3 R_3 = 0$$

  bdcb: *right-hand loop in counterclockwise*

$$-i_3 R_3 - i_2 R_2 - \varepsilon_2 = 0$$

- You can apply the loop rule as often as needed as long as a new circuit element or a new current appears in each new equation.



Equivalent loop and wise

big loop in counterclockwise

$$\varepsilon_1 - i_1 R_1 - i_2 R_2 - \varepsilon_2 = 0$$

right-hand loop in clockwise

$$\varepsilon_2 + i_2 R_2 + i_3 R_3 = 0$$

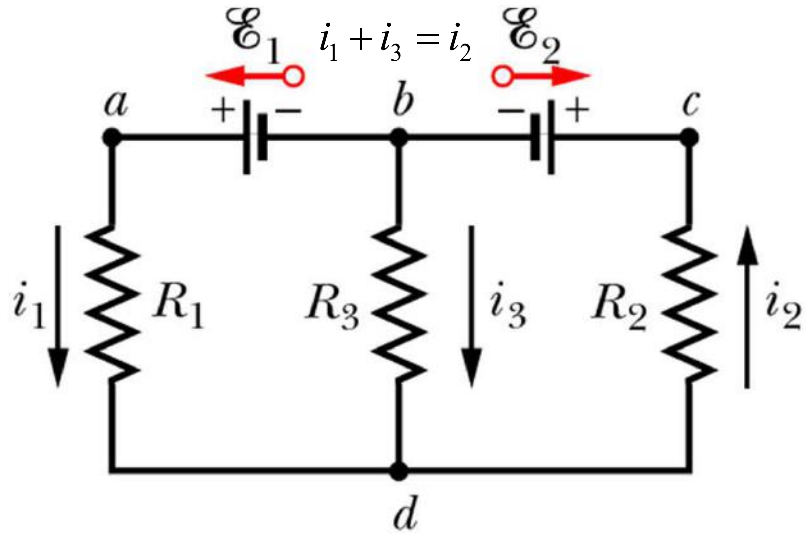
Multiloop Circuits III

- In general, to solve a particular circuit problem, the number of independent equations you need to obtain from the two rules equals the number of unknown currents.

$$i_1 + i_3 = i_2$$

$$\varepsilon_1 - i_1 R_1 + i_3 R_3 = 0$$

$$-i_3 R_3 - i_2 R_2 - \varepsilon_2 = 0$$



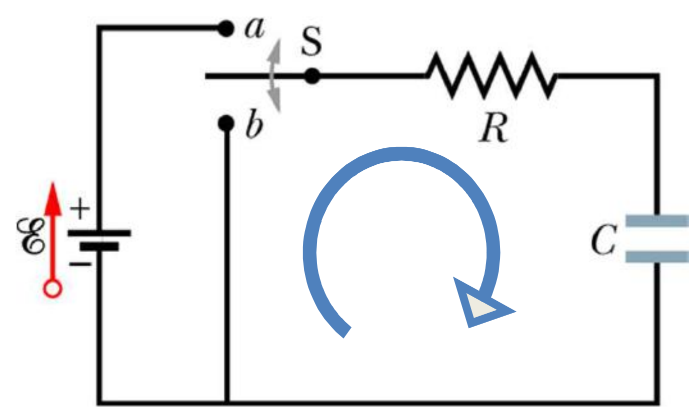
- Solution:

$$i_1 = \frac{\varepsilon_1 R_2 + \varepsilon_1 R_3 - \varepsilon_2 R_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}$$

$$i_2 = \frac{\varepsilon_1 R_2 - \varepsilon_2 R_3 - \varepsilon_2 R_1}{R_1 R_2 + R_2 R_3 + R_1 R_3}$$

$$i_3 = \frac{-\varepsilon_2 R_1 - \varepsilon_1 R_2}{R_1 R_2 + R_2 R_3 + R_1 R_3}$$

RC Circuits – Charging a Capacitor



- RC circuits: time-varying currents, switch to a
- Start with, Loop rule

$$\varepsilon - iR - \frac{q}{C} = 0$$

- Then,

$$i = \frac{dq}{dt}$$

- Substituting and rearranging,

$$R\frac{dq}{dt} + \frac{q}{C} = \varepsilon$$

- Boundary condition,

$$q(t=0) = 0; \quad i(t=0) = \frac{\varepsilon}{R};$$

$$q(\max) = C\varepsilon; \quad i = 0;$$

- Therefore,

$$\frac{dq}{dt} = \frac{\varepsilon}{R} - \frac{q}{RC}$$

$$\frac{dq}{dt} = \frac{C\varepsilon}{RC} - \frac{q}{RC} = -\frac{q - C\varepsilon}{RC}$$

$$\frac{dq}{q - C\varepsilon} = -\frac{1}{RC}dt$$

- Integrating,

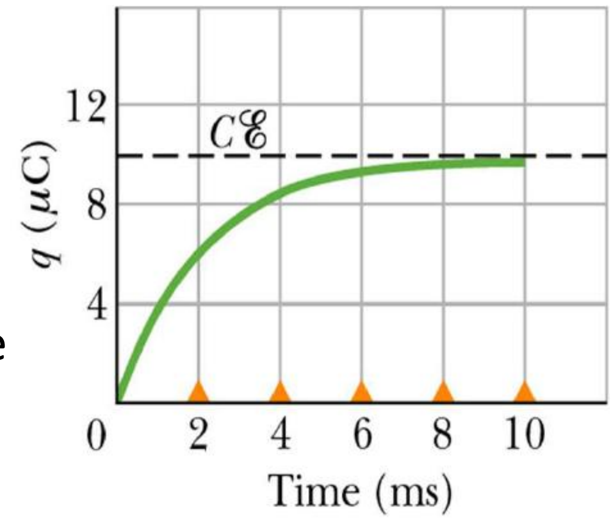
$$\int_0^q \frac{dq}{q - C\varepsilon} = -\frac{1}{RC}\int_0^t dt$$

$$\ln\left(\frac{q - C\varepsilon}{-C\varepsilon}\right) = -\frac{t}{RC}$$

- Charge, $q(t) = C\varepsilon(1 - e^{-t/RC})$

- For charging current, $i(t) = \dfrac{dq(t)}{dt} = \dfrac{\varepsilon}{R} e^{-t/RC}$

- A capacitor that is being charged initially acts like ordinary connecting wire relative to the charging current. A long time later, it acts like a broken wire.



(a)

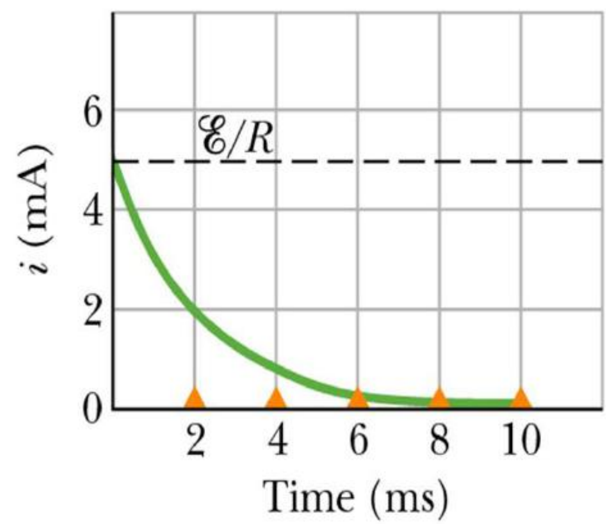
$$V_C(t) = \frac{q(t)}{C} = \varepsilon(1 - e^{-t/RC})$$

- Potential difference,

- t = 0: q = 0, V_c = 0, i = ε/R;

- t => ∞: q = cε, V_c = ε, i = 0;

- t = RC: q = cε(1-e^{-1}) = 0.632cε; i = ε/Re^{-1} = 0.368 ε/R



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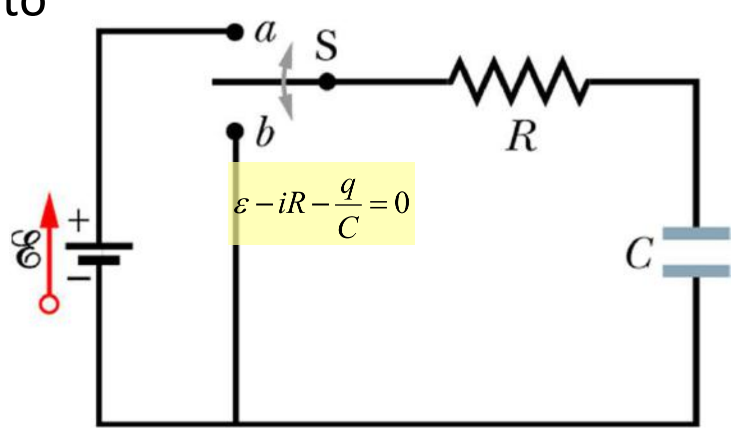
RC Circuits – Discharging a Capacitor



- RC circuits: time-varying currents, switch to b
- Start with, Loop rule $$-\frac{q}{C} - iR = 0$$
- Then, $$-R\frac{dq}{dt} = \frac{q}{C} \qquad \frac{dq}{q} = -\frac{1}{RC}dt$$
- Boundary condition, $q(t=0) = q_0$
- Therefore, $$\int_{q_0}^{q} \frac{dq}{q} = -\frac{1}{RC}\int_0^t dt \qquad \ln\left(\frac{q}{q_0}\right) = -\frac{t}{RC}$$
- Hence, $$q(t) = q_0 e^{-t/RC} \qquad i(t) = \frac{dq(t)}{dt} = -\frac{q_0}{RC}e^{-t/RC}$$
- t = 0: $q = q_0 = CV_0$, $i = q_0/RC$;
- $t \Rightarrow \infty$: q = 0, i = 0;

Example: Multiple Batteries

- What is the potential difference and power between the terminals of battery 1 and 2?
- Current i in this single-loop: (counterclockwise)

$$-\varepsilon_1 + ir_1 + iR + ir_2 + \varepsilon_2 = 0$$

$$i = \frac{\varepsilon_1 - \varepsilon_2}{r_1 + R + r_2} = 0.2396A$$

- Potential difference: (clockwise)

$$V_b - ir_1 + \varepsilon_1 = V_a$$

$$V_a - V_b = -ir_1 + \varepsilon_1 = +3.84V$$

$$V_a - \varepsilon_2 - ir_2 = V_c$$

$$V_a - V_c = \varepsilon_2 + ir_2 = +2.53V$$

- Power:

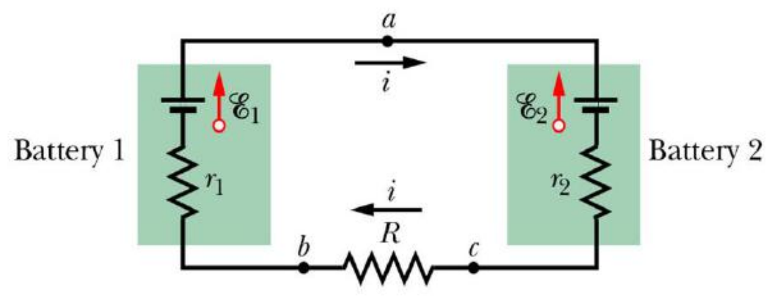
$$P_{\varepsilon 1} = iV_{ab} = 0.92W$$

$$P_{\varepsilon 2} = iV_{ac} = 0.60W \qquad P_{\varepsilon 1} = P_{\varepsilon 2} + P_R$$

$$P_R = i^2 R = 0.32W$$

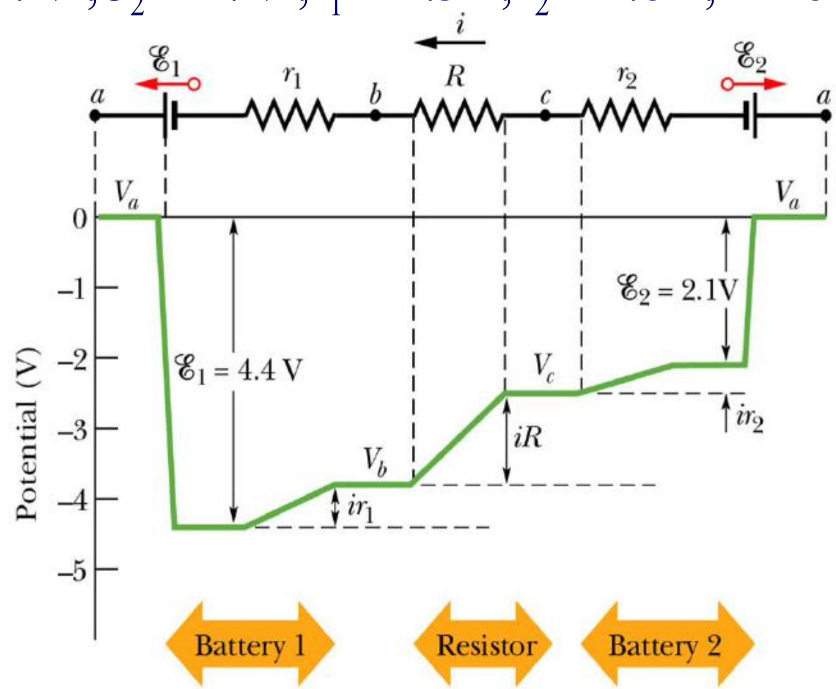
$i \cdot \varepsilon$

A battery (EMF) absorbs power (charges up) when *i* is opposite to ε.



(a)

$$\varepsilon_1 = 4.4V, \varepsilon_2 = 2.1V, r_1 = 2.3\Omega, r_2 = 1.8\Omega, R = 5.5\Omega$$



(b)

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Capacitance

Capacitance

- Definition
- Depends on Geometry
- Capacitors in parallel
- Capacitors in series
- Dielectric

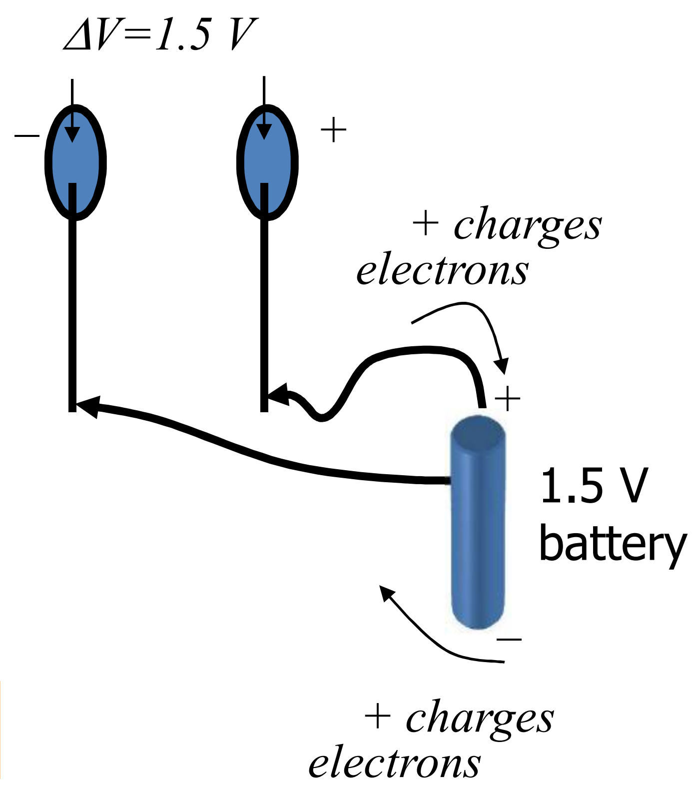
What is Capacitance?

From the word "capacity," it describes how much charge an arrangement of conductors can hold for a given voltage applied.

- Charges will flow until the right conductor's potential is the same as the + side of the battery, and the left conductor's potential is the same as the – side of the battery.
- How much charge is needed to produce an electric field whose potential difference is 1.5 V?
- Depends on capacitance:

$$q = CV$$

definition of capacitance

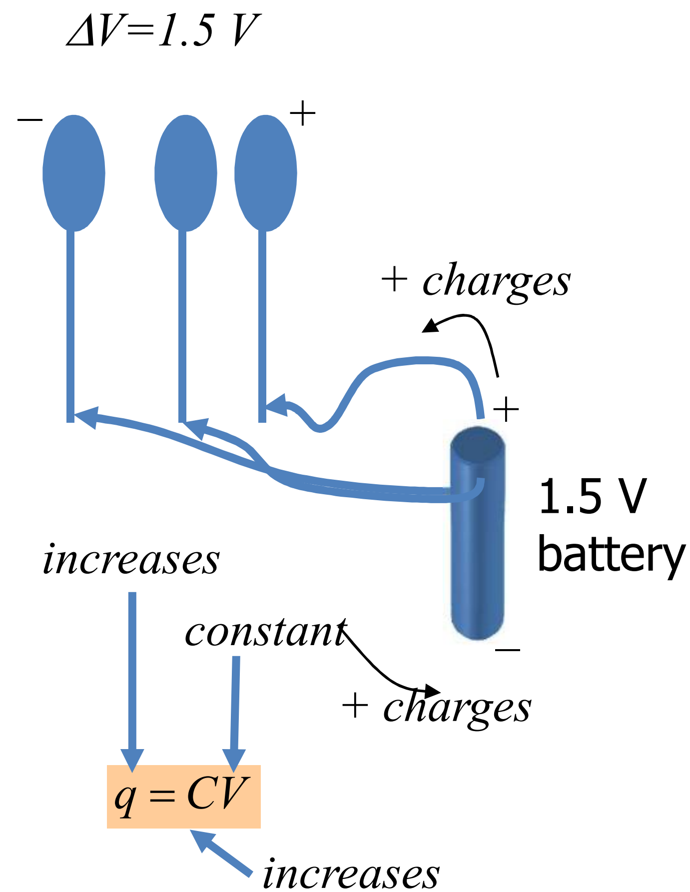


"Charging" the capacitor

Capacitance Depends on Geometry

What happens when the two conductors are moved closer together?

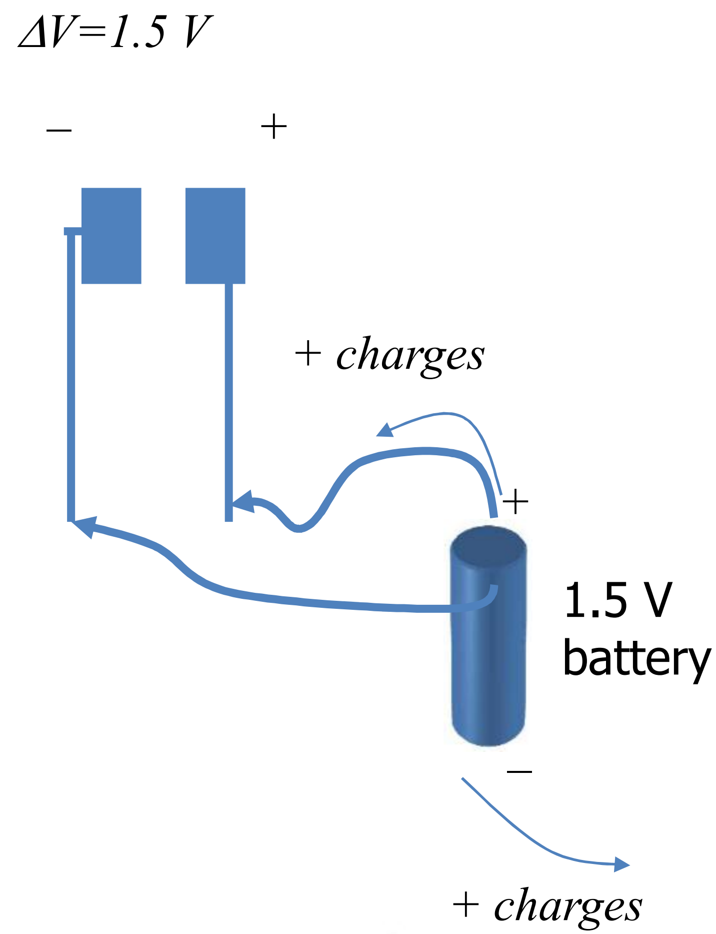
- They are still connected to the battery, so the potential difference cannot change.
- But recall that $V = -\int \vec{E} \cdot d\vec{s}$
- Since the distance between them decreases, the E field has to increase.
- Charges have to flow to make that happen, so now these two conductors can hold more charge. I.e. the capacitance increases.



What happens if we replace the small conducting spheres with large conducting plates?

The plates can hold a lot more charge, so the capacitance goes way up.

- Here is a capacitor that you can use in an electronic circuit.
- We will discuss several ways in which capacitors are useful.
- But first, let's look in more detail at what capacitance is.

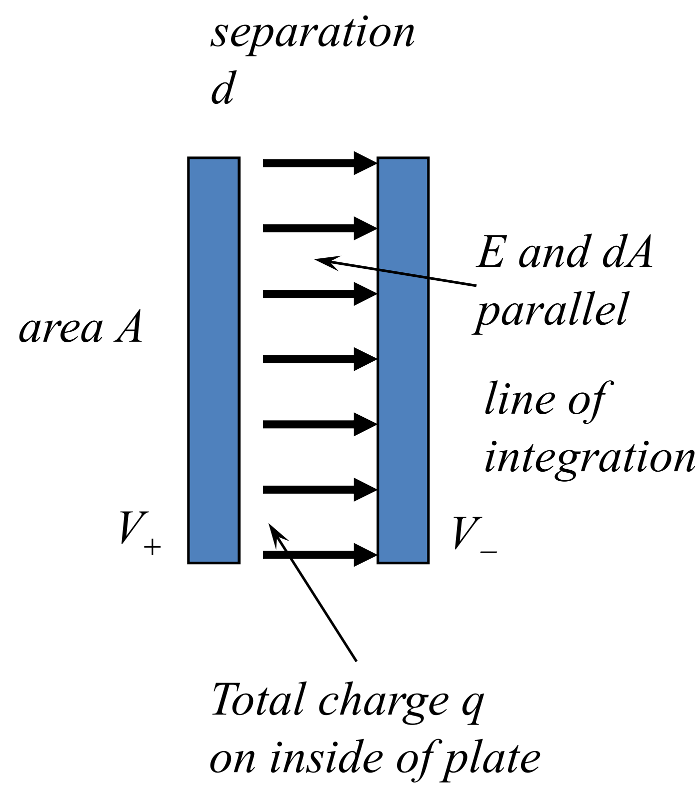


Circular plates →

Capacitance for Parallel Plates

- Parallel plates make a great example for calculating capacitance, because
  - The E field is constant, so easy to calculate.
  - The geometry is simple, only the area and plate separation are important.
- To calculate capacitance, we first need to determine the E field between the plates. We use Gauss' Law, with one end of our gaussian surface closed inside one plate, and the other closed in the region between the plates (neglect fringing at ends):

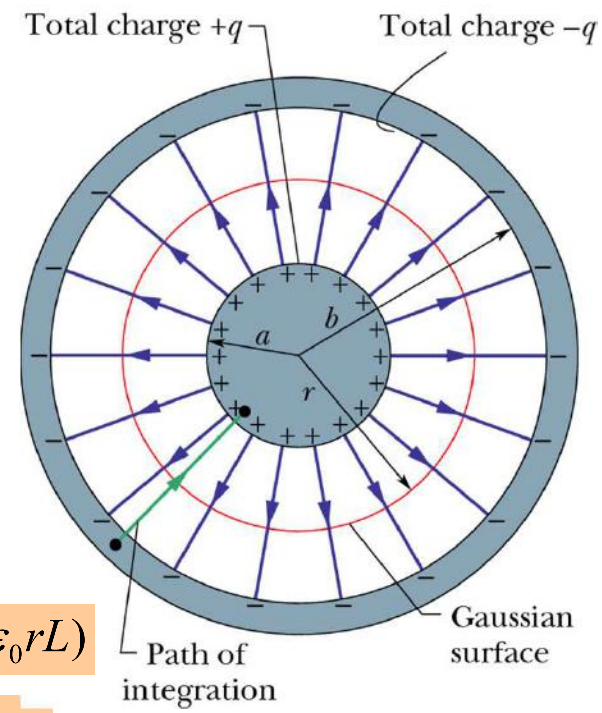
  $\varepsilon_0 \oint \vec{E} \cdot d\vec{A} = q$ so $q = \varepsilon_0 E A$



- Need to find potential difference $V = V_+ - V_- = -\int \vec{E} \cdot d\vec{s}$
- Since E=constant, we have $V = Ed$, so the capacitance is $C = q/V = \dfrac{\varepsilon_0 E A}{Ed} = \dfrac{\varepsilon_0 A}{d}$

Capacitance for Other Configurations (Cylindrical)

- Cylindrical capacitor
  - The E field falls off as $1/r$.
  - The geometry is fairly simple, but the V integration is slightly more difficult.
- To calculate capacitance, we first need to determine the E field between the plates. We use Gauss' Law, with a cylindrical gaussian surface closed in the region between the plates (neglect fringing at ends):

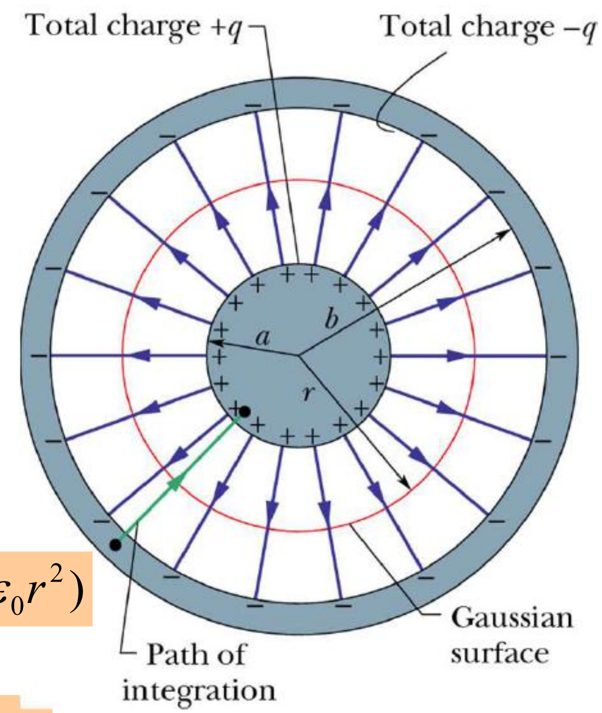


$\varepsilon_0 \oint \vec{E} \cdot d\vec{A} = q$ So $q = \varepsilon_0 EA = \varepsilon_0 E(2\pi rL)$ or $E = q/(2\pi\varepsilon_0 rL)$

- Need to find potential difference $V = V_+ - V_- = -\int \vec{E} \cdot d\vec{s}$
- Since E~1/r, we have $V = \frac{q}{2\pi\varepsilon_0 L}\int_b^a \frac{dr}{r} = \frac{q}{2\pi\varepsilon_0 L}\ln\left(\frac{b}{a}\right)$, so the capacitance is $C = q/V = 2\pi\varepsilon_0 \frac{L}{\ln(b/a)}$

Capacitance for Other Configurations (Spherical)

- Spherical capacitor
  - The E field falls off as $1/r^2$.
  - The geometry is fairly simple, and the V integration is similar to the cylindrical case.
- To calculate capacitance, we first need to determine the E field between the spheres. We use Gauss' Law, with a spherical gaussian surface closed in the region between the spheres:



$\varepsilon_0 \oint \vec{E} \cdot d\vec{A} = q$ So $q = \varepsilon_0 EA = \varepsilon_0 E(4\pi r^2)$ or $E = q/(4\pi\varepsilon_0 r^2)$

- Need to find potential difference $V = V_+ - V_- = -\int \vec{E} \cdot d\vec{s}$
- Since $E \sim 1/r^2$, we have $V = \dfrac{q}{4\pi\varepsilon_0}\int_b^a \dfrac{dr}{r^2} = \dfrac{q}{4\pi\varepsilon_0}\left(\dfrac{1}{a} - \dfrac{1}{b}\right)$, so the capacitance is

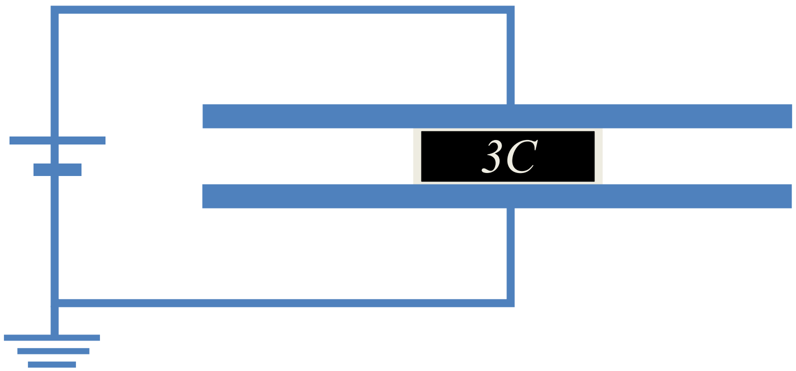
$$C = q/V = 4\pi\varepsilon_0 \frac{ab}{b-a}$$

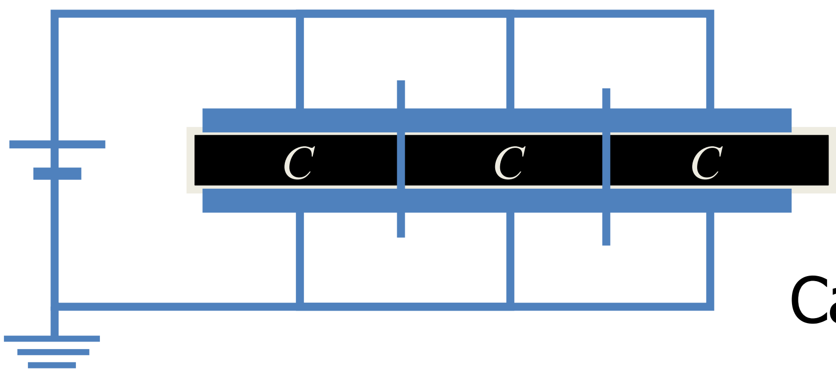
Capacitance Summary

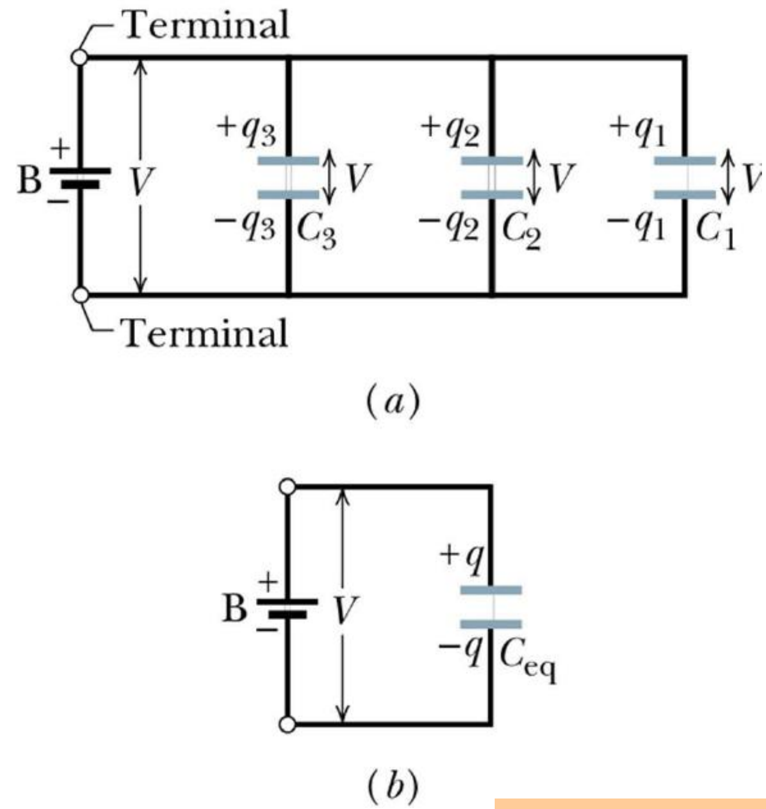
- Parallel Plate Capacitor $$C = \frac{\varepsilon_0 A}{d}$$
- Cylindrical (nested cylinder) Capacitor $$C = 2\pi\varepsilon_0 \frac{L}{\ln(b/a)}$$
- Spherical (nested sphere) Capacitor $$C = 4\pi\varepsilon_0 \frac{ab}{b-a}$$
- Capacitance for isolated Sphere $$C = 4\pi\varepsilon_0 R$$
- Units: $\varepsilon_0 \times$length = C^2/Nm = F (farad), named after Michael Faraday. [note: ε_0 = 8.85 pF/m]

Capacitors in Parallel

- No difference between



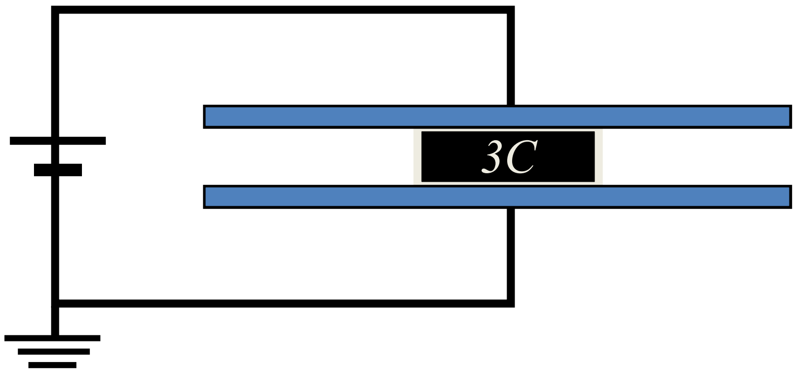




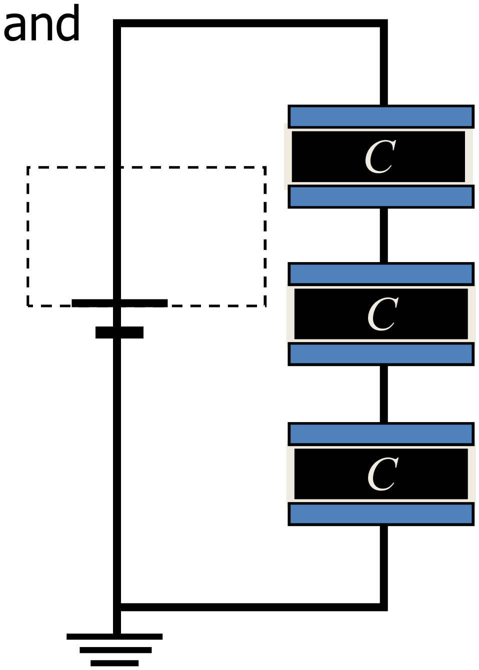
Capacitors in parallel: $C_{eq} = \sum_{j=1}^{n} C_j$

Capacitors in Series

- There *is* a difference between



and



- Charge on lower plate of one and upper plate of next are equal and opposite. (show by gaussian surface around the two plates).
- Total charge is q, but voltage on each is only $V/3$.

Capacitors in series: $$\frac{1}{C_{eq}} = \sum_{j=1}^{n} \frac{1}{C_j}$$

Capacitors in Series 2

- To see the series formula, consider the individual voltages across each capacitor

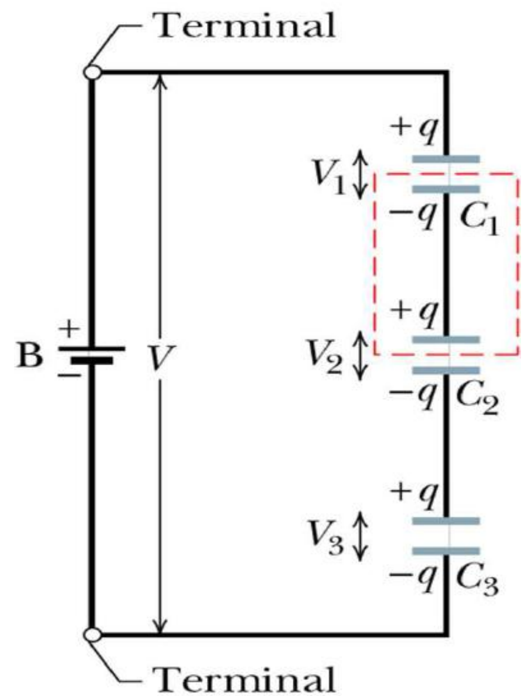
$$V_1 = \frac{q}{C_1},\ V_2 = \frac{q}{C_2},\ V_3 = \frac{q}{C_3}$$

- The sum of these voltages is the total voltage of the battery, V

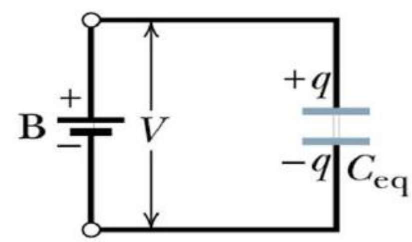
$$V = V_1 + V_2 + V_3 = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

- Since $V/q = 1/C_{eq}$, we have

$$\frac{V}{q} = \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$



(a)

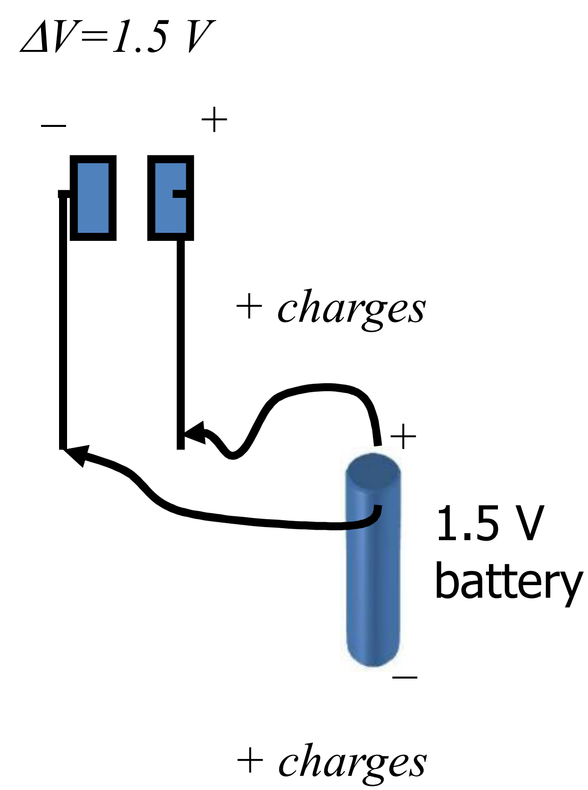


(b)

Capacitors Store Energy 1

- When charges flow from the battery, energy stored in the battery is lost. Where does it go?
- We learned last time that an arrangement of charge is associated with potential energy. One way to look at it is that the charge arrangement stores the energy.
- Recall the definition of electric potential $V = U/q$
- For a distribution of charge on a capacitor, a small element dq will store potential energy $dU = V\,dq$
- Thus, the energy stored by charging a capacitor from charge 0 to q is

$$U = \frac{1}{C}\int_0^q q'\,dq' = \frac{q^2}{2C} = \tfrac{1}{2}CV^2$$



Capacitors Store Energy 2

- Another way to think about the stored energy is to consider it to be stored in the electric field itself.
- The total energy in a parallel plate capacitor is

$$U = \tfrac{1}{2} C V^2 = \frac{\varepsilon_0 A}{2d} V^2$$

- The volume of space filled by the electric field in the capacitor is $vol = Ad$, so the *energy density* is

$$u = \frac{U}{vol} = \frac{\varepsilon_0 A}{2dAd} V^2 = \tfrac{1}{2} \varepsilon_0 \left(\frac{V}{d}\right)^2$$

- But $V = -\int \vec{E} \cdot d\vec{s} = Ed$ for a parallel plate capacitor, so

$$u = \tfrac{1}{2} \varepsilon_0 E^2$$

Energy stored in electric field

Dielectrics

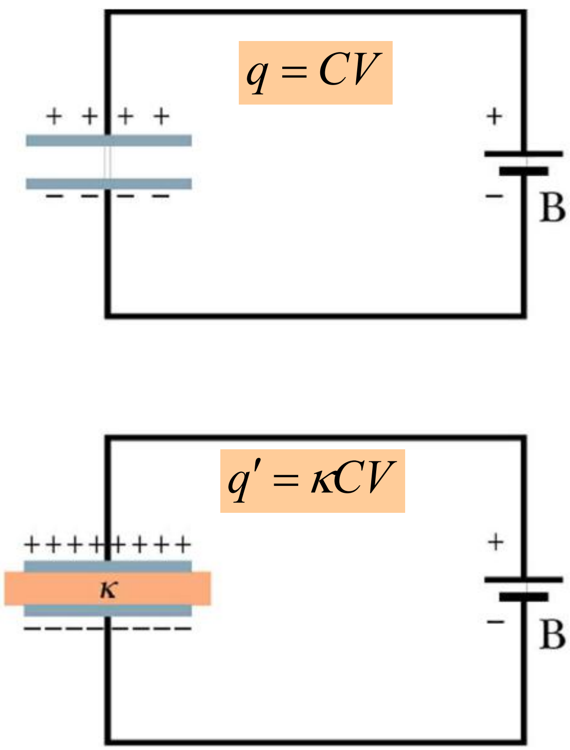
- You may have wondered why we write ε_0 (permittivity of free space), with a little zero subscript. It turns out that other materials (water, paper, plastic, even air) have different permittivities $\varepsilon = \kappa\varepsilon_0$. The κ is called the *dielectric constant*, and is a unitless number. For air, κ = 1.00054 (so ε for air is for our purposes the same as for "free space.")
- In all of our equations where you see ε_0, you can substitute $\kappa\varepsilon_0$ when considering some other materials (called dielectrics).
- The nice thing about this is that we can increase the capacitance of a parallel plate capacitor by filling the space with a dielectric:

$$C' = \frac{\kappa\varepsilon_0 A}{d} = \kappa C$$

Material	**Dielectric Constant** κ	**Dielectric Strength (kV/mm)**
Air	1.00054	3
Polystyrene	2.6	24
Paper	3.5	16
Transformer Oil	4.5	
Pyrex	4.7	14
Ruby Mica	5.4	
Porcelain	6.5	
Silicon	12	
Germanium	16	
Ethanol	25	
Water (20º C)	80.4	
Water (50º C)	78.5	
Titania Ceramic	130	
Strontium Titanate	310	8

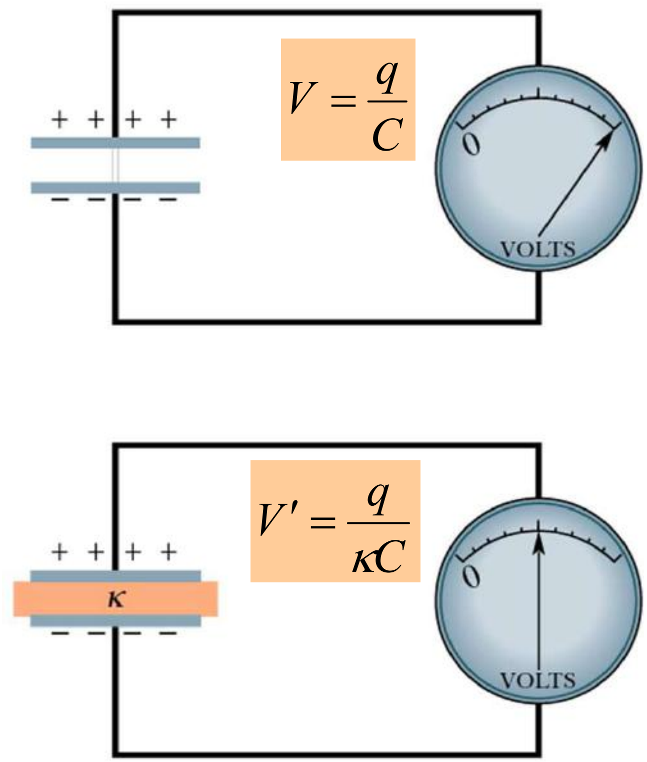
What Happens When You Insert a Dielectric?

- With battery attached, V= const, so more charge flows to the capacitor



V = a constant

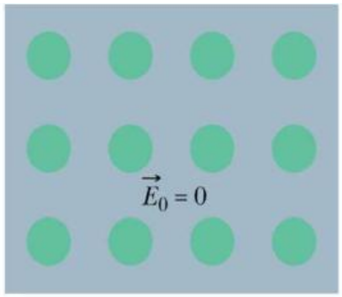
- With battery disconnected, q= const, so voltage (for given q) drops.



q = a constant

What Does the Dielectric Do?

- A dielectric material is made of molecules.
- Polar dielectrics already have a dipole moment (like the water molecule).
- Non-polar dielectrics are not naturally polar, but actually stretch in an electric field, to become polar.
- The molecules of the dielectric align with the applied electric field in a manner to oppose the electric field.
- This reduces the electric field, so that the net electric field is less than it was for a given charge on the plates.
- This lowers the potential (case b of the previous slide).
- If the plates are attached to a battery (case a of the previous slide), more charge has to flow onto the plates.



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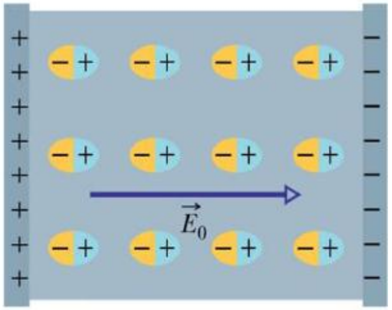

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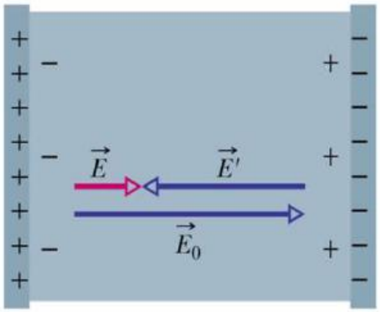
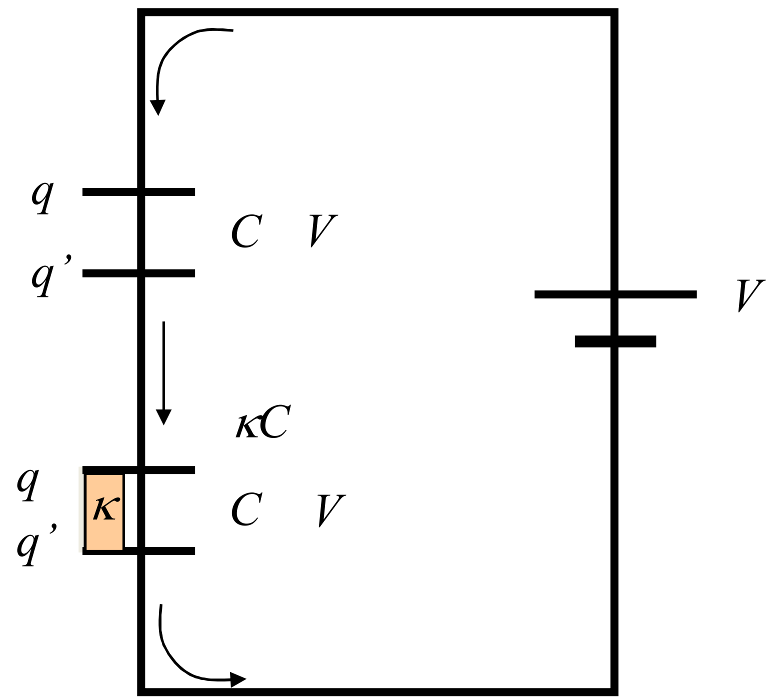


(c)

A Closer Look

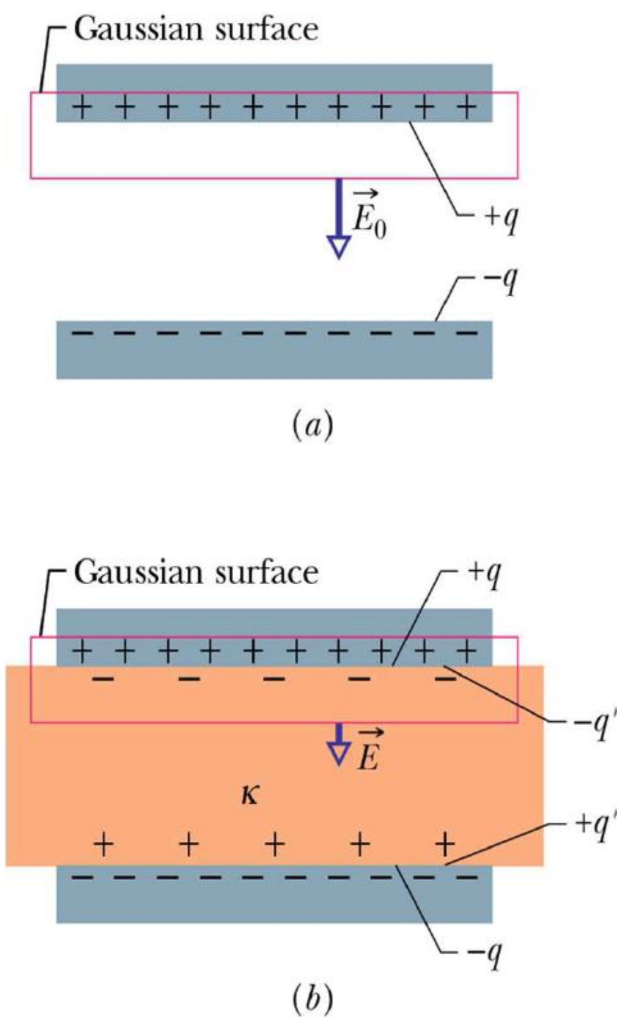
Insert dielectric

- Capacitance goes up by k
- Charge increases
- Charge on upper plate comes from upper capacitor, so its charge also increases.
- Since q’ = CV_1 increases on upper capacitor, V_1 must increase on upper capacitor.
- Since total V = $V_1 + V_2$ = constant, V_2 must decrease.



Dielectrics and Gauss' Law

- Gauss' Law holds without modification, but notice that the charge enclosed by our gaussian surface is less, because it includes the induced charge *q'* on the dielectric.
- For a given charge *q* on the plate, the charge enclosed is $q - q'$, which means that the electric field must be smaller. The effect is to weaken the field.
- When attached to a battery, of course, more charge will flow onto the plates until the electric field is again E_0.



Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Mechatronics

Introduction to Mechatronics

- Introduction
- About mechatronics
- Mechatronics system
- Mechatronics Integration & development
- Examples: mechatronics system, robot platform, PC based, PLC, etc.
- Intermezzo

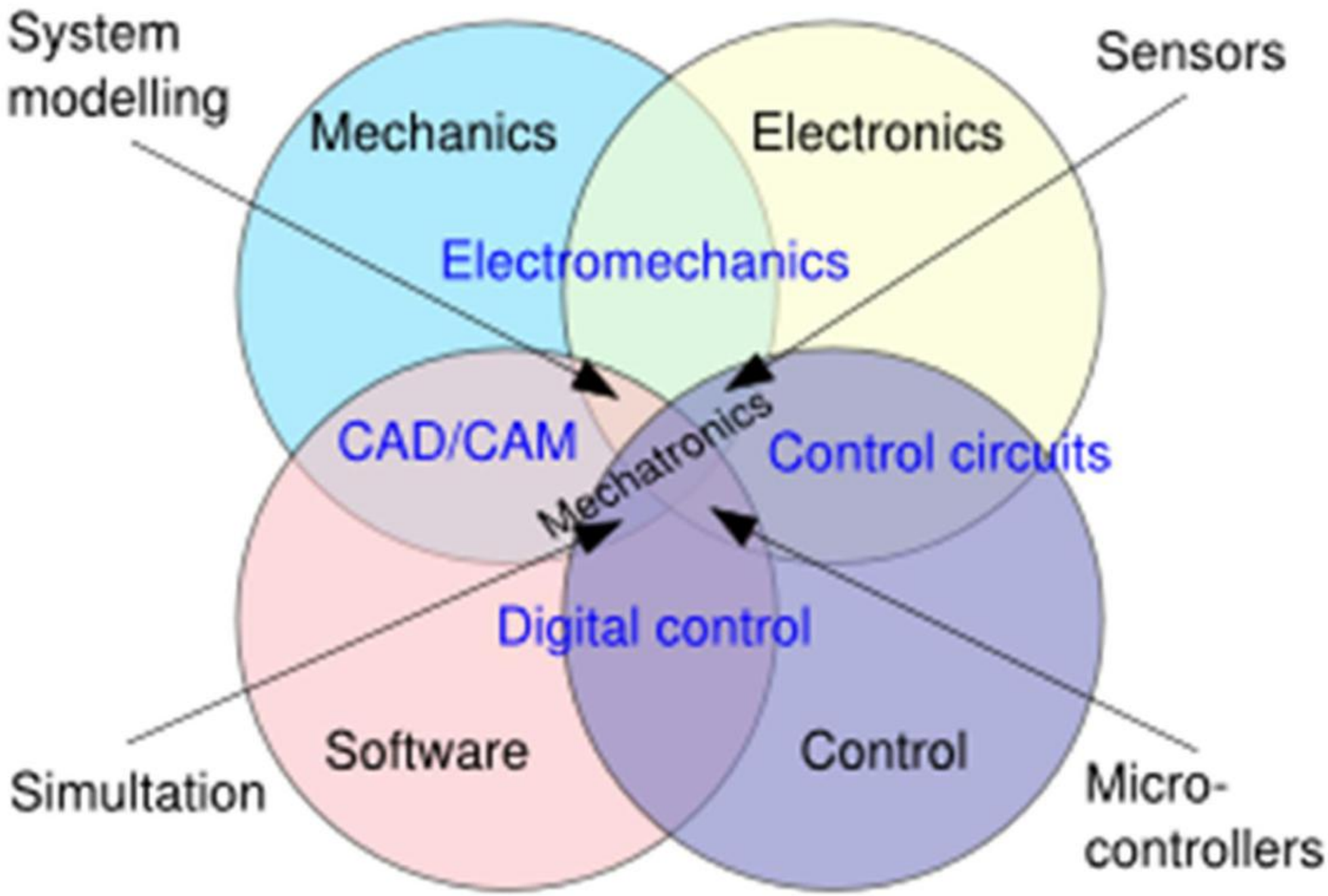
Introduction

- With the fast progress in microelectronics and computer science, products and systems undertook a drastic change.
- Most of today's products can no longer be assigned to a single discipline, but are highly multidisciplinary. For example, in a modern car the electronics and control play a dominant role (up to 50%), whereas a car from the seventies and even early eighties was nearly purely mechanical (90%).
- This trend to multidisciplinary (mechatronics) products, even if it has not yet reached its peak, has and will have an important impact on the design process and on engineering in general.
- Engineering design has clearly become a multidisciplinary undertaking, happening in multicultural and very diversified teams.

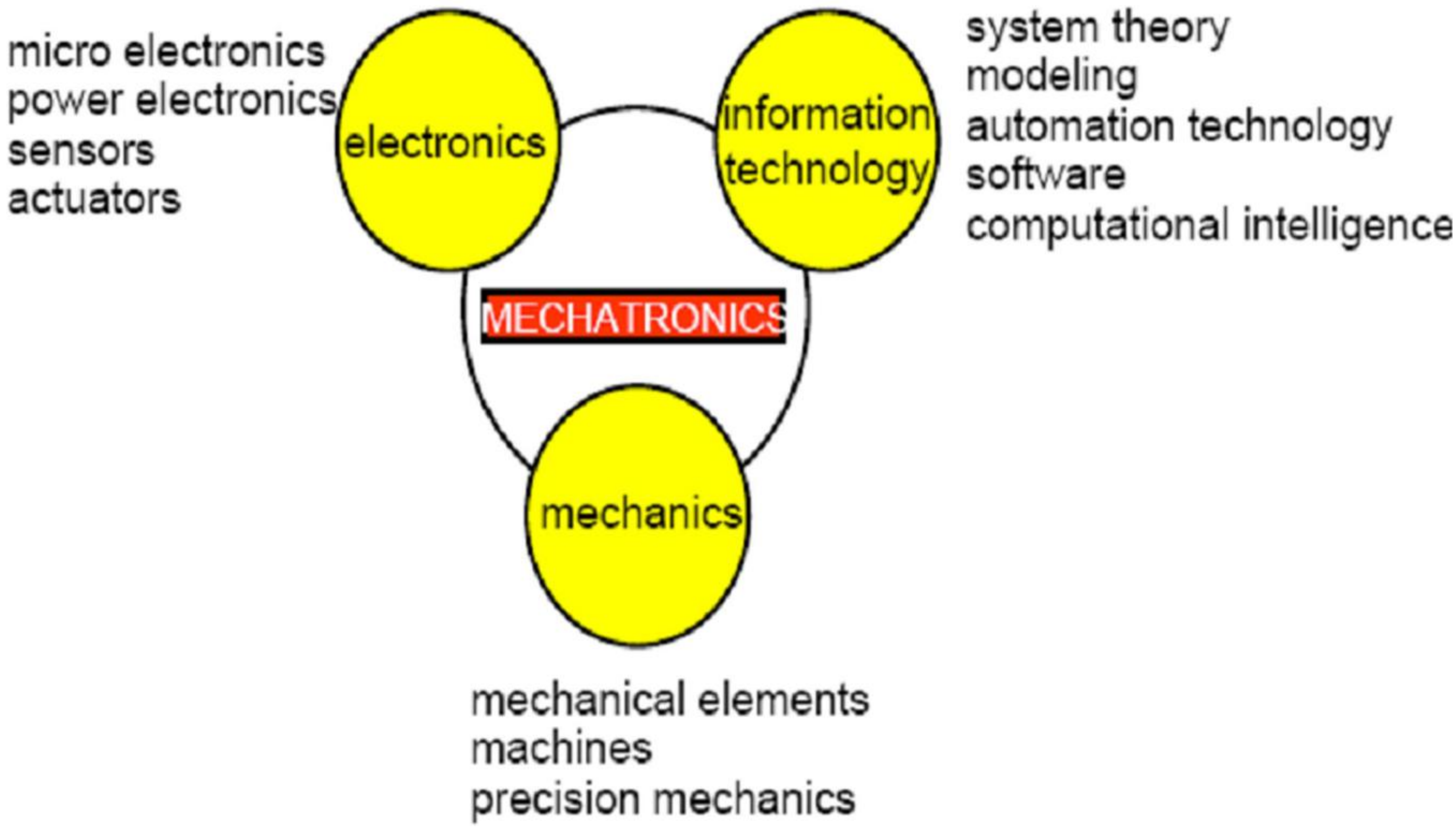
About Mechatronics

- It is an integration of Mechanical and Electronic engineering. It specifically refers to multidisciplinary approach to product and Manufacturing system design.
- Mechatronics is synergistic integration of mechanical engineering, electronics and intelligent computer control in design and manufacture of products and processes.
- Mechatronics basically refers to mechanical electrical systems and is centered on mechanics, electronics, computing and control which, combined, make possible the generation of simpler, more economical, reliable and versatile systems.
- Most existing mechatronics cover all the aspects from mechatronics design to sensors, actuators and control theory.

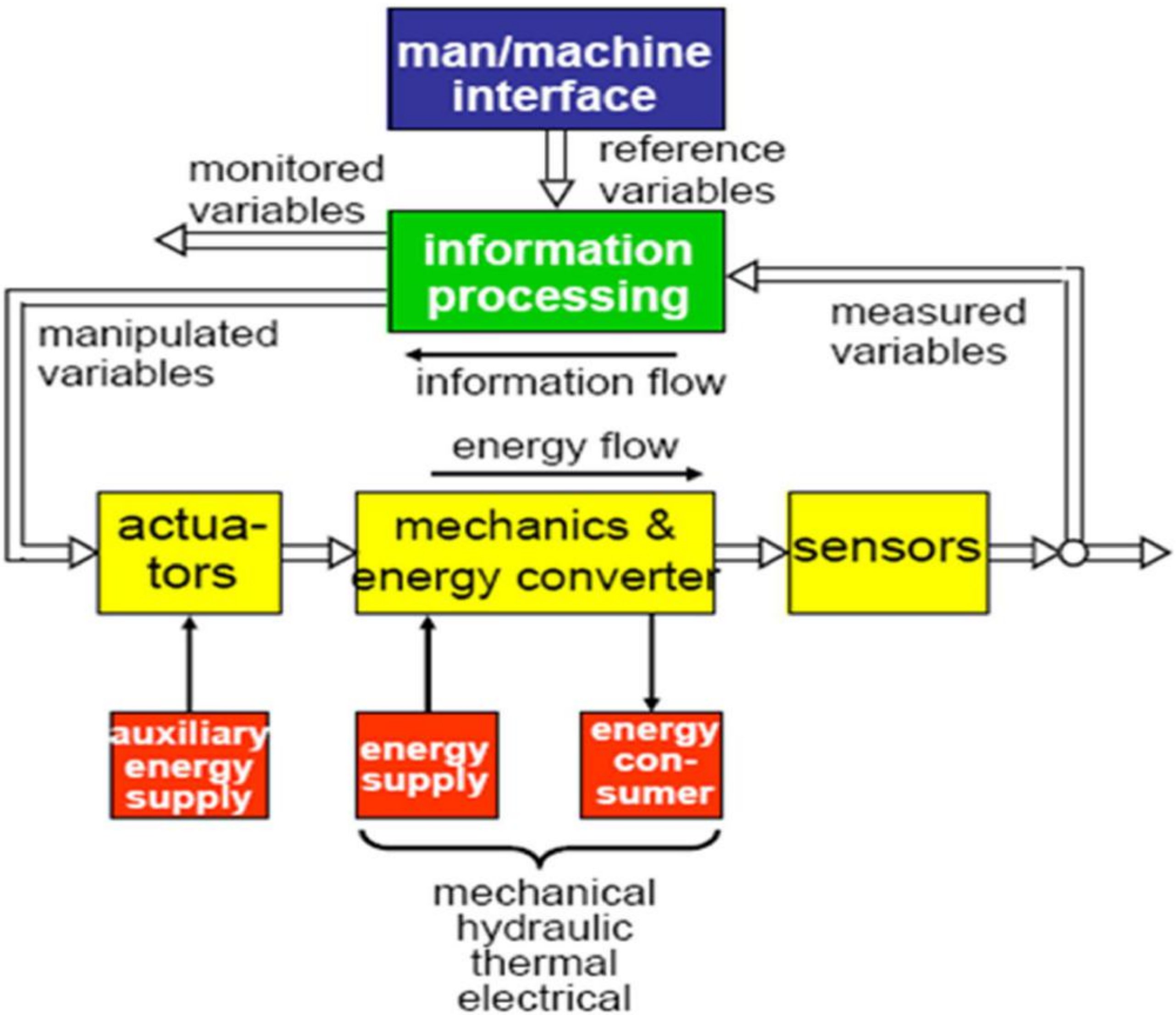
Multidisciplinary



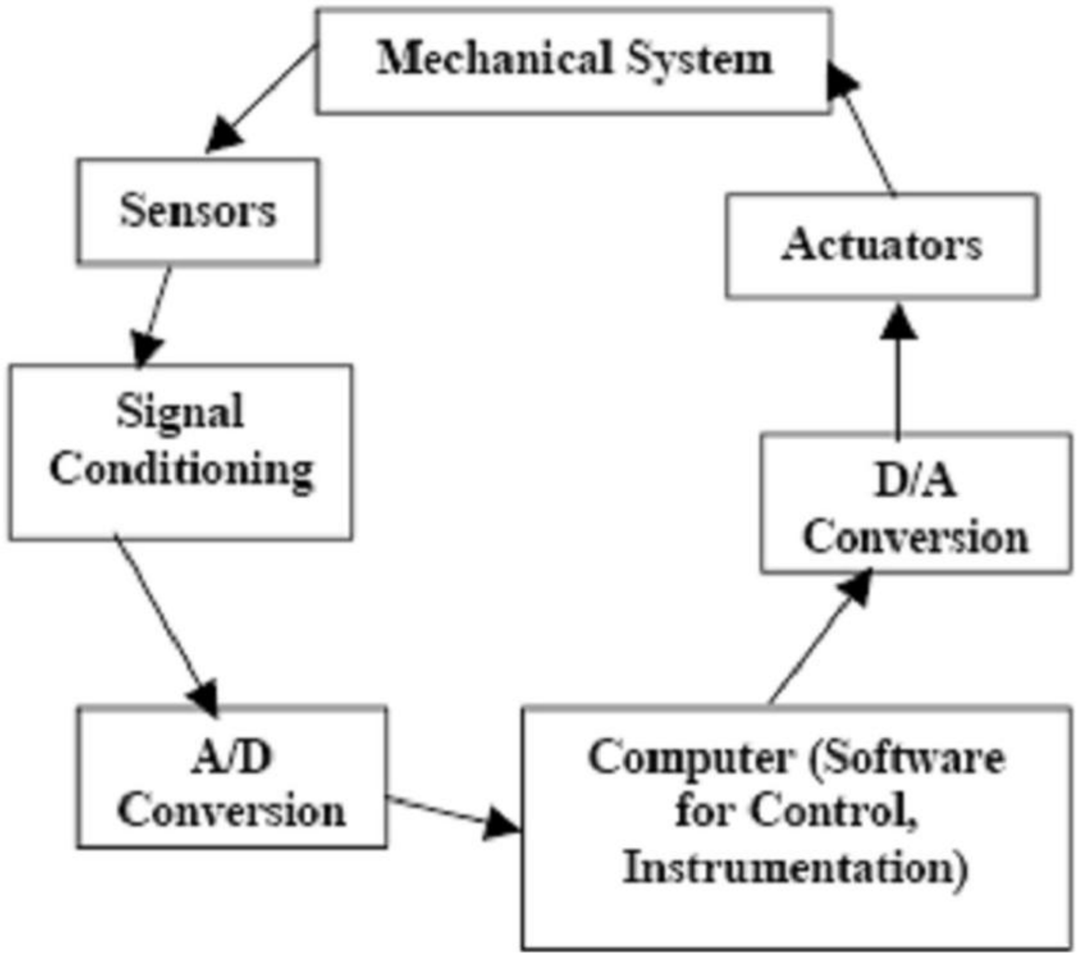
Knowledge Base



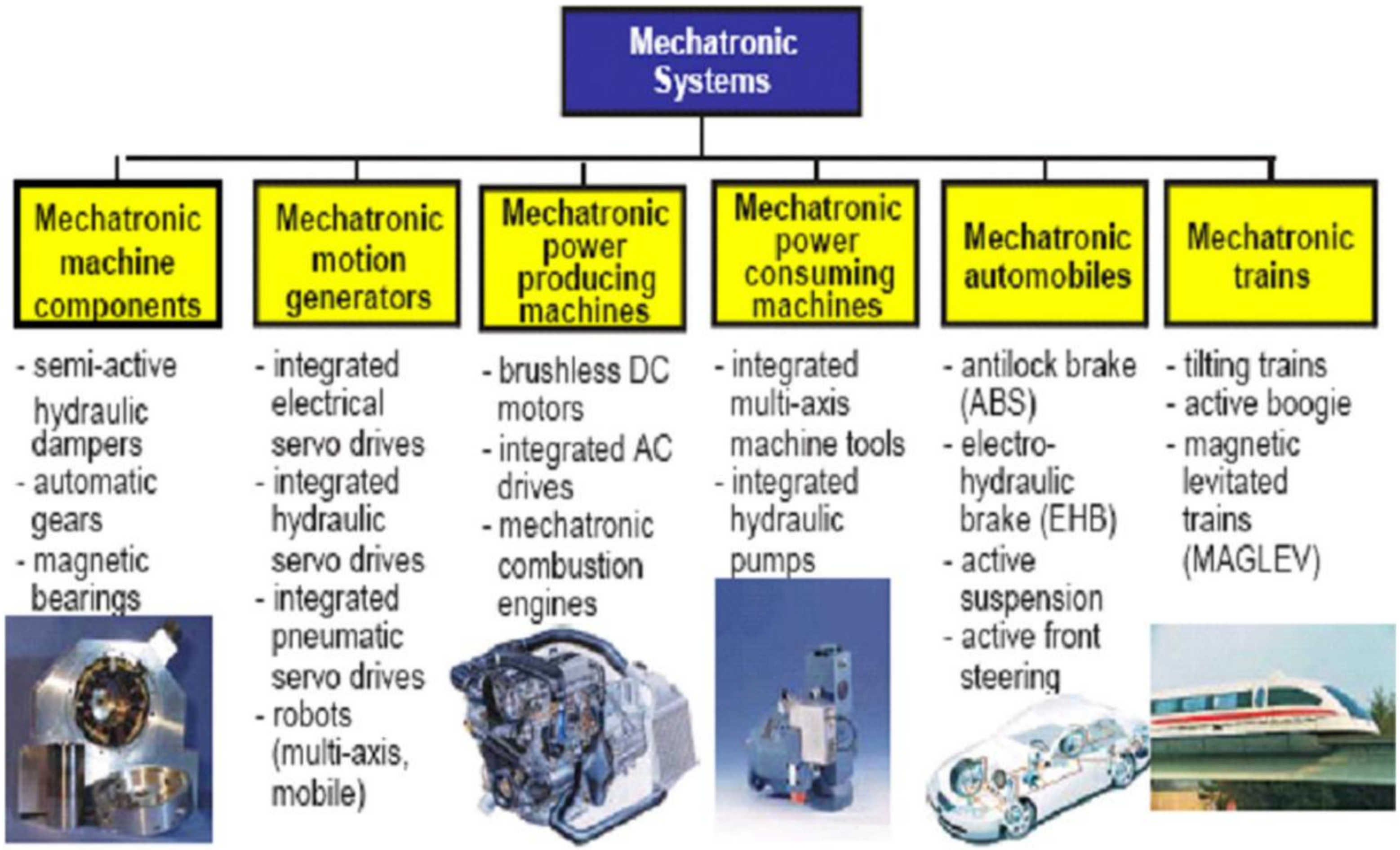
Process Flow Diagram



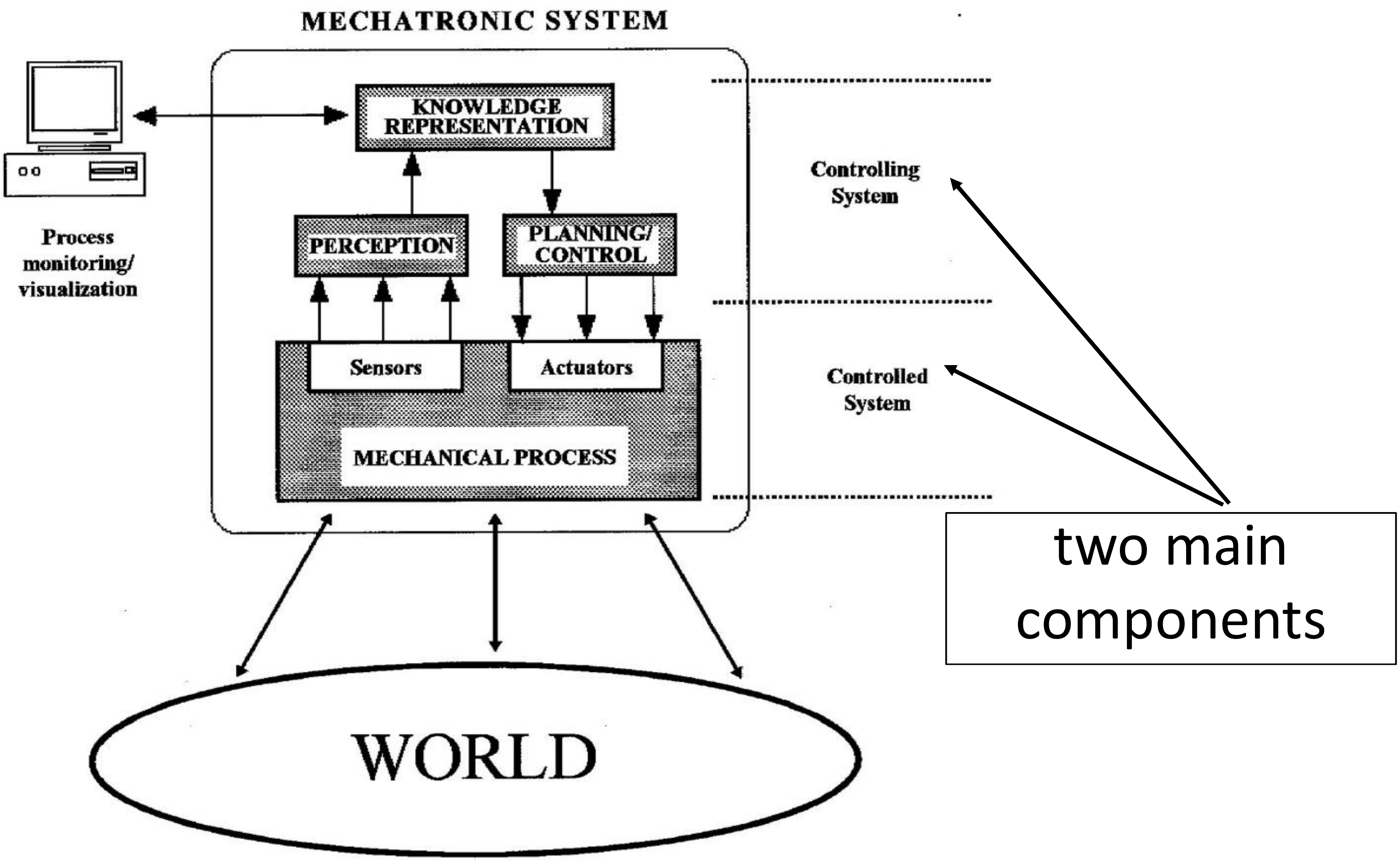
Mechatronic System Model



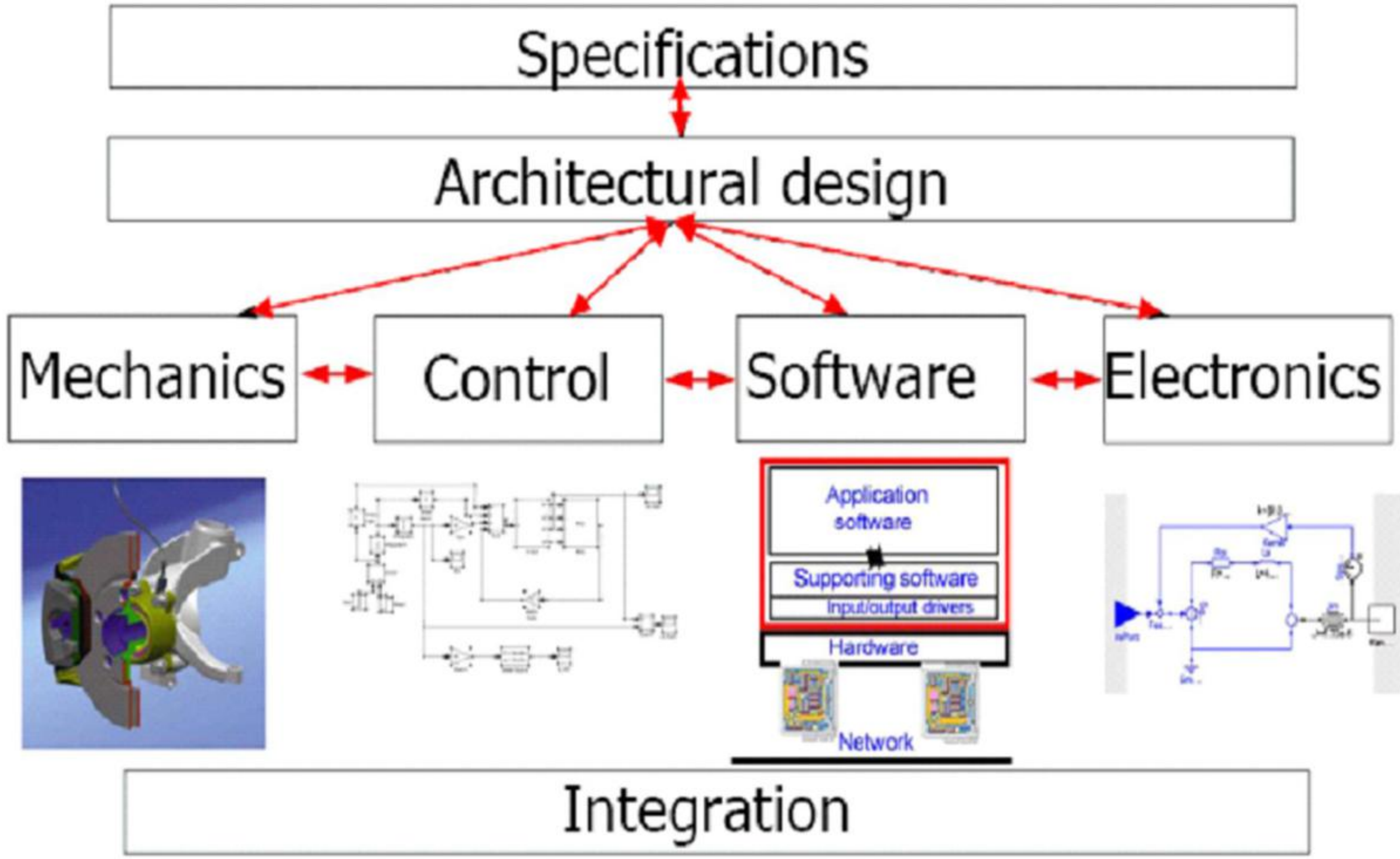
Mechatronics System



Mechatronic System Architecture



Integration Diagram



Embedded Systems

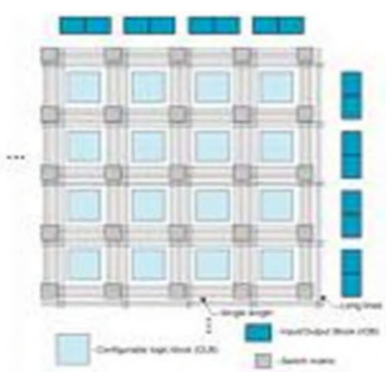
- An embedded system is designed to run on its own without human intervention, and may be required to respond to events in real time.
- A combination of hardware, software, and firmware which together form a component of a Mechatronics systems.
- Having integration of information processing and integration of components

Hardware, Software, and Firmware

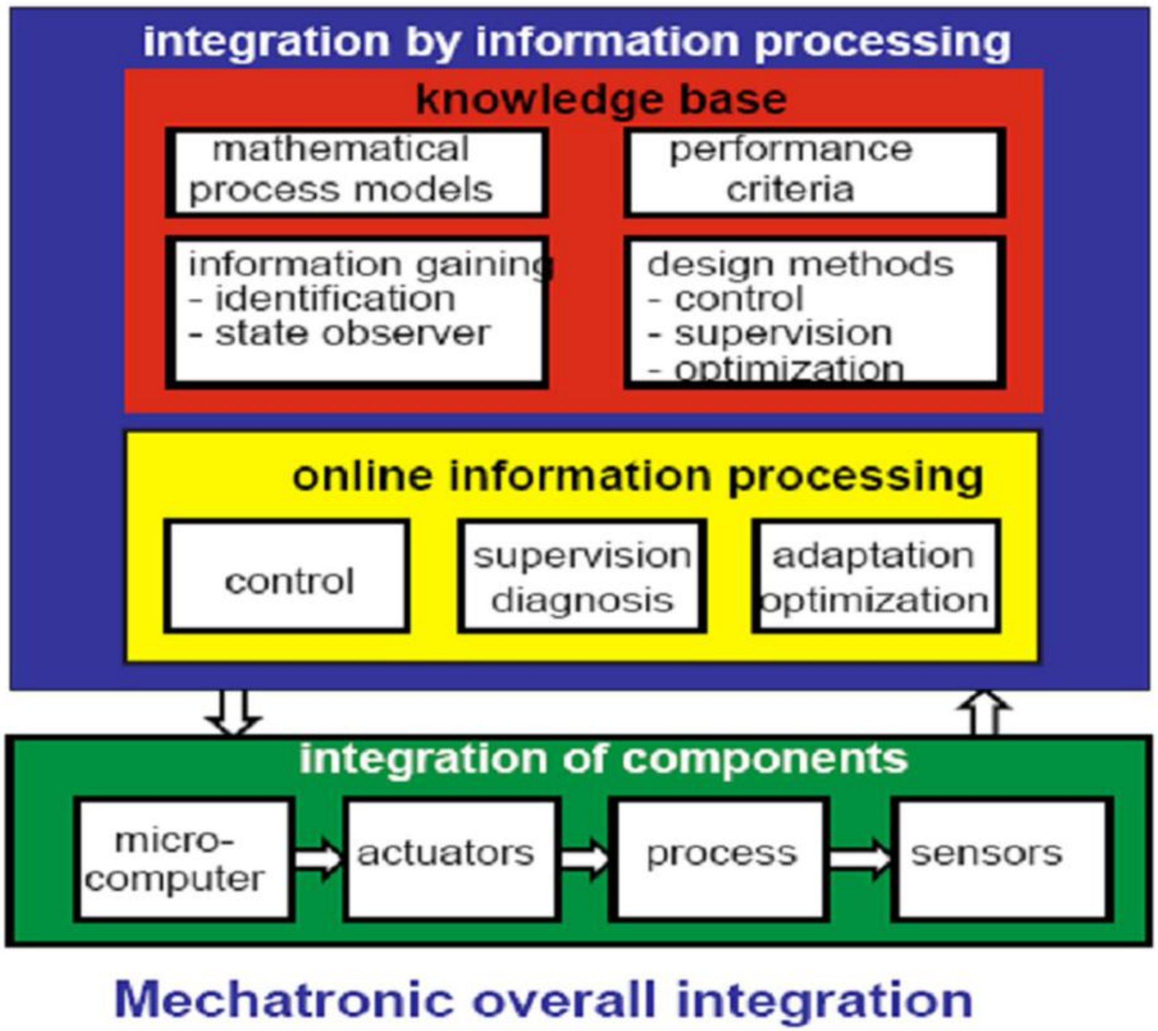
- Hardware is the name given to the physical devices and circuitry of the computer.

- Software refers to the programs written for the computer.

- Firmware is the term given to programs stored in ROMs or in Programmable devices which permanently keep their stored information.



Integration of Information Processing & Components



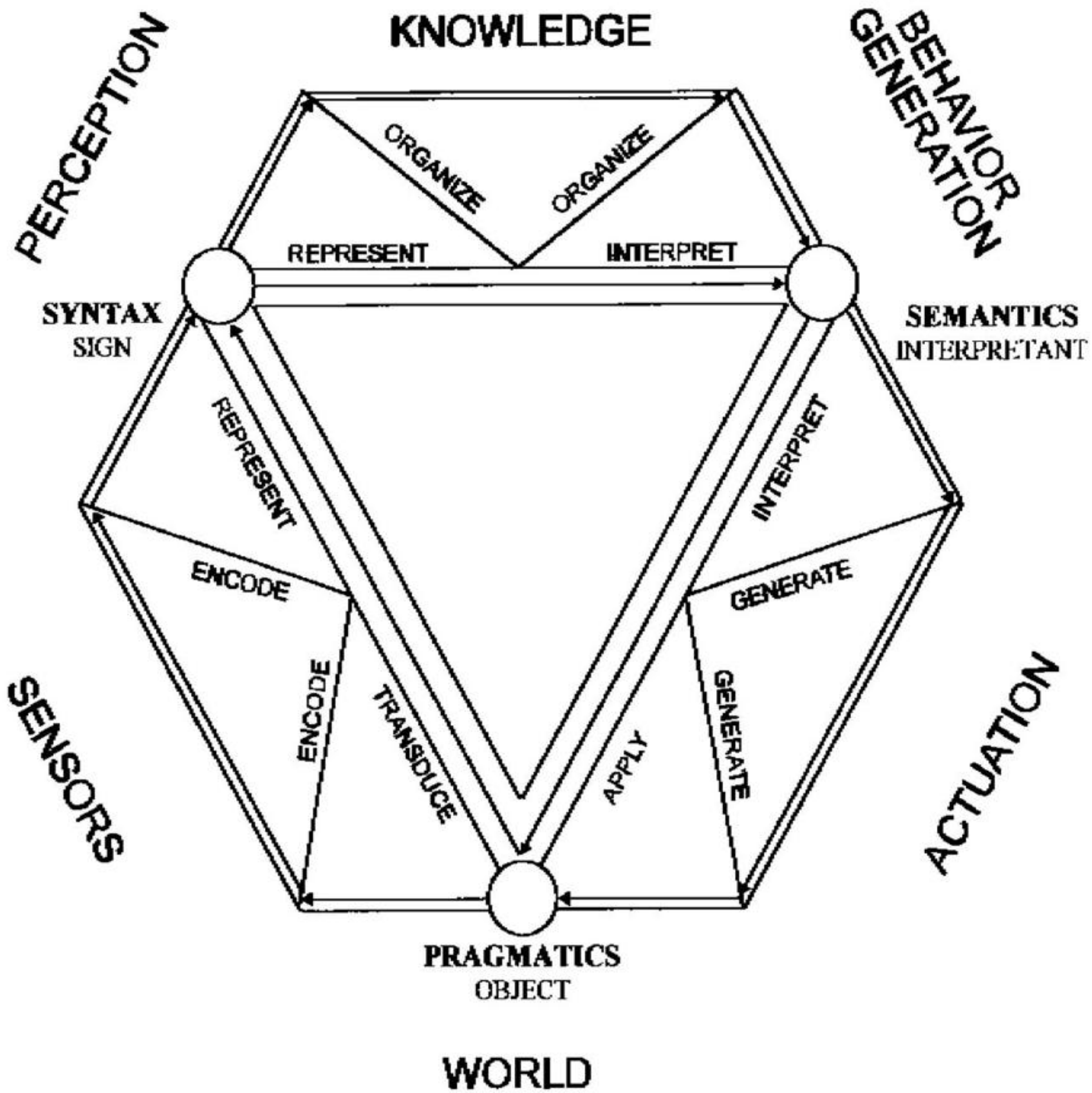
Computer Control Device Basic Functions:

- Control of mechanical movement process on-line with current sensor data analysis.
- Arrangements to control MS functional movements.
- Interaction with operator via human-machine interface off-line and on-line interaction at the moment of MS movement.
- Data exchange between peripheral devices, sensors and other devices of the system.

Basic Advantages in Comparison with Traditional Means of Automation

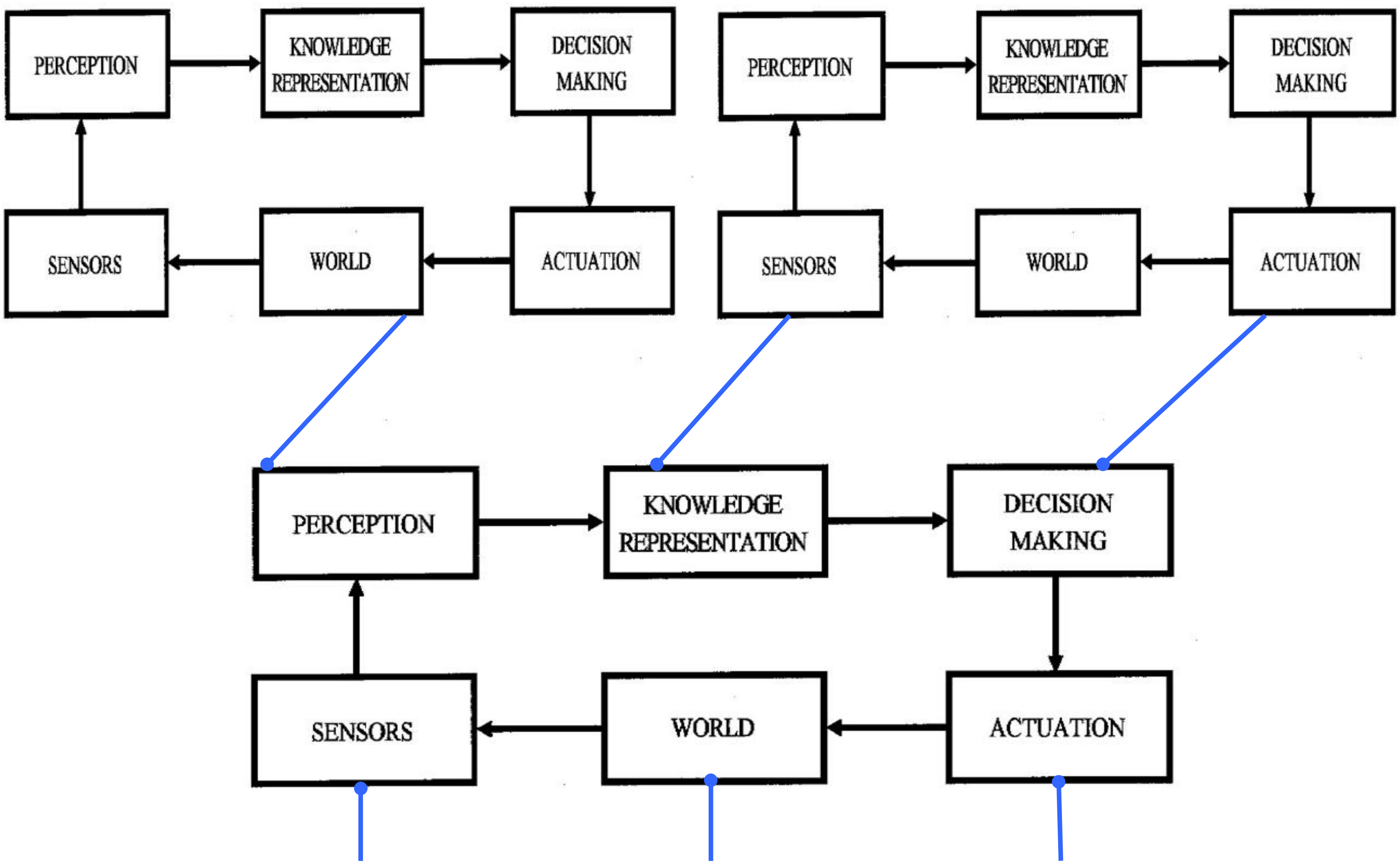
- Rather low cost
- Ability to perform complicated and precise movements (of high quality)
- High reliability, durability and noise immunity
- Constructive compactness of modules
- Improved overall dimension and dynamic characteristics of machines
- Opportunity to rebuild functional modules to sophisticated systems and complexes.

The Functional Diagram of Semiotics



Semiotics is proposed as a new paradigm of science in the 21st Century

The Six-Box Diagram of Behavior Formation



It indicates a Multiresolution Hierarchy

First Level of MS Integration

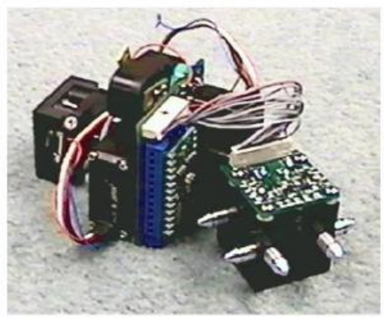
- conveyors,
- rotary tables,
- auxiliary manipulators

Second Level of MS Integration

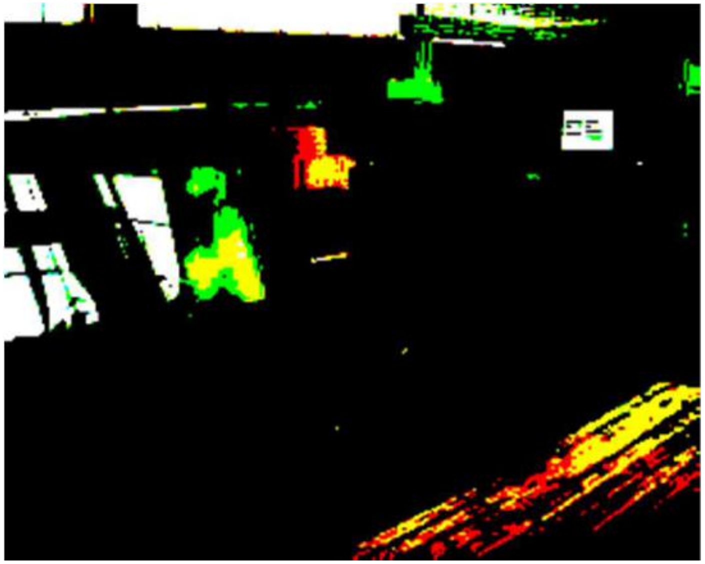
- operated power machines (turbines and generators), machine tools and industrial robots with numerical program management

Third Level of MS Integration

Synthesis of new precise, information and measuring high technologies gives a basis for designing and producing intellectual mechatronic modules and systems.



Modern Trends of MS Development 1



- Machine- tool construction and equipment for automation of technological processes;
- Robotics;

- Office equipment;
- Computer facilities;
- Photo and video equipment;

Modern Trends of MS Development 2

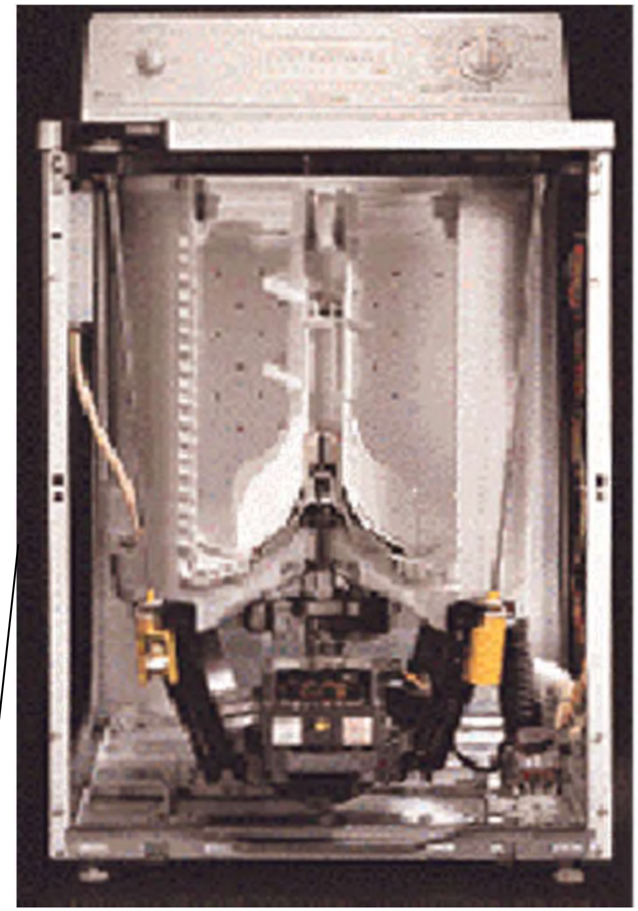
- Micro machines;
- Control and measuring devices and machines;
- Simulators for training of pilots and operators;
- Show-industry;
- Non-conventional
- vehicles.

Modern Trends of MS Development 3

- Aviation, space and military techniques;
- Motor car construction;

Examples of Mechatronic Systems

computer disk drive



clothes washer

Robot Platforms (1)

Indoor Robots

DLR Gripper

NASA Mars Rover

Asimo Humanoid

Outdoor Robots

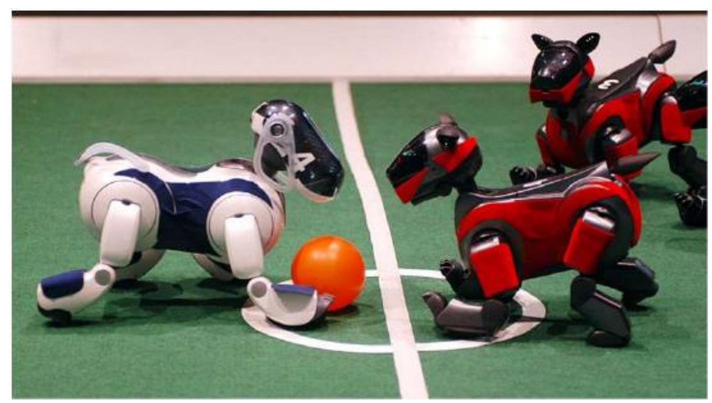
Robot Base Station

KUKA Manipulator

Robot Platforms (2)

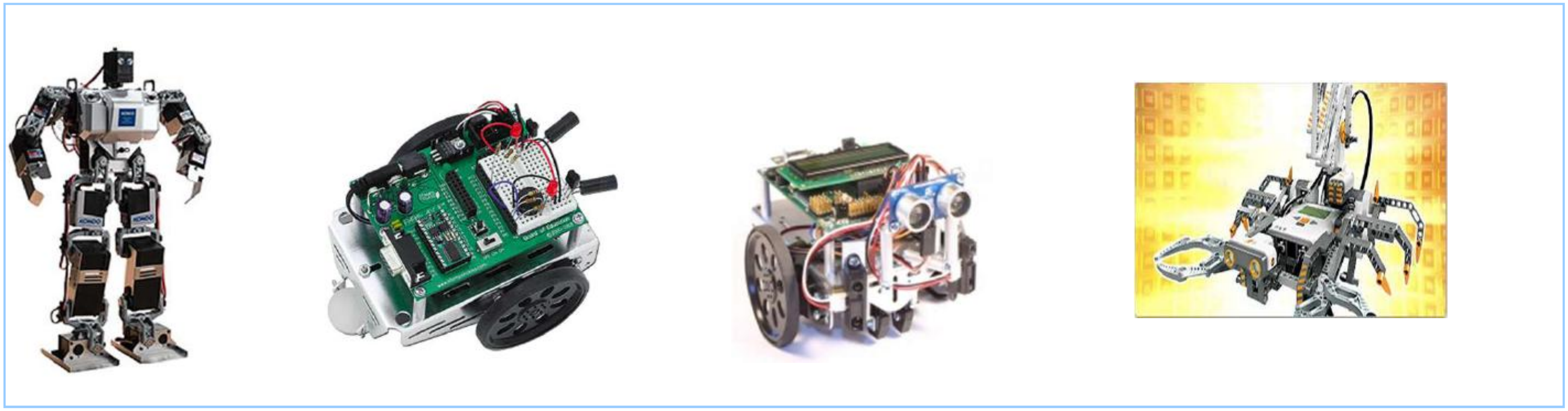
Aibo 4 legged Robot

Qurio Humanoid



Robocup Team

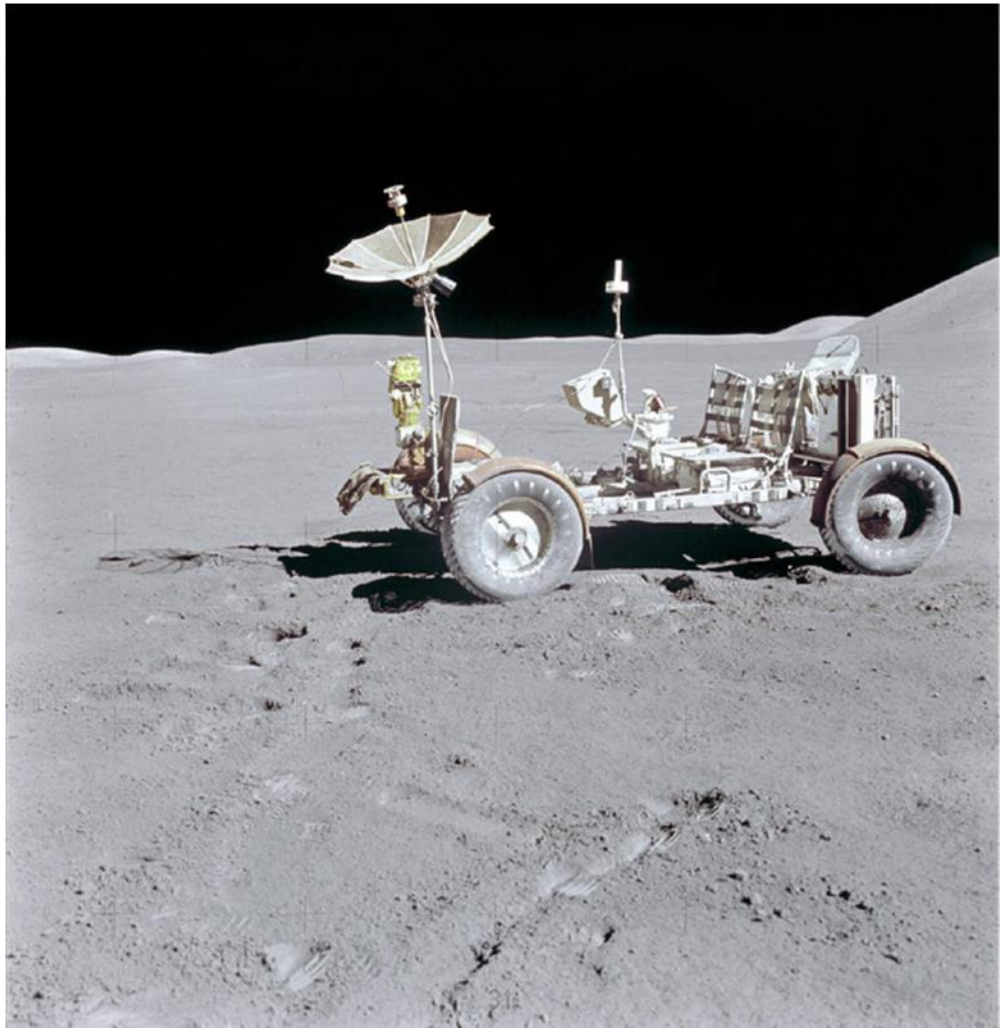
Robot Platforms (3)



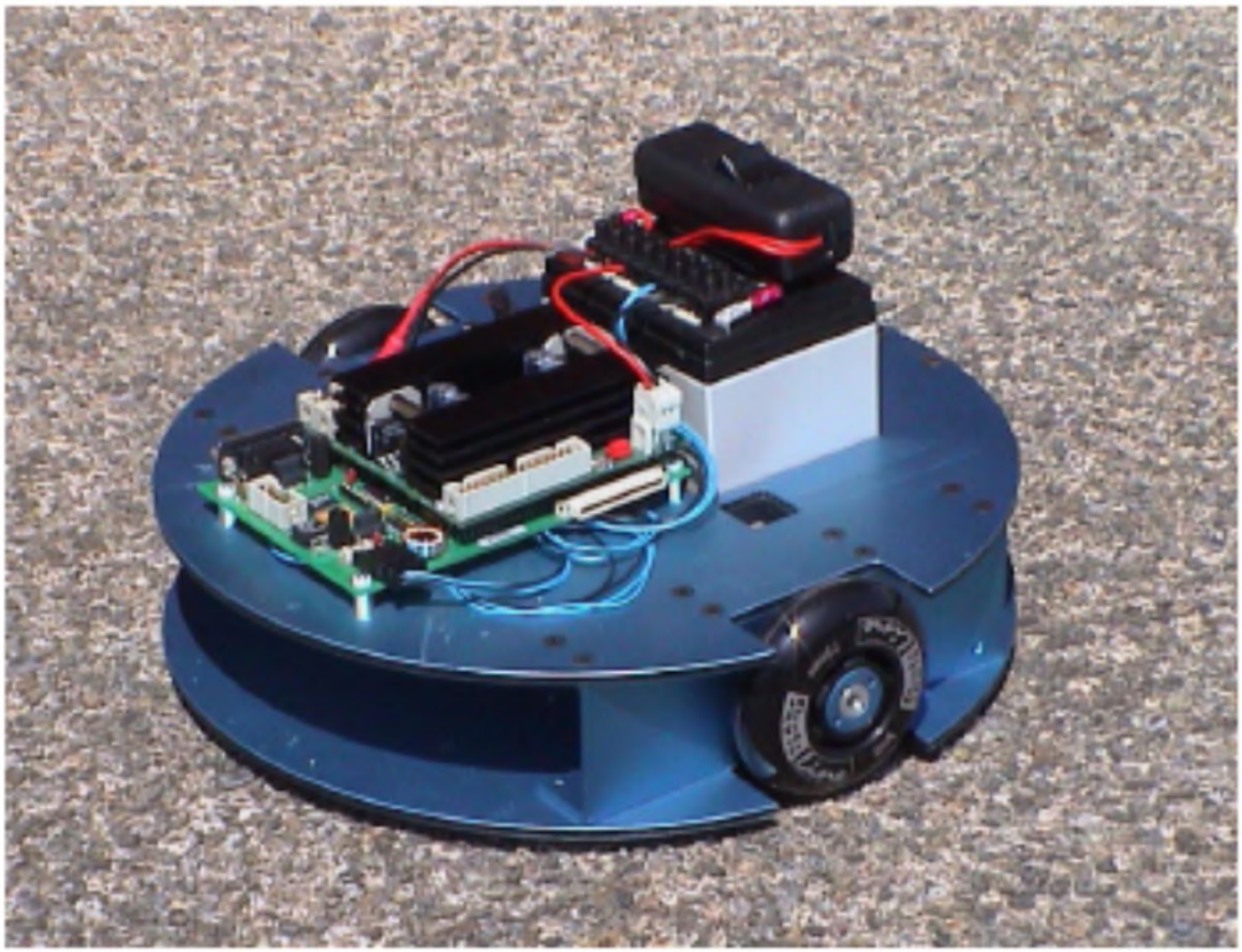
Robot educational kits

Robot sensors

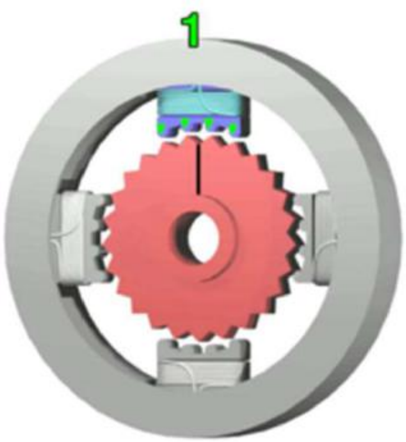
Lunar Rover Vehicle

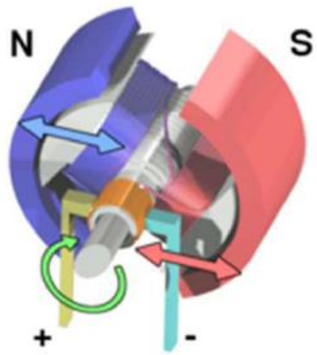


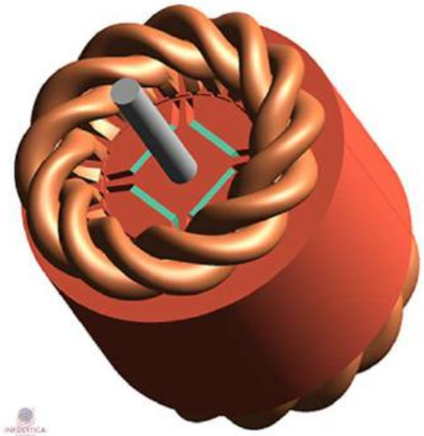
SmartEase mobile robot platform

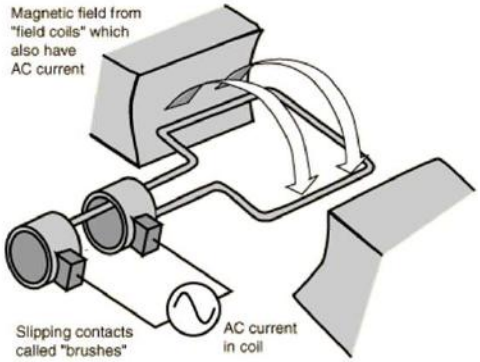


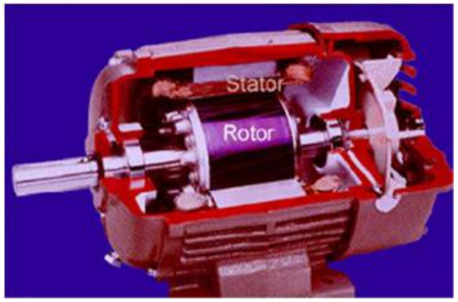
Stepper, AC and DC Motors









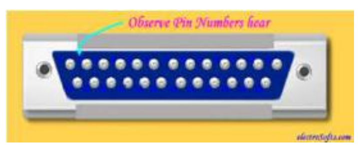


PC-based Measurement and Control

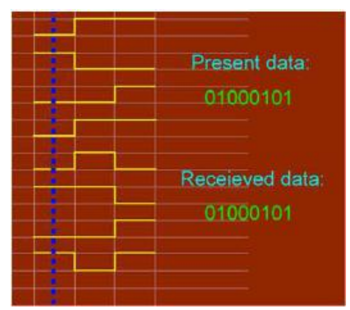
Pc Board

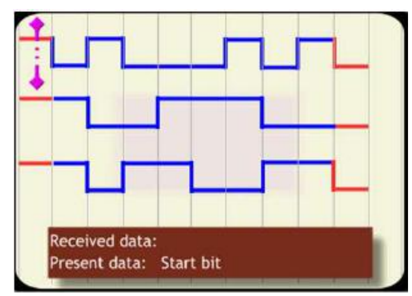
CAN BUS

GPIB

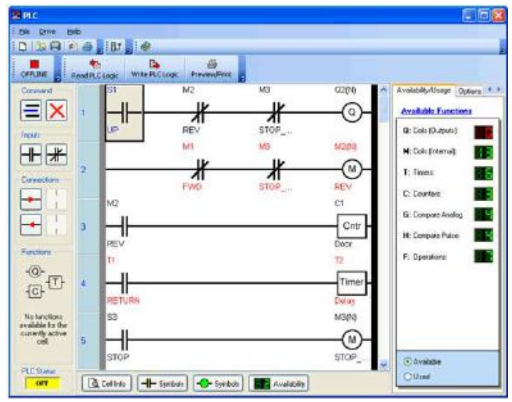


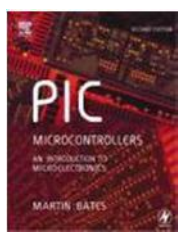
Serial/paralell



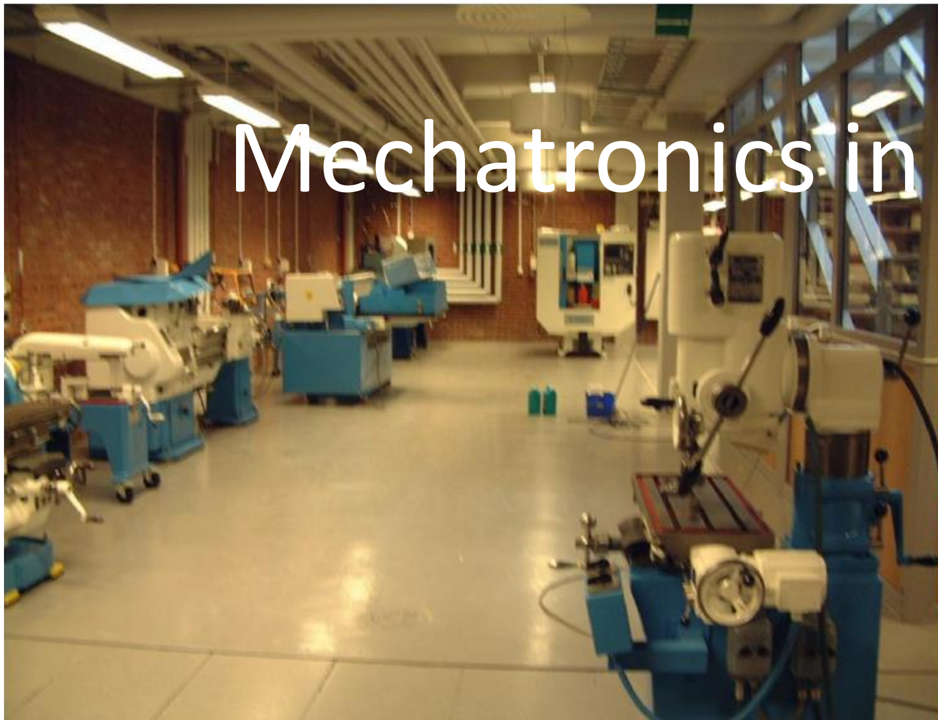


PLC and Microcontrollers





Mechatronics in Campus / Factory



Mechatronics, Providing enormous possibilities

- New functionally
- Improved design and ergonomic (ex: X-by-wire)
- Improved performance
- Diagnostics
- Flexibility & upgrades
- Internal & external communication
- New business models

The Core of Mechatronic Approach consists in integrating of components probably of different physical nature into a uniform functional module

Fundamental Mechatronic Problems

- Structural integration of mechanical, electronic and information departments into a uniform creative staff.
- Education and training of engineers specialized in mechatronics.
- Integration of information technologies from various scientific and technical fields into a uniform toolkit to provide computer support of mechatronic problems.
- Work collaboratively across disciplines on mechatronics
- Make appropriate use of sensors, actuators and mechanisms in mechatronics applications

Career Paths in Mechatronics

- Mechatronics is seen as a prime career path for mechanical engineers of the future;
- mechanical engineers with a mechatronics background will have a better chance of becoming managers;
- classically trained mechanical engineers will run the risk of being left out of the interesting work.

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Transformers

Transformers

- Transformer
- Transformer types
- Constructional detail
- Transformer operation
- Working of Transformer
- Turns ratio & efficiency
- The control transformer

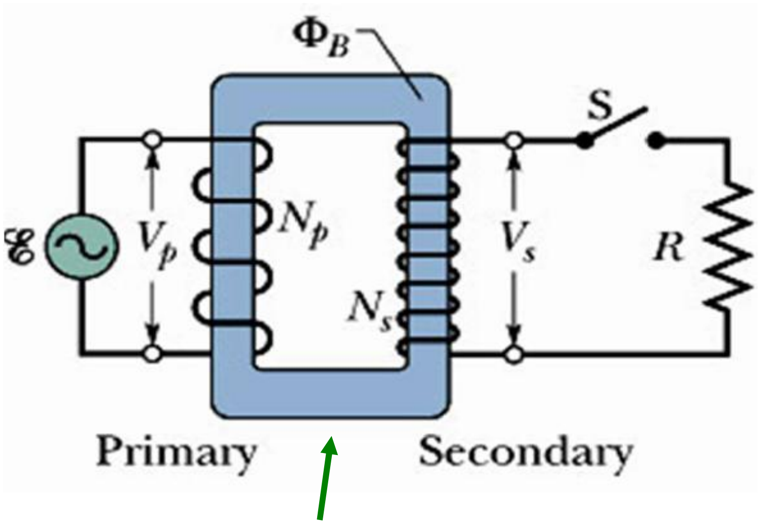
Transformer

- An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency

  In brief,

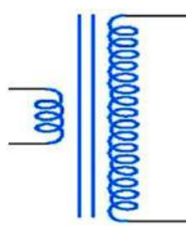
  1. Transfers electric power from one circuit to another
  2. It does so without a change of frequency
  3. It accomplishes this by electromagnetic induction
  4. Where the two electric circuits are in mutual inductive influence of each other.

- Devices used to change AC voltages. They have primary winding, secondary winding, power ratings
- Input and output are AC
- They do this by the principle of electromagnetic induction



iron core

circuit symbol



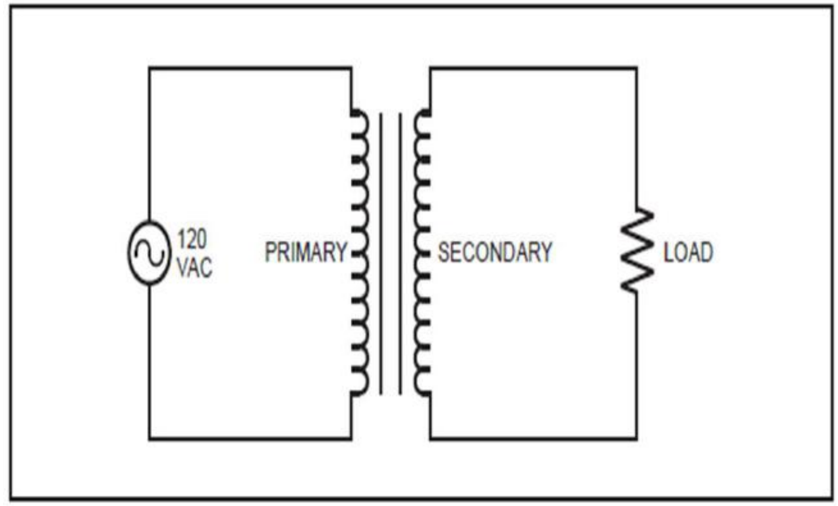
Transformer Types

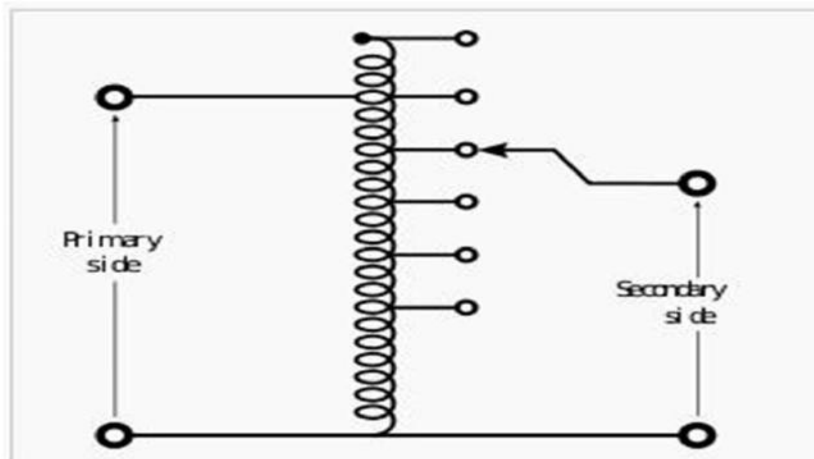
- Isolation Transformer

In isolation transformer, the primary and secondary are physically isolated (no electrical connection)

- Autotransformer

An autotransformer uses only one coil for the primary and secondary. It uses taps on the coil to produce the different ratios and voltages.



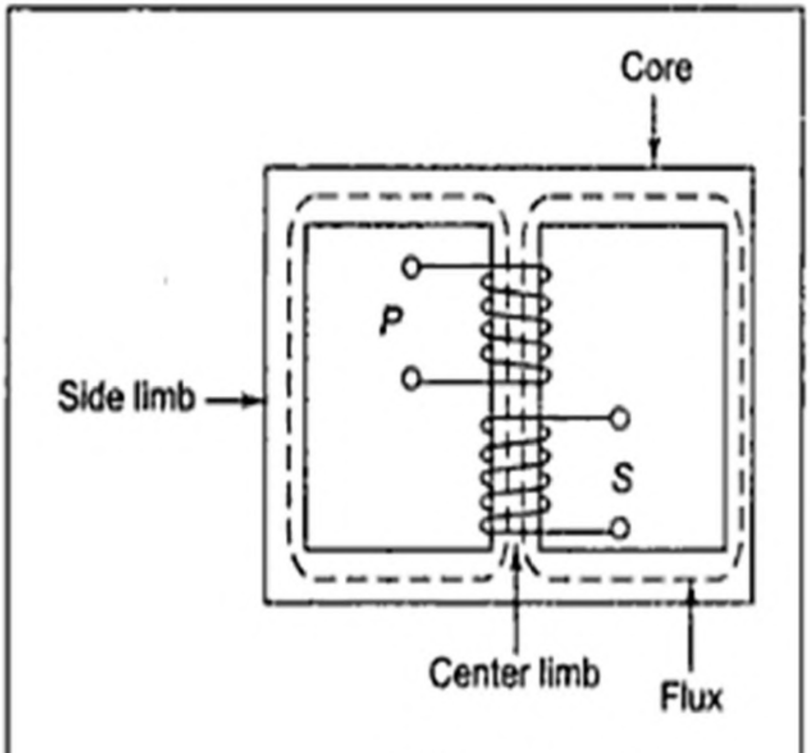


Single-phase tapped autotransformer with output voltage range of 40%–115% of input

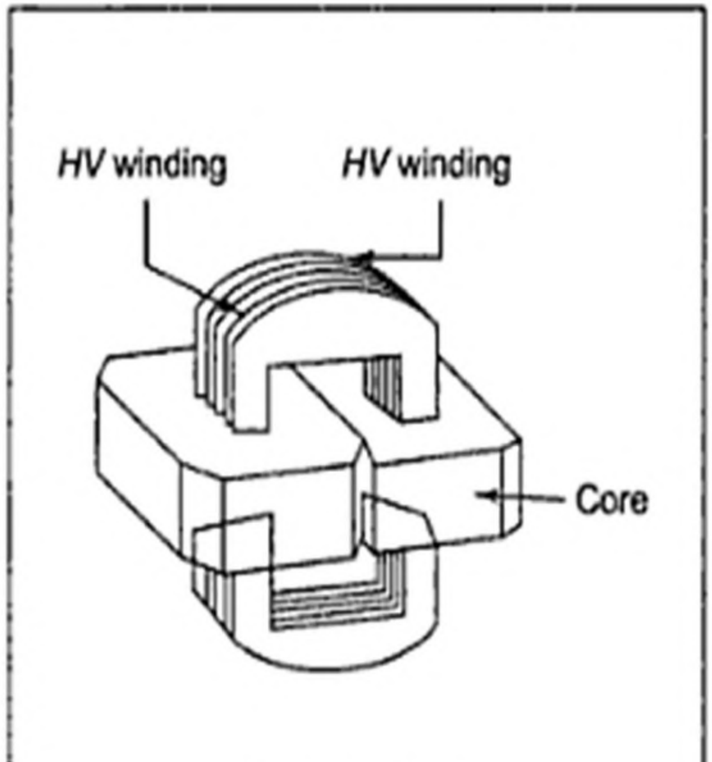
Advantages of Isolation Transformer

- Voltage spikes that might occur on the primary are greatly reduced or eliminated in the secondary
- If the primary is shorted somehow, any load connected to the secondary is not damaged
- Example: In TV monitors to protect the picture tube from voltage spikes in main power lines

Constructional detail: Shell type



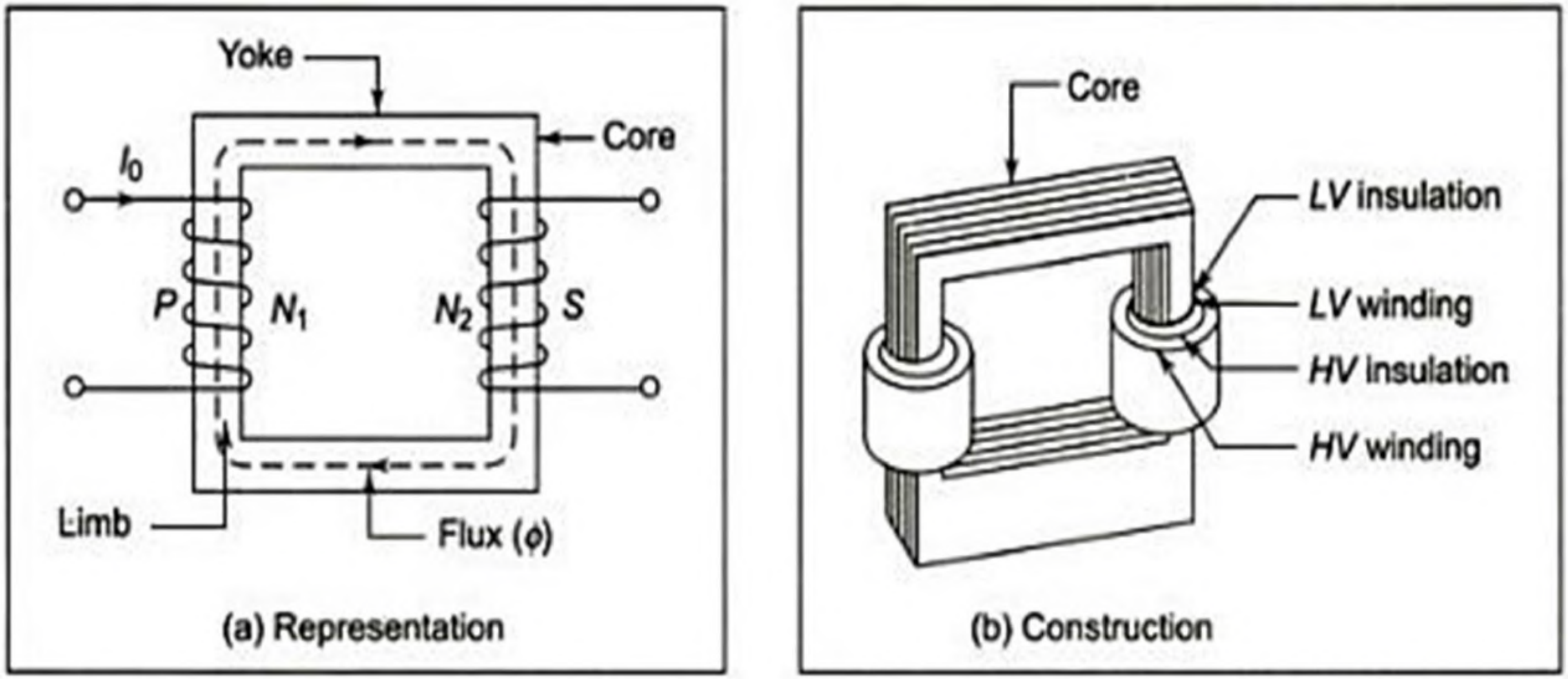
(a) Representation



(b) Construction

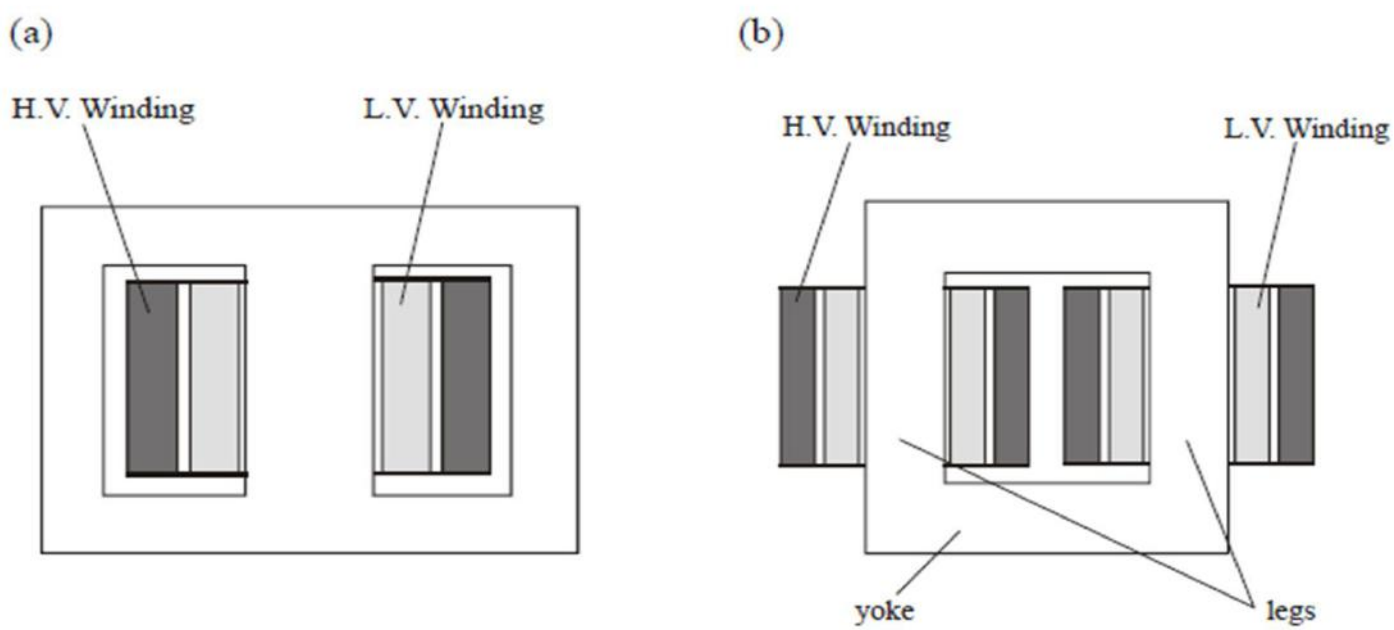
Windings are wrapped around the center leg of a laminated core.

Core type



Windings are wrapped around two sides of a laminated square core.

Sectional view of transformers

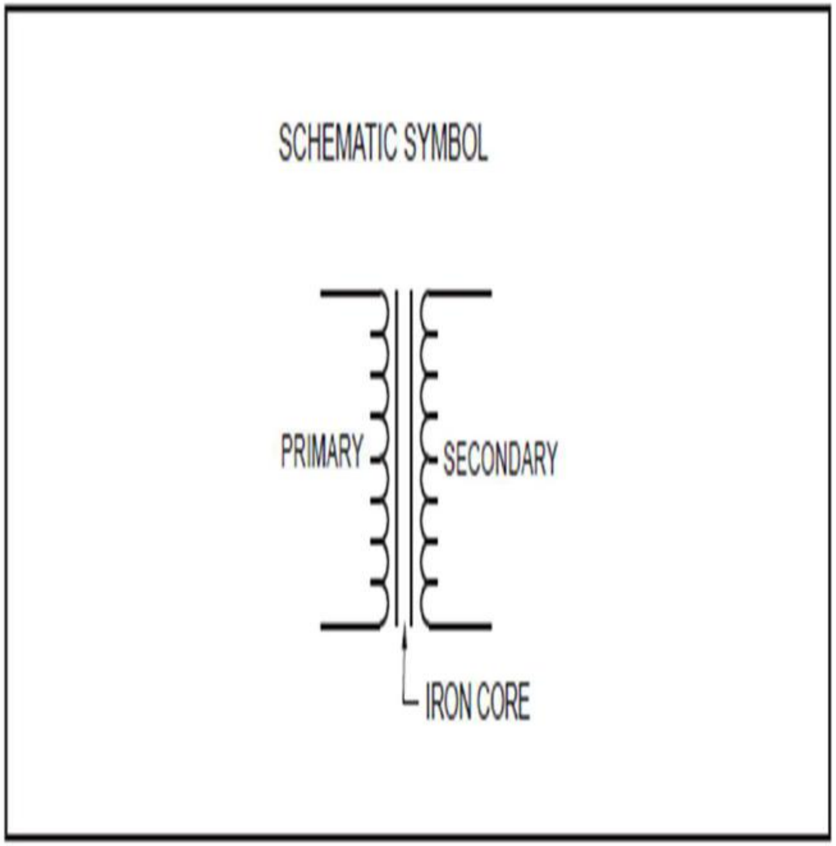


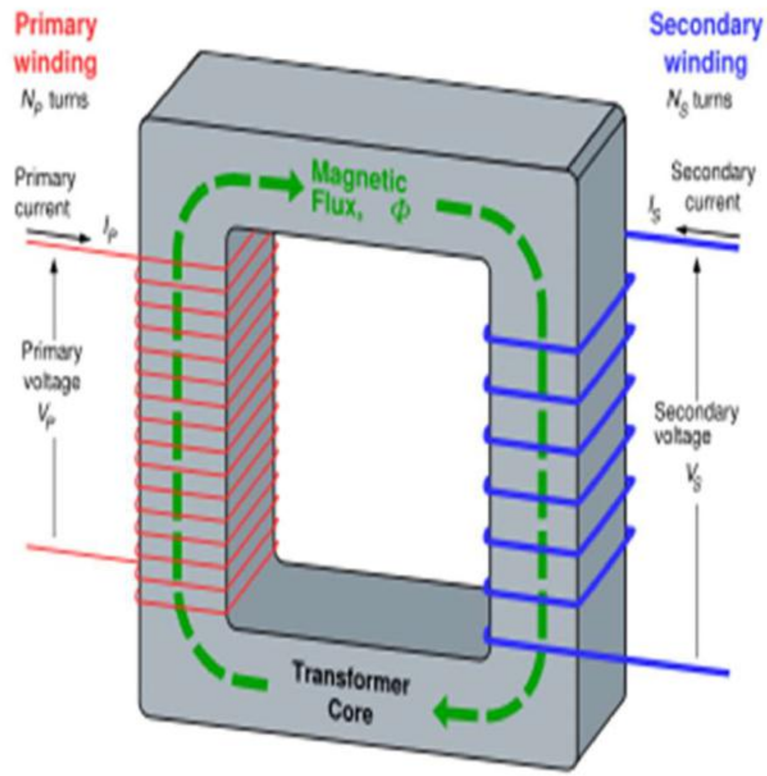
(a) Shell-type transformer, (b) core-type transformer

Note:

High voltage conductors are smaller cross section conductors than the low voltage coils

Symbol & Structure of Transformer



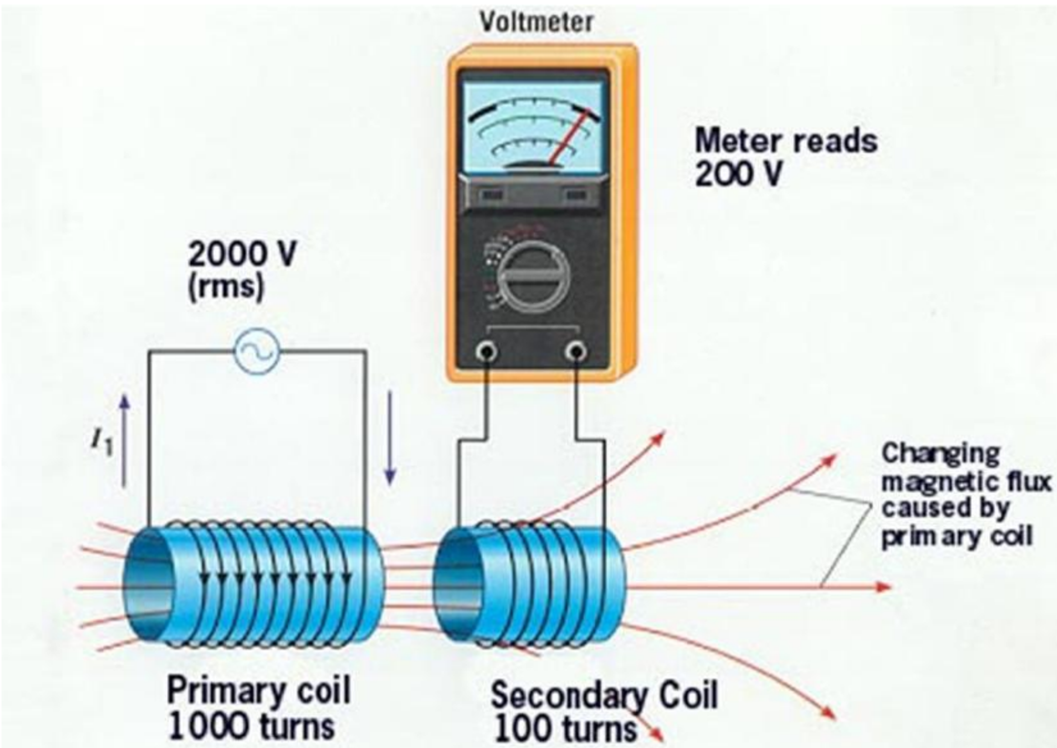


Parts of a Transformer

A transformer consists of 3 basic components

- Primary Coil or Primary Winding : It is an electrical wire wrapped around the core on the input side
- Secondary Coil or Secondary Winding: It is an electrical wire wrapped around the core on the output side
- Core : A ferromagnetic material that can conduct a magnetic field through it. Example: Iron

Transformer Operation

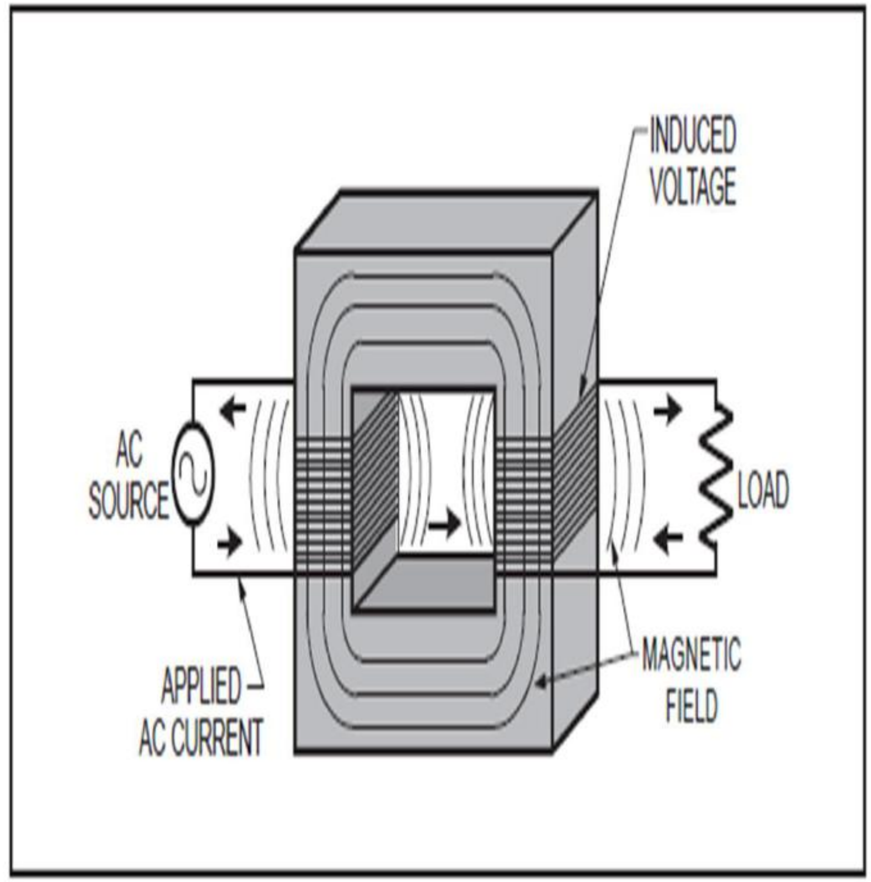


It is based on principle of MUTUAL INDUCTION.

According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

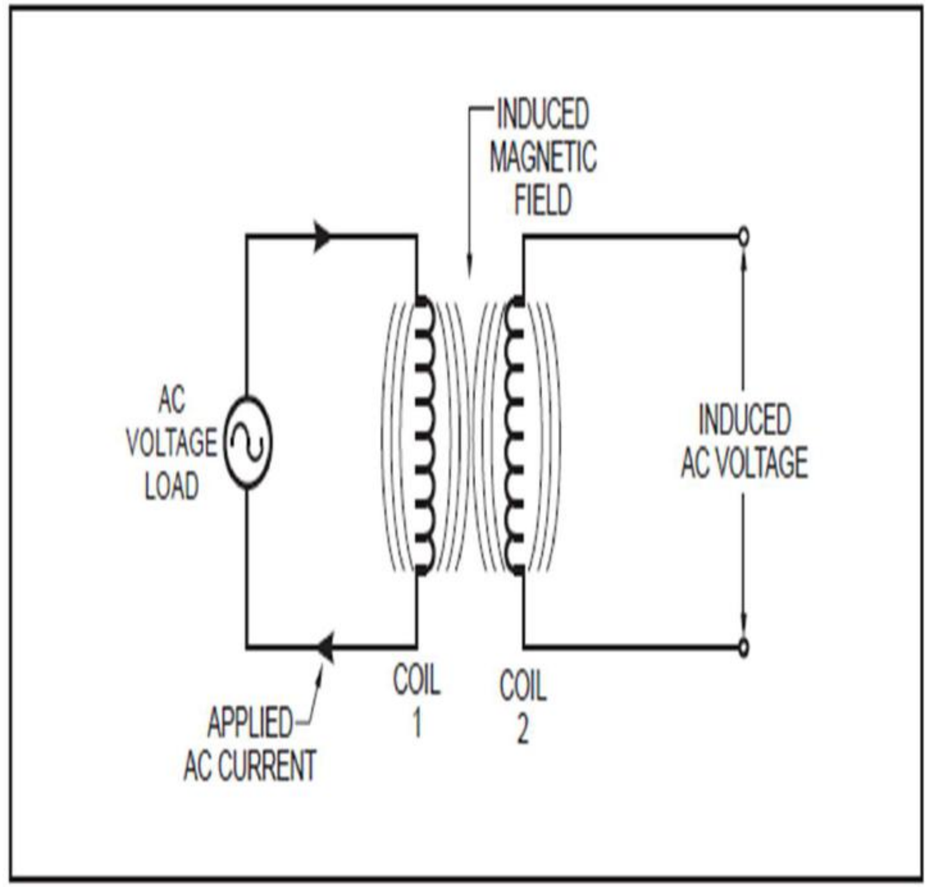
Principle of operation

- An electrical transformer normally consists of a ferromagnetic core and two coils called "windings".
- A transformer uses the principle of mutual inductance to create an AC voltage in the secondary coil from the alternating electric current flowing through the primary coil.
- The voltage induced in the secondary can be used to drive a load.



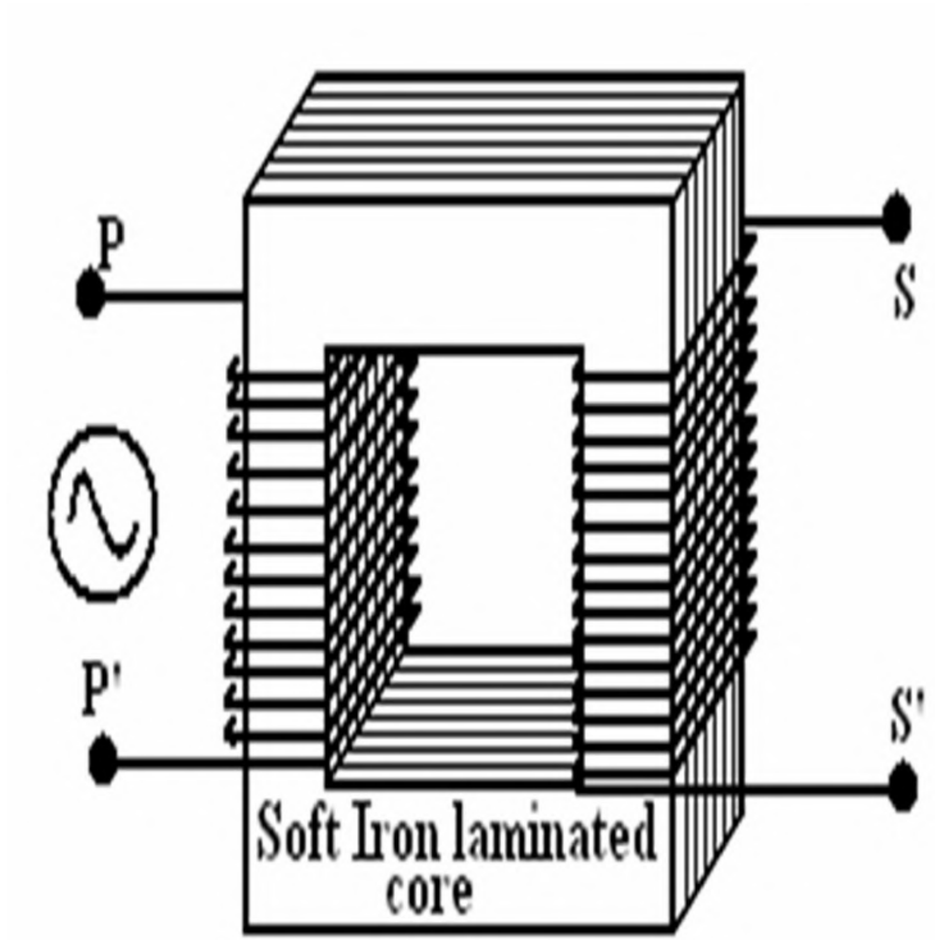
What is Mutual Inductance?

- The principle of mutual inductance says that when two electrical coils are placed near to each other, AC electrical current flowing in one coil induces an AC voltage in the other coil.
- This is because current in the first coil creates a magnetic field around the first coil which in turn induces a voltage in second coil



Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



Turns Ratio & Efficiency

- The transformer improves the efficiency of the transfer of energy from one coil to another by using a core to concentrate the magnetic field.
- The primary coil creates a magnetic field that is concentrated by the core and induces a voltage in the secondary coil
- The voltage at the secondary coil can be different from the voltage at the primary. This happens when the number of turns of the coil in primary and secondary are not the same
- The Turns Ratio (TR) is the ratio of the number of turns in the primary coil to the number of turns in the secondary coil

Assume zero internal resistances,
EMFs $\mathcal{E}_p$, $\mathcal{E}_s$ = terminal voltages V_p, V_s

Faradays Law for primary and secondary:

$$V_p = -N_p \frac{d\Phi_B}{dt} \qquad V_s = -N_s \frac{d\Phi_B}{dt}$$

Assume: The same amount of flux Φ_B cuts each turn in both primary and secondary windings in ideal transformer (counting self- and mutual-induction)

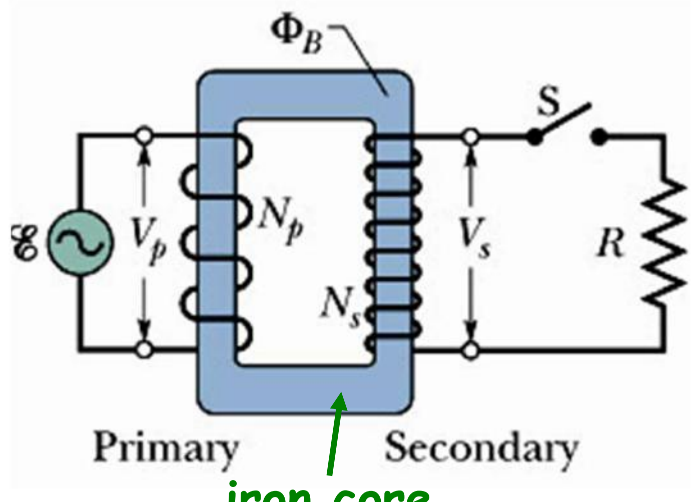
$$\frac{\text{induced voltage}}{\text{per turn}} \equiv \frac{d\Phi_B}{dt} = \frac{V_p}{N_p} = \frac{V_s}{N_s}$$

$$\therefore\ V_s = \frac{N_s}{N_p} V_p$$

Turns ratio fixes the step up or step down voltage ratio

V_p, V_s are instantaneous (time varying) or RMS averages, as can be the power and current.

Ideal Transformer



- zero resistance in coils
- no hysteresis losses in iron core
- all field lines are inside core

Assuming no losses: energy and power are conserved

$$P_s = V_s I_s = \text{conserved} = P_p = V_p I_p$$

$$\therefore\ \frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Turns Ratio & Transformer Output Voltage Formula

TURNS RATIO FORMULA

$$TR = \frac{N_P}{N_S}$$

Where

N_P = *number of turns in the primary*
N_S = *number of turns in the secondary*

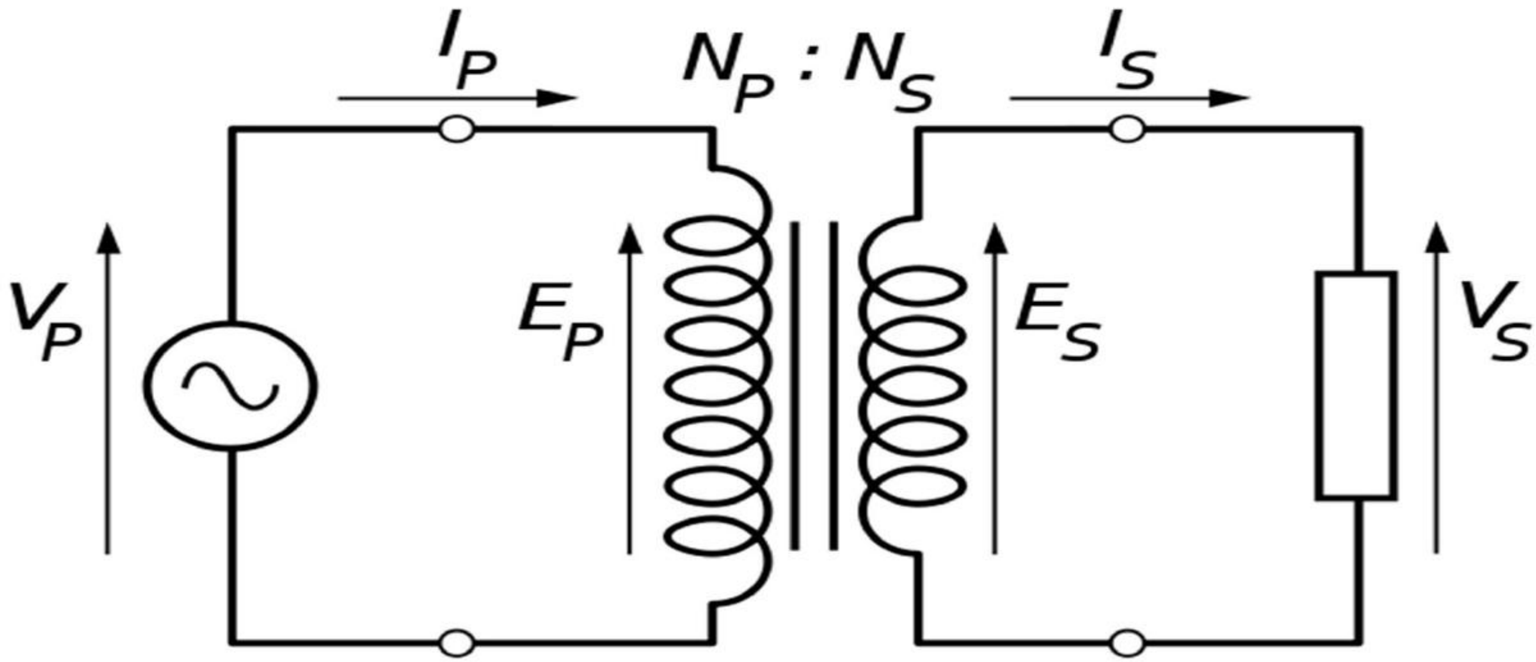
TRANSFORMER OUTPUT VOLTAGE FORMULA

$$V_S = \frac{V_P}{TR}$$

Where

V_S = *secondary voltage (Volts)*
V_P = *primary voltage (Volts)*
TR = *turns ratio*

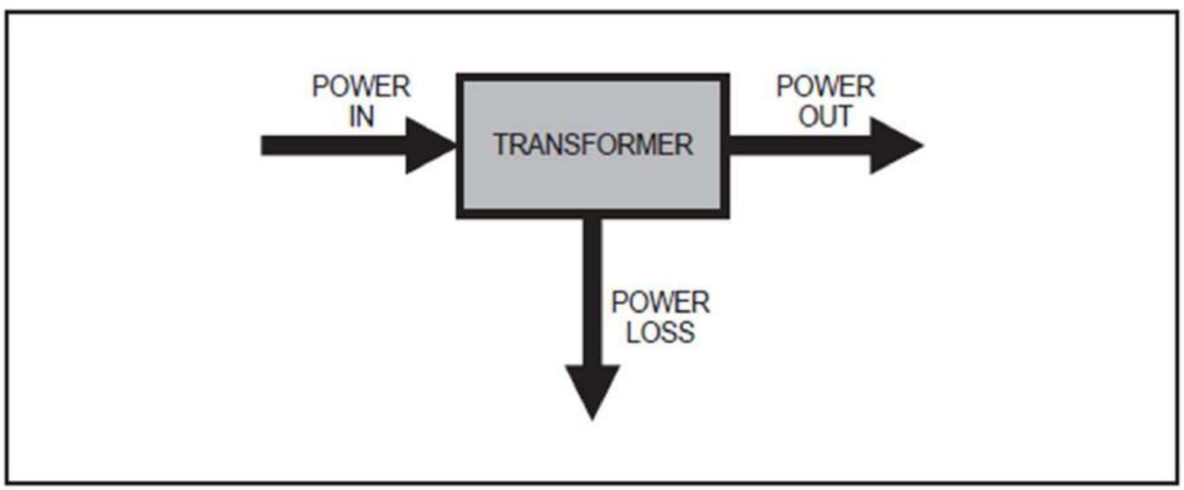
Transformer Voltages & Currents



$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$

Input Power and Output Power of a Transformer

- Under ideal conditions input power and output power should be the same. But there is power loss between the primary and secondary and so practically they are not exactly equal.
- So, $P_{in} = P_{out} + P_{loss}$



Transformer Efficiency

- The power loss is converted to heat . The heat produced can be found by calculating the transformer efficiency.

TRANSFORMER EFFICIENCY FORMULA

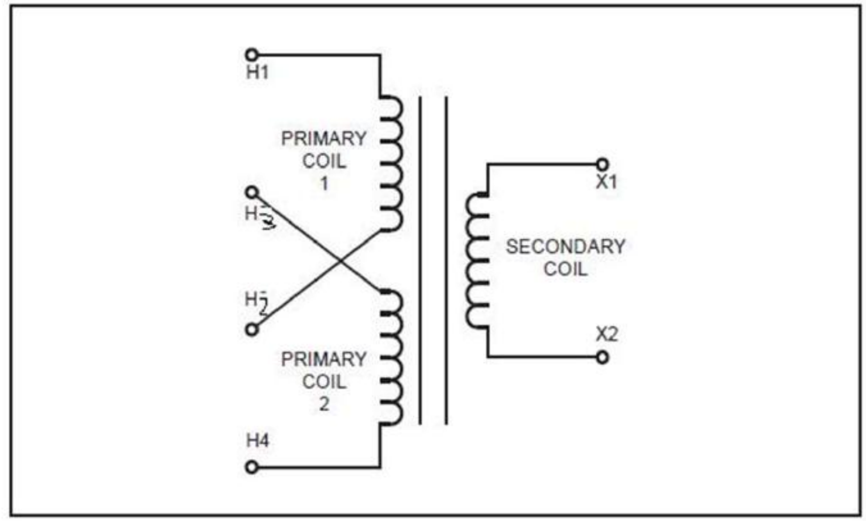
$$Transformer\ Efficiency\ \% = \frac{Power\ Out}{Power\ In} \times 100$$

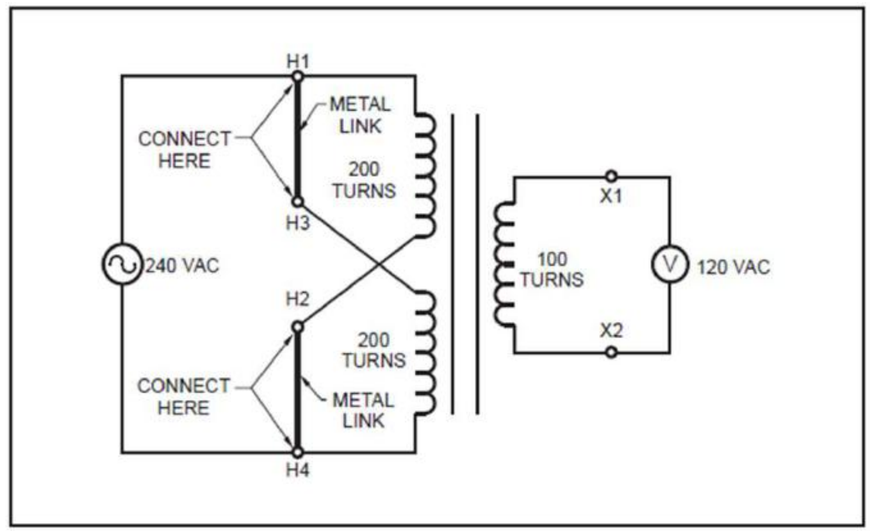
Where

Power Out = *output power (Watts or VA)*
Power In = *input power (Watts or VA)*

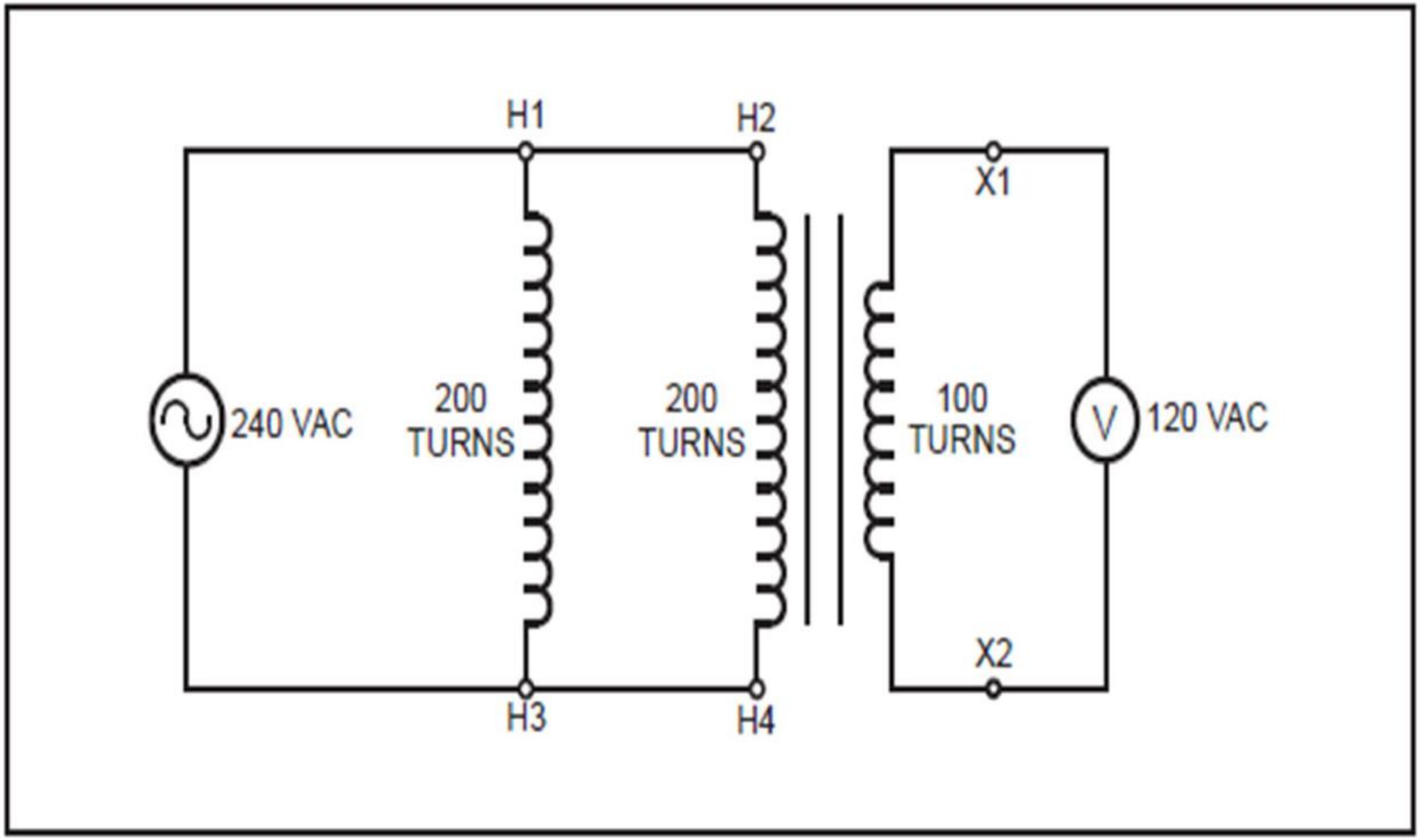
The Control Transformer

- A control transformer is used to reduce voltage from the main power line to a lower voltage that operates a machine’s electrical control system.
- The most common type of control transformer has two primary coils (H1H2 and H3H4) and one secondary coil (X1X2). Note that the primary windings are crossed.
- To get 120V at the secondary from 240 V at the primary using a control transformer

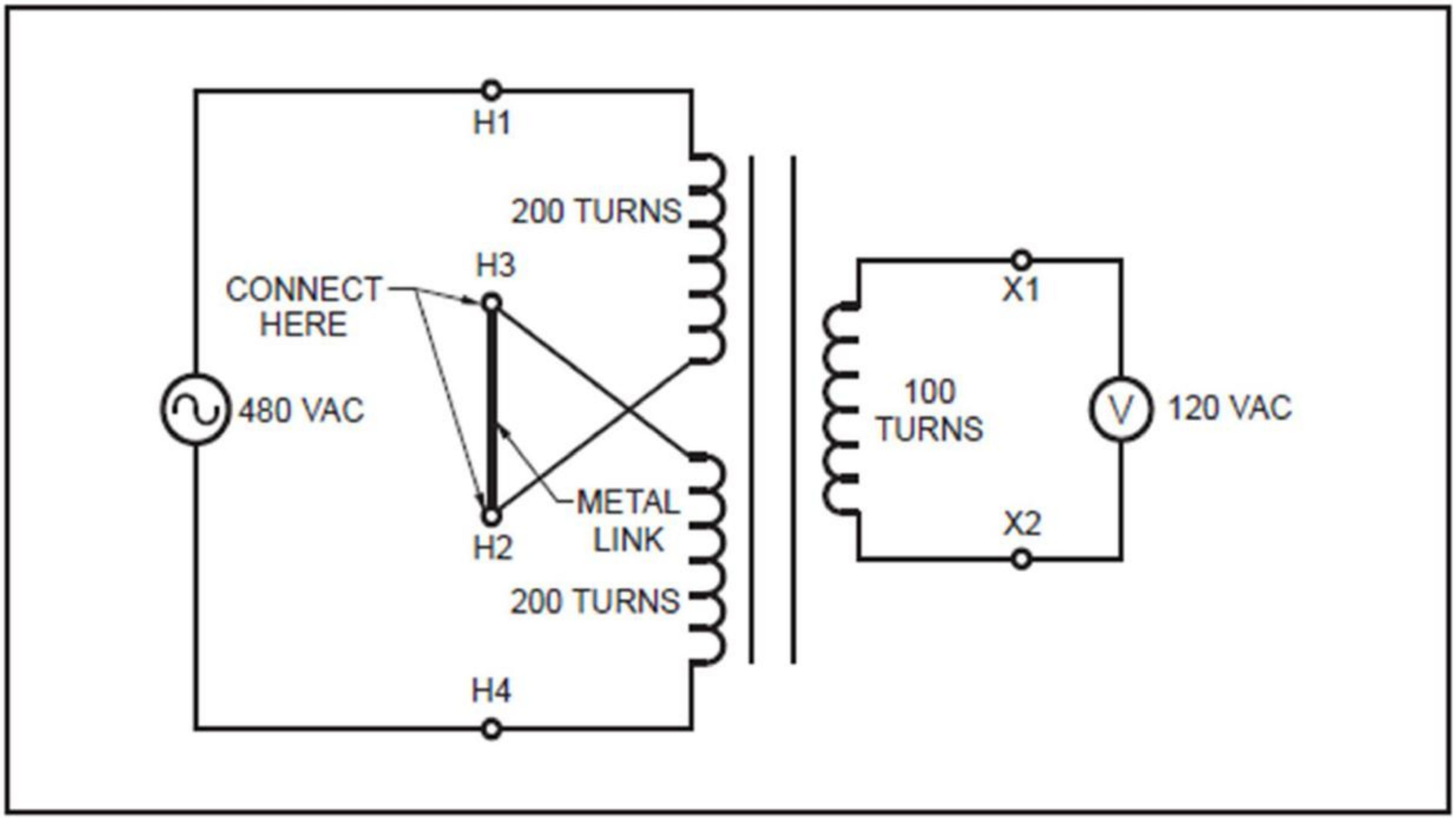




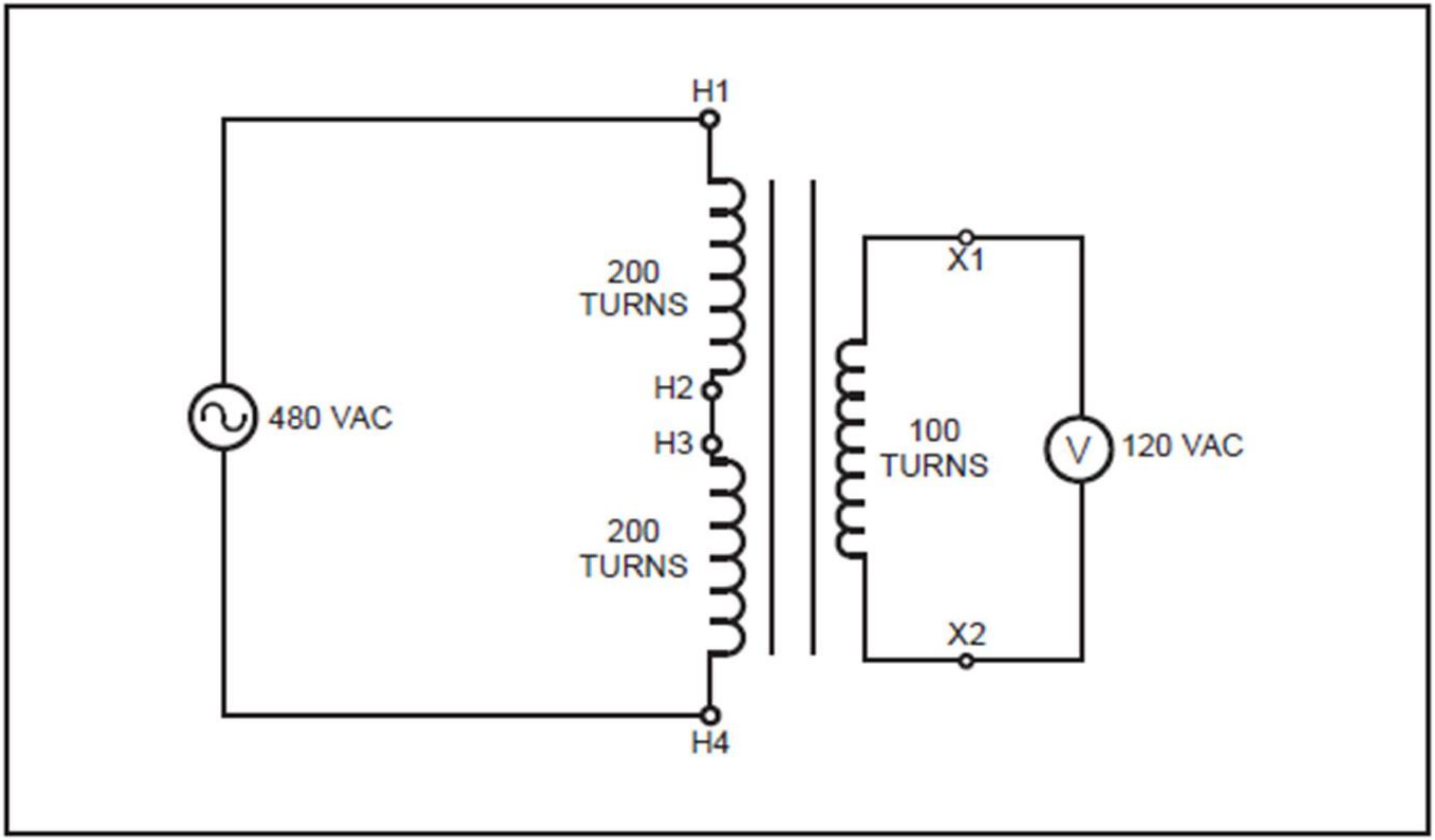
It is actually a parallel connection of the primary coils



To get 120V at the secondary from 480 V at the primary using a control transformer



This is actually a series connection of the primary coils



Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Introduction to Energy

Introduction to Energy: Forms and Changes

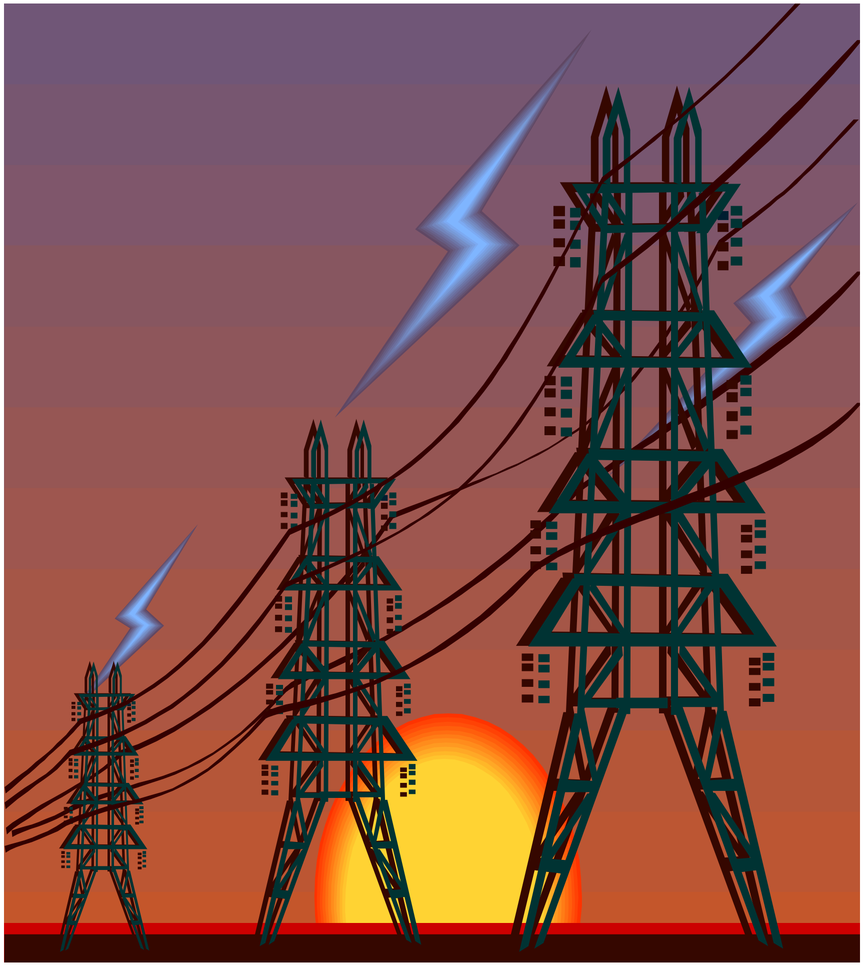
- Nature and Forms of Energy
- Heat energy
- Chemical energy
- Electromagnetic energy
- Nuclear energy
- Mechanical energy
- Kinetic energy
- Potential energy
- Gravitational potential energy
- Energy conversion
- Law of conservation of energy
- Renewable energy: Ocean (wave) Energy

Nature of Energy

- Energy is all around us. Living organisms need energy for growth and movement.
  - We can hear energy as sound, we can see energy as light, we can feel it as wind.
- Energy is involved when:
  - a bird flies, a bomb explodes, rain falls from the sky, electricity flows in a wire.
- What is energy that it can be involved in so many different activities?
  - Energy can be defined as the ability to do work.
  - If an object or organism does work (exerts a force over a distance to move an object) the object or organism uses energy.
- Because of the direct connection between energy and work, energy is measured in the same unit as work: joules (J). In addition to using energy to do work, objects gain energy because work is being done on them.

Forms of Energy

- The five main forms of energy are:
  - Heat Energy
  - Chemical Energy
  - Electromagnetic Energy
  - Nuclear Energy
  - Mechanical Energy



Heat Energy

- The internal motion of the atoms is called heat energy, because moving particles produce heat.

- Heat energy can be produced by friction.

- Heat energy causes changes in temperature and phase of any form of matter.

Chemical Energy

- Chemical Energy is required to bond atoms together.
- And when bonds are broken, energy is released.
- Fuel and food are forms of stored chemical energy.

Electromagnetic Energy

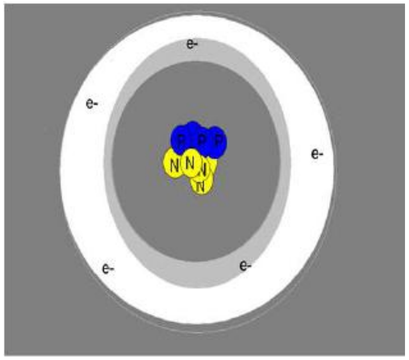
- Power lines carry electromagnetic energy into your home in the form of electricity.

- Light is a form of electromagnetic energy.

- Each color of light (Roy G Bv) represents a different amount of electromagnetic energy.

- Electromagnetic Energy is also carried by X-rays, radio waves, and laser light.

Nuclear Energy



- The nucleus of an atom is the source of nuclear energy.
- When the nucleus splits (fission), nuclear energy is released in the form of heat energy and light energy.
- Nuclear energy is also released when nuclei collide at high speeds and join (fuse).
- The sun's energy is produced from a nuclear fusion reaction in which hydrogen nuclei fuse to form helium nuclei.
- Nuclear energy is the most concentrated form of energy.

Mechanical Energy

- When work is done to an object, it acquires energy. The energy it acquires is known as mechanical energy.

- When you kick a football, you give mechanical energy to the football to make it move.

- When you throw a balling ball, you give it energy. When that bowling ball hits the pins, some of the energy is transferred to the pins (transfer of momentum).

Kinetic Energy

- The energy of motion is called kinetic energy.
- The faster an object moves, the more kinetic energy it has.
- The greater the mass of a moving object, the more kinetic energy it has.
- Kinetic energy depends on both mass and velocity.
- What has a greater affect of kinetic energy, mass or velocity? Why?

Potential Energy

- Potential Energy is stored energy.
  - Stored chemically in fuel, the nucleus of atom, and in foods.
  - Or stored because of the work done on it:
    - Stretching a rubber band.
    - Winding a watch.
    - Pulling back on a bow's arrow.
    - Lifting a brick high in the air.

- Energy that is stored due to being stretched or compressed is called elastic potential energy.

Gravitational Potential Energy

- Potential energy that is dependent on height is called gravitational potential energy.
- A waterfall, a suspension bridge, and a falling snowflake all have gravitational potential energy.
- If you stand on a 3-meter diving board, you have 3 times the G.P.E, than you had on a 1-meter diving board.
- "The bigger they are the harder they fall" is not just a saying. It's true. Objects with more mass have greater G.P.E. The formula to find G.P.E. is

  G.P.E. = Weight X Height.

Energy Conversion

- Energy can be changed from one form to another. Changes in the form of energy are called energy conversions.

- All forms of energy can be converted into other forms.
  - The sun's energy through solar cells can be converted directly into electricity.
  - Green plants convert the sun's energy (electromagnetic) into starches and sugars (chemical energy).

Other Energy Conversions

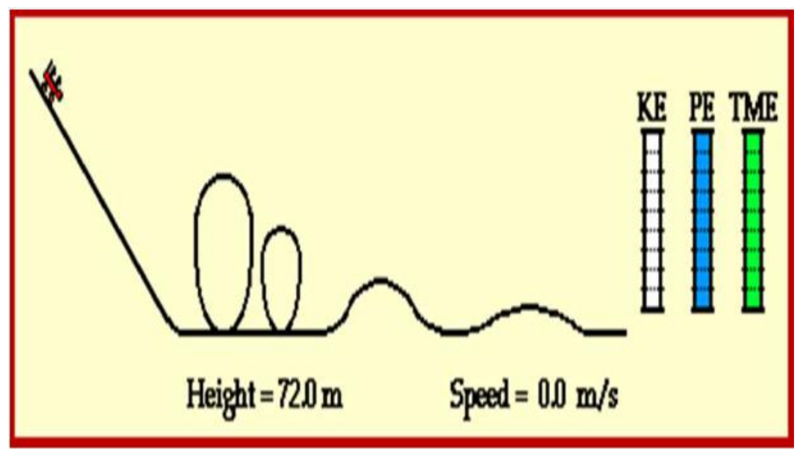
- In an electric motor, electromagnetic energy is converted to mechanical energy.
- In a battery, chemical energy is converted into electromagnetic energy.
- The mechanical energy of a waterfall is converted to electrical energy in a generator.
- In an automobile engine, fuel is burned to convert chemical energy into heat energy. The heat energy is then changed into mechanical energy. Chemical → Heat →Mechanical

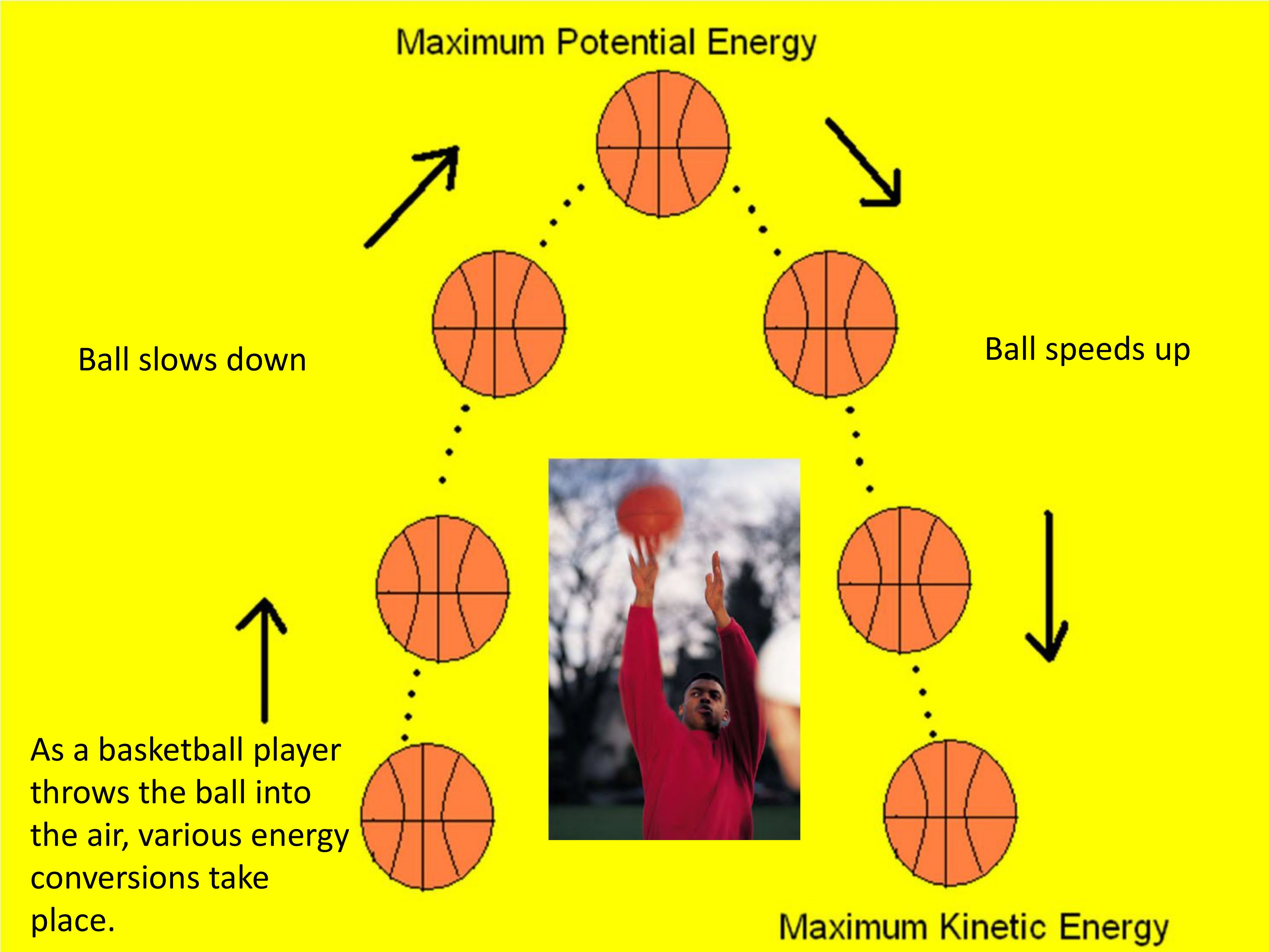
States of Energy

- The most common energy conversion is the conversion between potential and kinetic energy.
- All forms of energy can be in either of two states:
  – Kinetic Energy
  – Potential Energy
- Kinetic Energy is the energy of motion. Potential Energy is stored energy.

Kinetic-Potential Energy Conversion

Roller coasters work because of the energy that is built into the system. Initially, the cars are pulled mechanically up the tallest hill, giving them a great deal of potential energy. From that point, the conversion between potential and kinetic energy powers the cars throughout the entire ride. At the point of maximum potential energy, the car has minimum kinetic energy.





Maximum Potential Energy
Ball slows down
Ball speeds up
As a basketball player throws the ball into the air, various energy conversions take place.
Maximum Kinetic Energy

The Law of Conservation of Energy

- Energy can be neither created nor destroyed by ordinary means.
  - It can only be converted from one form to another.
  - If energy seems to disappear, then scientists look for it – leading to many important discoveries.

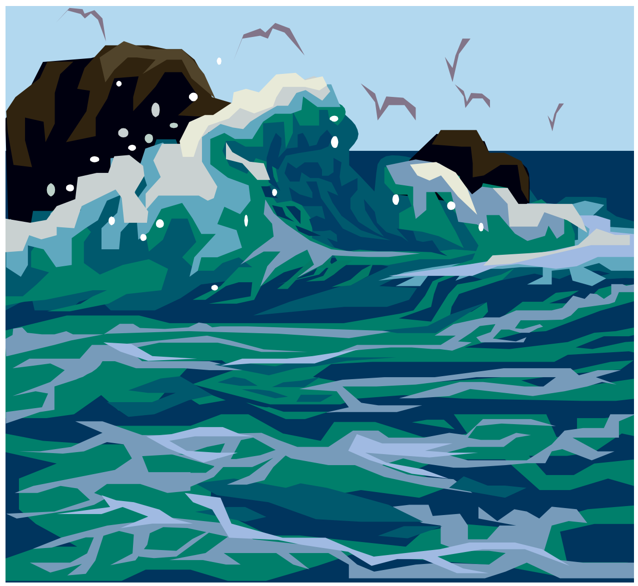
- In 1905, Albert Einstein said that mass and energy can be converted into each other.

- He showed that if matter is destroyed, energy is created, and if energy is destroyed mass is created. E = M C^2

Renewable Energy: Ocean (Wave) Energy

- Renewable energy technologies provide alternatives to fossil-fueled power plants for the generation of electricity, an essential step towards reducing our nation's dependence on fossil fuels.
- One category of emerging renewable energy technologies relates to **OCEAN ENERGY**. Among other types of renewable energy, oceans contain energy in the form of waves & tidal currents.
- The amount of energy transferred and the size of the resulting wave depend on
  - the wind speed
  - the length of time for which the wind blows
  - the distance over which the wind blows, or fetch

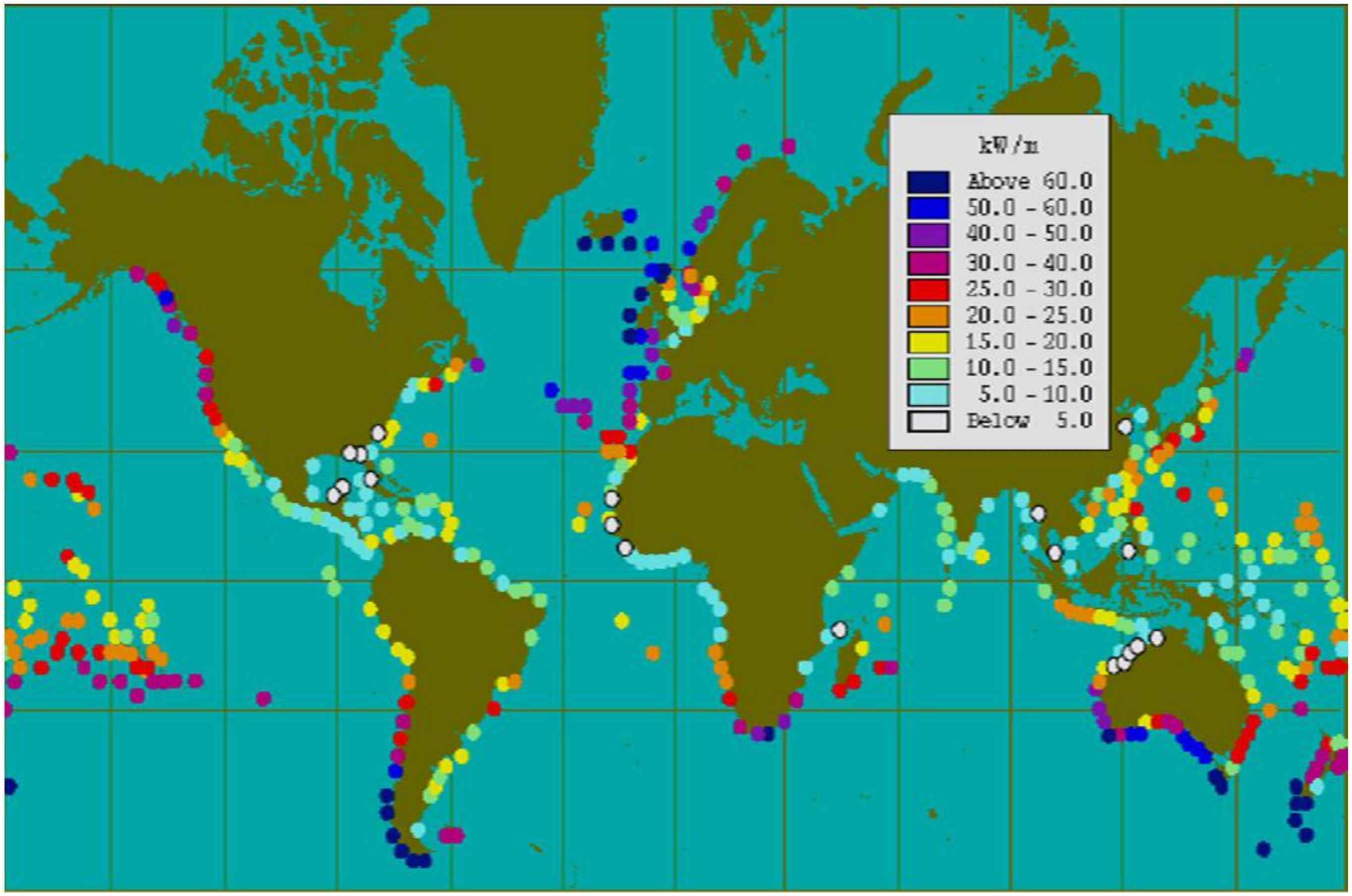
- Therefore, coasts that have exposure to the prevailing wind direction and that face long expanses of open ocean have the greatest wave energy levels
- Differential warming of the earth causes pressure differences in the atmosphere, which generate winds
- As winds move across the surface of open bodies of water, they transfer some of their energy to the water and create waves
- In order to extract this energy, wave energy conversion devices must create a system of reacting forces, in which two or more bodies move relative to each other, while at least one body interacts with the waves.



Wave Energy

The strongest winds blow between 30˚ and 60˚ in latitude.

Western coastlines at these latitudes experience the most powerful waves.



Global Wave Energy Resource Distribution
(measuring the amount of power in kW contained in each linear meter of wave front)

Wave Energy Power in US

- The Electric Power Research Institute (EPRI) estimates that the annual average incident wave energy off of the U.S. coastline amounts to 2100 terawatt hours per year. (A terawatt equals a trillion watts.)
- Harnessing 20% of that total energy at 50% conversion efficiency would generate as much electricity as conventional hydropower currently provides – 7% of total U.S. electricity consumption, or 270 terawatt hours per year.
- How about Indonesia ? Do we have one ? ☺

How Do We Harness Wave Energy?

In order to extract this energy, wave energy conversion devices must create a system of reacting forces, in which two or more bodies move relative to each other, while at least one body interacts with the waves.

There are many ways that such a system could be configured.

Wave Energy Technologies

- Waves retain energy differently depending on water depth
  - Lose energy slowly in deep water
  - Lose energy quickly as water becomes shallower because of friction between the moving water particles and the sea bed
- Wave energy conversion devices are designed for optimal operation at a particular depth range. Therefore, devices can be characterized in terms of their placement or location.
  - At the shoreline, near the shoreline, and off-shore
- One wave energy conversion system that has proven successful at each of these locations is the **OSCILLATING WATER COLUMN**.

On-shore Technologies

In spite of the success of this technology in an on-shore application, most wave energy experts agree that off-shore or near-shore devices offer greater potential than shoreline devices.

Advantages

- Easier to access for construction and maintenance
- Less installment costs and grid connection charges
- Could be incorporated into harbor walls or water breaks, performing a dual service for the community

Disadvantages

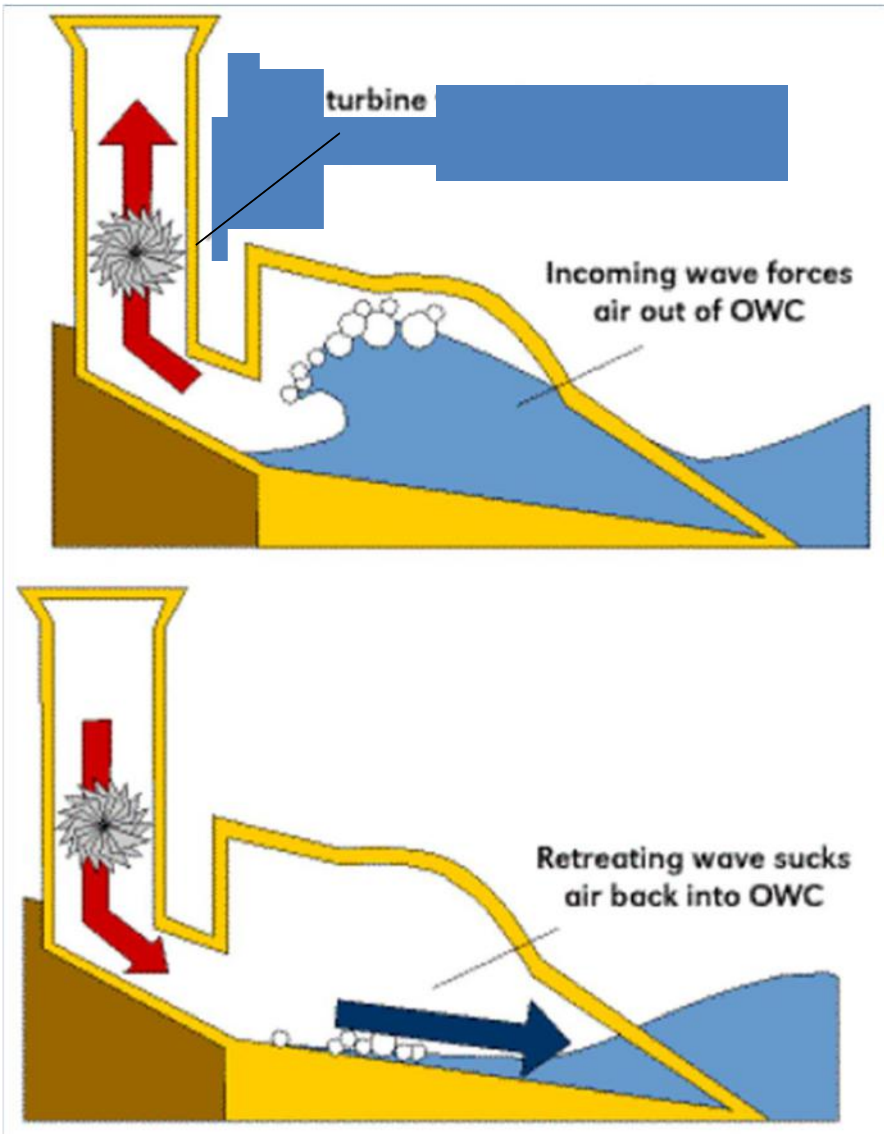
- Limited number of suitable sites / high competition for use of the shoreline
- Environmental concerns for on-shore devices may be greater
- Much less energy available to on-shore devices because water depth usually decreases closer to the shore

Oscillating Water Column

- An Oscillating Water Column (OWC) consists of a partially submerged structure that opens to the ocean below the water surface. This structure is called a wave collector.

- This design creates a water column in the central chamber of the collector, with a volume of air trapped above it.

OWC Design



- As a wave enters the collector, the surface of the water column rises and compresses the volume of air above it.
- The compressed air is forced into an aperture at the top of the chamber, moving past a turbine.
- As the wave retreats, the air is drawn back through the turbine due to the reduced pressure in the chamber.

Oscillating Water Column

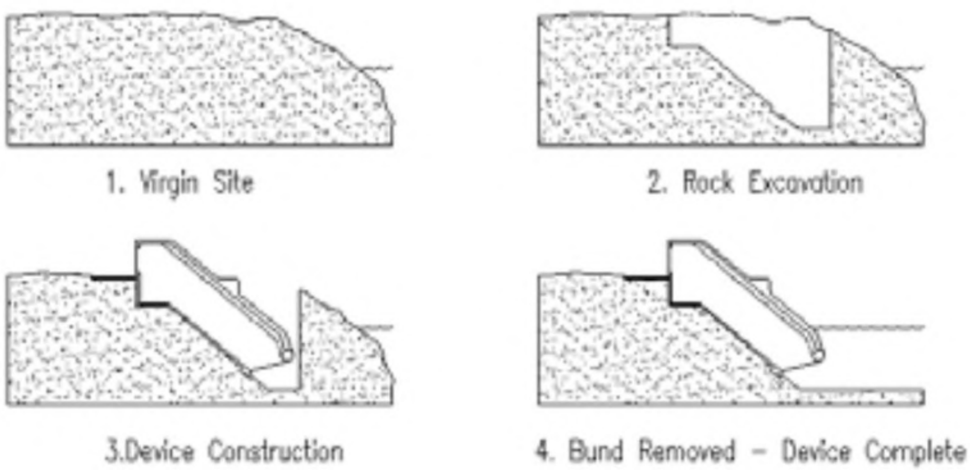
- The turning of the turbine drives a generator, producing electricity. The type of turbine used is a key element to the conversion efficiency of an OWC.

- Traditional turbines function by gas or liquid flowing in one direction and at a constant velocity. When the flow is not always from the same direction or at a constant velocity – such as in the OWC – traditional turbines become ineffective. Different types of turbines have been developed for the OWC to address this problem.

- The technologies have been demonstrated to work in a number of locations, with varying degrees of efficiency.
  - Wavegen's LIMPET.
  - Energetech's Australia Wave Energy System .

LIMPET

LIMPET (Land Installed Marine Powered Energy Transformer), an Oscillating Water Column located on the Isle of Islay, Scotland, and designed by Wavegen. Constructed in a man-made gully on a rocky shoreline facing the open Atlantic ocean



LIMPET System

- Designed to supply power into the Islay grid. LIMPET has a generation capacity of 500 kW
- The system contains a pair of Wells turbines, each of which is connected to a 250 kW induction generator
- To overcome the problems of traditional turbines, LIMPET employs a Wells turbine that turns in the same direction irrespective of the airflow direction.
- LIMPET became operational in November 2000. Although the grid could accept 150 kW, LIMPET has only occasionally produced that high of an output since that time.
- Wavegen has determined that LIMPET's performance was lower than expected because of issues specific to that project rather than fundamental issues of the design of the device or technology.

- Wavegen has concluded that in spite of its low performance, LIMPET is a success:
  - Provided valuable experience in construction and operation to be used to develop future projects
  - Demonstrated the ability of the structure to withstand hostile conditions on an exposed cliff edge
  - Community approved of its low profile as less intrusive
  - The generated electricity is being used to power an electric bus



Energetech's Australia Wave Energy

Pictured here the Australia Wave Energy System, an Oscillating Water Column located off the coast of Port Kembla, New South Wales, Australia and designed by Energetech

Energetech's Australia Wave Energy System

- Located 200 meters from the Port Kembla Harbour Breakwater. Typically waves at Port Kembla exceed 1m in height 63% of the time (producing greater than 110kW on those occasions) and exceed 2m in height 5.5% of the time (producing greater than 400 kW on those occasions).
- Designed to generate 500 kW, enough to power 500 homes. The system uses a variable pitch turbine called a Denniss-Auld turbine, potentially with a higher conversion efficiency than the Wells turbine. The turbine drives an induction generator
- System components are computer controlled
- The plant also includes a small desalination unit that can produce nearly 2000 liters of fresh drinkable water per day using nothing but the seawater and wave energy.

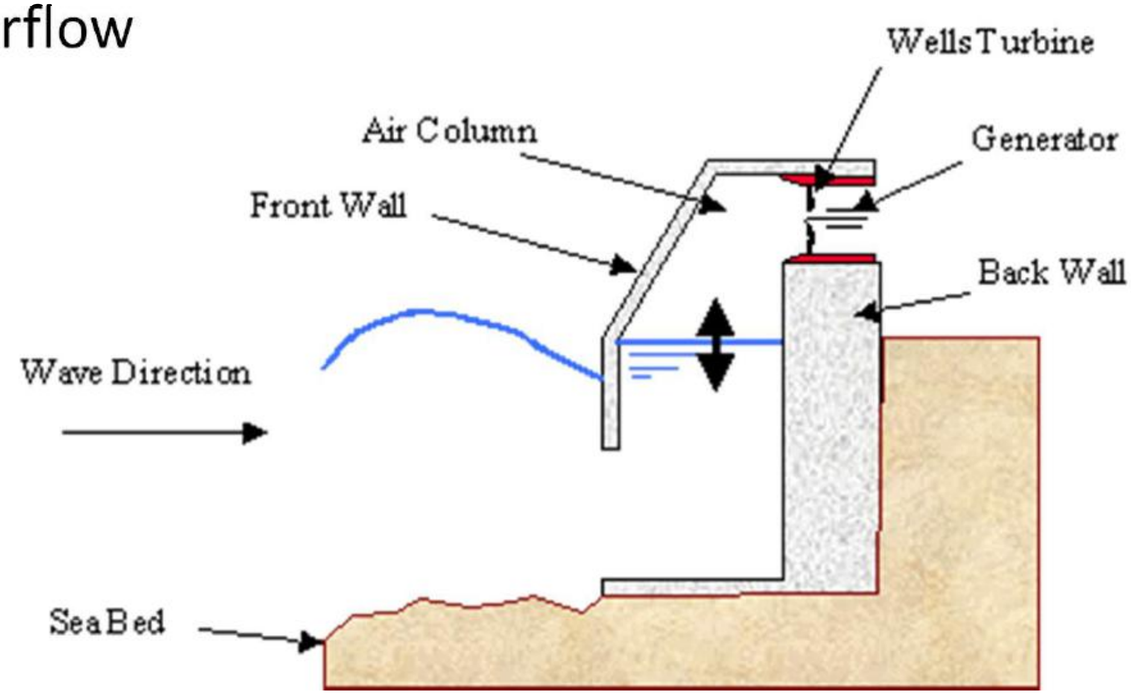
Conclusion: Critical Comments on Wave Energy Technology

- There is a large supply of wave energy available
- The technology already exists for extraction of this energy
- The technical challenges are solvable
- The problems lie in facilitating the testing and development of the technology to make it more affordable
  - Need federal funding
  - Need a regulatory process conducive for rapid deployment of prototypes and research equipment

LIMPET Construction

LIMPET

To overcome the problems of traditional turbines, LIMPET employs a Wells turbine that turns in the same direction irrespective of the airflow direction.



LIMPET

- The collector is tilted such that the resonance of the internal water column coincides with the peak energy period of the waves, easing passage of water into the water column
- The collector was divided into 3 chambers, with large holes at the top of each dividing wall to allow the air above the 3 water columns to combine to feed the turbine-generation system
- This design optimized performance for annual average wave intensities of 15 – 25 kW/m

On-shore versus Off-shore

In spite of the success of this technology in an on-shore application, most wave energy experts agree that off-shore or near-shore devices offer greater potential than shoreline devices.

On-shore technologies

Advantages	Disadvantages
• Easier to access for construction and maintenance • Less installment costs and grid connection charges • Could be incorporated into harbor walls or water breaks, performing a dual service for the community	• Limited number of suitable sites / high competition for use of the shoreline • Environmental concerns for on-shore devices may be greater • Much less energy available to on-shore devices because water depth usually decreases closer to the shore

Energetech’s Australia Wave Energy System

Energetech's Australia Wave Energy System

- System components are computer controlled
  - The computer uses a sensor system with a pressure transducer to measure the pressure exerted on the ocean floor by each wave as it approaches the collector
  - The transducer sends a signal proportional to that pressure to a Programmable Logic Controller which adjusts various parameters
    - Optimizes conversion for the particular conditions and energy content of the wave
    - Protects system components and ensures safety

Energetech's Australia Wave Energy System

- The device employs a parabolic wall to focus the wave energy into the collector
  - The ends of the wave plane are reflected by the parabolic wall and converge on the focus of the parabola
  - At the focus, the water will rise and fall with an amplitude of approximately 3 times that of the incoming waves
  - The center of the collector sits at the focus of the parabolic wall

Energetech's Australia Wave Energy System

- The plant also includes a small desalination unit that can produce nearly 2000 liters of fresh drinkable water per day using nothing but the seawater and wave energy.

Energetech's Australia Wave Energy System

- The project became operational in December 2006.
- A local power utility is purchasing the electricity generated and selling it to residents in the local community.

Obstacles to Development

These developments and applications of the OWC technology in the on-shore and near-shore environments demonstrate that there isn’t a lack of conceptual ideas or design solutions to engineering obstacles.

Are there any obstacles to wave energy technologies from becoming more commercially available?

Obstacles to Development

The greatest challenge is generating electricity from wave energy at a cost that is acceptable to the market.

Currently, costs are high

- Lack of federal funding
  - The Energy Policy Act of 2005 authorizes the Department of Energy to conduct research, development, demonstration, and commercial application programs for ocean and wave energy technologies
  - Yet the President's budgets have never appropriated any funds for these activities, including 2008's budget

Obstacles to Development

- Typically, technologies are being developed by small companies with limited capital, increasing the chance of failure with early prototypes. These failures may lead potential investors to lose confidence in the technologies.
- Being relatively new technologies, they are unfamiliar to licensing and resource agencies and costly to permit.

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Electric Charge

Electric Charge

- The atom
- Electricity in life
- Insulators & conductors
- Metals conduction
- Spherical conductors
- Electric forces between charges

The Atom

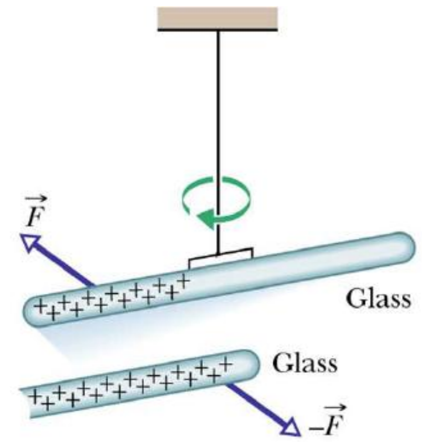
- We now know that all atoms are made of positive charges in the nucleus, surrounded by a cloud of tiny electrons.
- Atoms are normally neutral, meaning that they have exactly the same number of protons as they do electrons.
- The charges balance, and the atom has no net charge.
- In fact, protons are VASTLY more difficult to remove, and for all practical purposes it NEVER happens except in radioactive materials. In this course, we will ignore this case. Only electrons can be removed.
- If we cannot remove a proton, how do we ever make something charged negatively? By adding an “extra” electron.
- Proton charge +e, electron charge -e, where $e = 1.602\times10^{-19}$ C

Electricity in Life

- Most dramatic natural electrical phenomenon is lightning.
- Static electricity (balloons, comb & paper, shock from a door knob)
- Uses—photocopying, ink-jet printing
- Demonstrations of Electrostatics: glass rod/silk, plastic rod/fur, electroscope, van de Graaf Generator

Glass Rod/Plastic Rod

- A glass rod rubbed with silk gets a positive charge, and a plastic rod rubbed with fur gets a negative charge. The ability to gain or lose electrons through rubbing is called Triboelectricity.
- Suspend a charged glass rod from a thread, and another charged glass rod repels it. A charged plastic rod, however, attracts it. This mysterious force is called the electric force.
- Many similar experiments of all kinds led Benjamin Franklin (around 1750) to the conclusion that there are two types of charge, which he called *positive* and *negative*.
- He also discovered that charge was not created by rubbing, but rather the charge is transferred from the rubbing material to the rubbed object, or vice versa.



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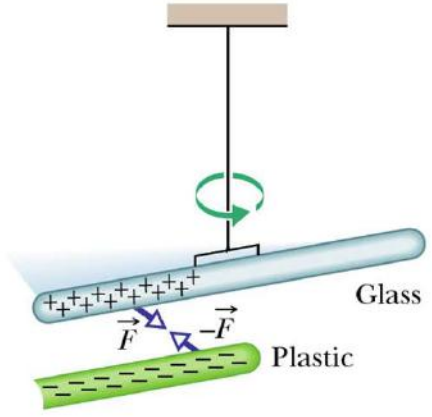
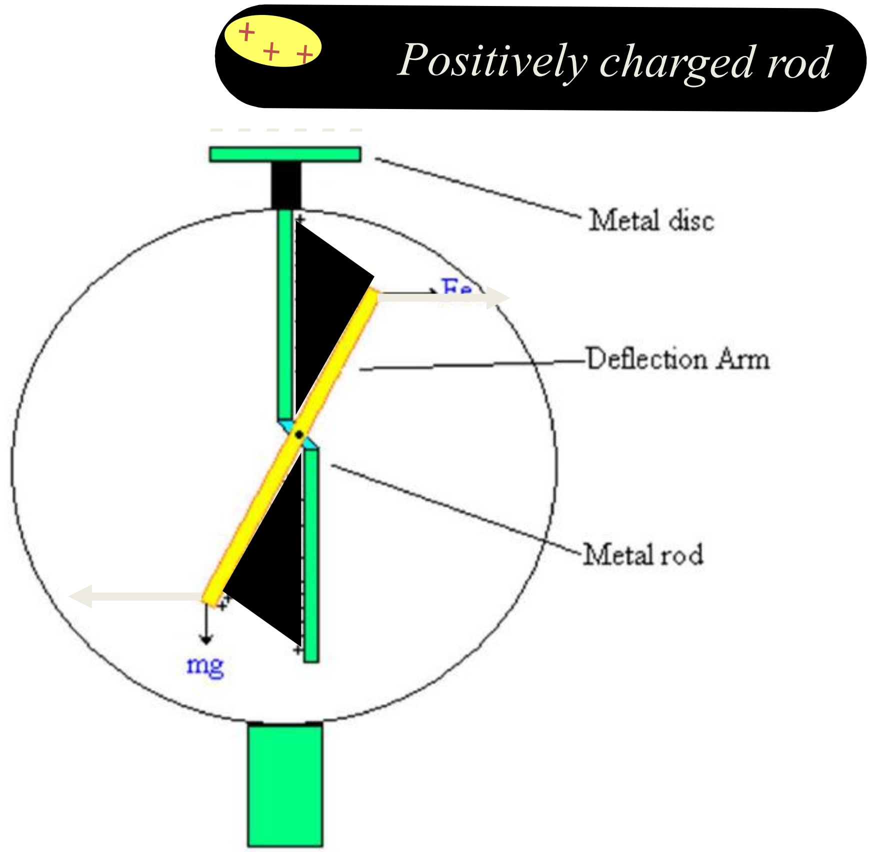


(*b*)

Electroscope

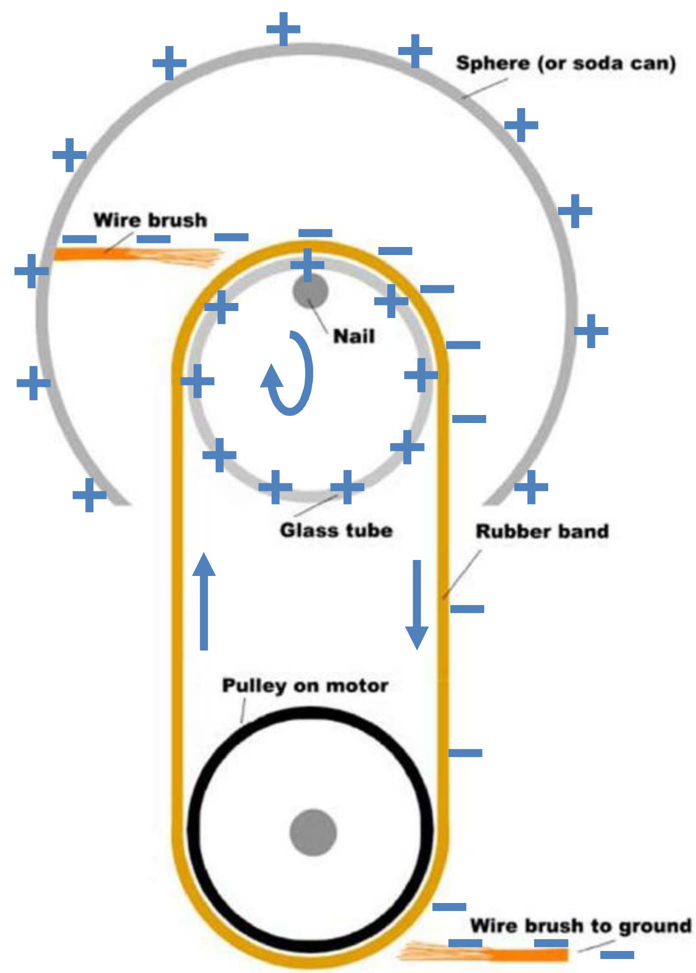
- This is a device that can visually show whether it is charged with static electricity.
- Here is an example charged positive.
- Notice that the charges collect near the ends, and since like charges repel, they exert a force sideways.
- You can make the deflection arm move by adding either positive or negative charge.
- But, we seem to be able to make it move without touching it.
- What is happening?



Electrostatic Induction

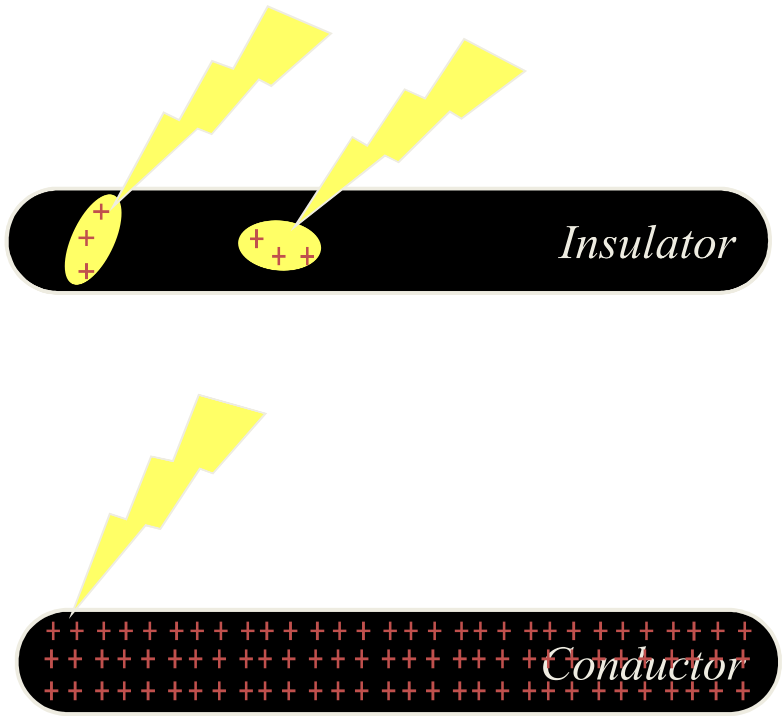
Van de Graaf Generator

- Rubber band steals electrons from glass
- Glass becomes positively charged
- Rubber band carries electrons downward
- Positively charged glass continues to rotate
- Wire “brush” steals electrons from rubber band
- Positively charged glass steals electrons from upper brush
- Sphere (or soda can) becomes positively charged—to 20,000 volts!



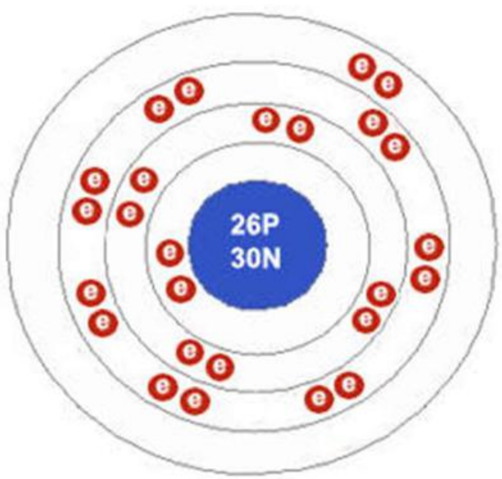
Insulators and Conductors

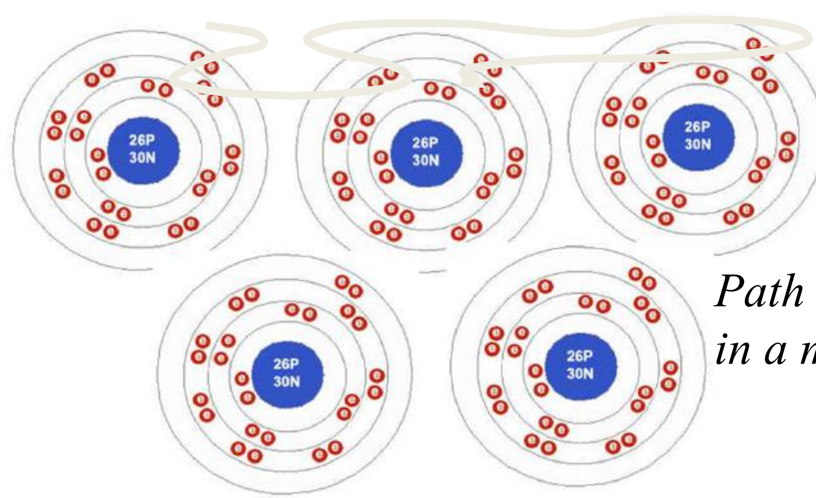
- Both insulators and conductors can be charged.
- The difference is that
  - On an insulator charges are not able to move from place to place. If you charge an insulator, you are typically depositing (or removing) charges only from the surface, and they will stay where you put them.
  - On a conductor, charges can freely move. If you try to place charge on a conductor, it will quickly spread over the entire conductor.



Metals and Conduction

- Notice that metals are not only good electrical conductors, but they are also good heat conductors, tend to be shiny (if polished), and are malleable (can be bent or shaped).
- These are all properties that come from the ability of electrons to move easily.
- This iron atom (26 protons, 26 electrons) has two electrons in its outer shell, which can move from one iron atom to the next in a metal.

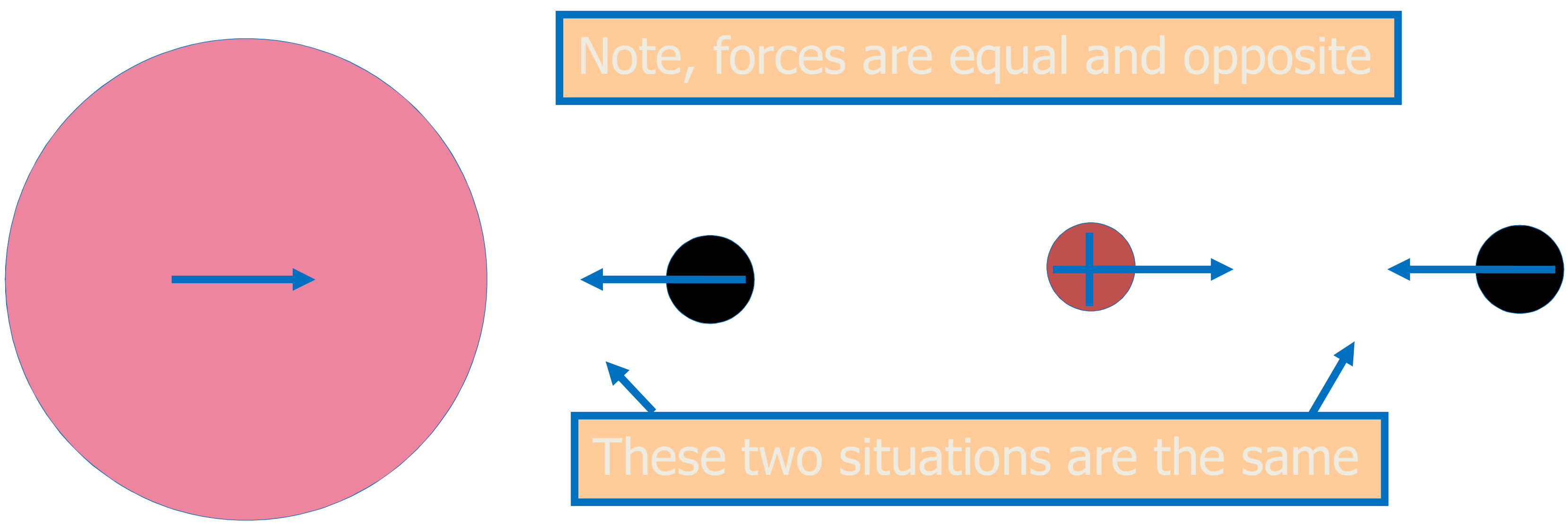




Path of electron in a metal

Spherical Conductors

- Because it is conducting, charge on a metal sphere will go everywhere over the surface.
- You can easily see why, because each of the charges pushes on the others so that they all move apart as far as they can go. Because of the symmetry of the situation, they spread themselves out uniformly.
- There is a theorem that applies to this case, called the shell theorem, that states that the sphere will act as if all of the charge were concentrated at the center.

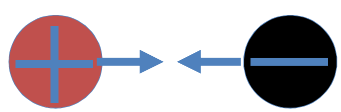


Forces Between Charges

- We observe that

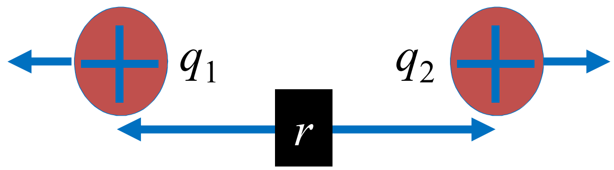
Like charges repel each other

Opposite charges attract each other

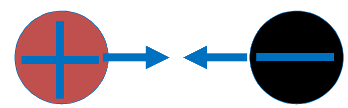


Electric Force and Coulomb's Law

- We can measure the force of attraction or repulsion between charges, call them q_1 and q_2 (we will use the symbol q or Q for charge).



- When we do that, we find that the force is proportional to the each of the charges, is inversely proportional to the distance between them, and is directed along the line between them (along r).



- In symbols, the magnitude of the force is $F = k\dfrac{|q_1||q_2|}{r^2}$ where k is some constant of proportionality.
- This force law was first studied by Coulomb in 1785, and is called Coulomb's Law. The constant $k = 8.98755 \times 10^9$ N m^2/C^2 is the Coulomb constant.

Let's Calculate the Exact Location

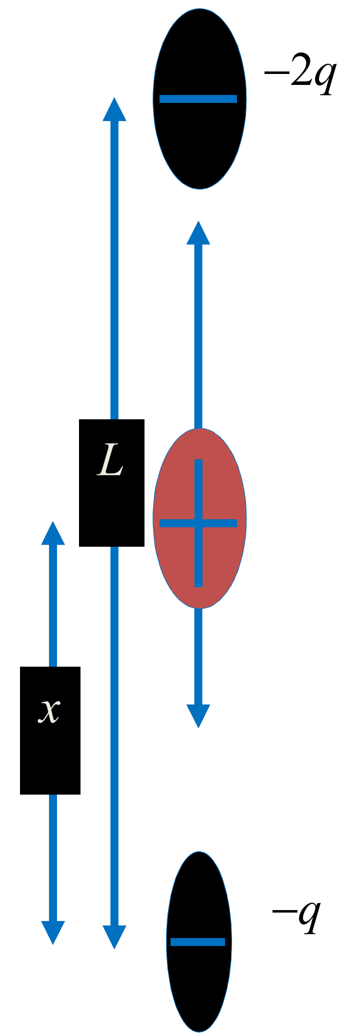
- Force is attractive toward both negative charges, hence could balance.
- Need a coordinate system, so choose total distance as *L*, and position of + charge from -*q* charge as *x*.
- Force is sum of the two force vectors, and has to be zero, so

$$F = F_1 + F_2 = k\frac{2qQ}{(L-x)^2} - k\frac{qQ}{x^2} = 0$$

- A lot of things cancel, including *Q*, so our answer does not depend on knowing the + charge value. We end up with

$$\frac{2}{(L-x)^2} = \frac{1}{x^2} \qquad \frac{(L-x)^2}{x^2} = 2 \Rightarrow \frac{L-x}{x} = \sqrt{2}$$

- Solving for *x*, $x = \frac{L}{1+\sqrt{2}} = 0.412L$, so slightly less than half-way between.



Summary

- Charge is an intrinsic property of matter. Charge comes in two opposite senses, positive and negative.
- Mobil charges we will usually deal with are electrons, which can be removed from an atom to make positive charge, or added to an atom to make negative charge. A positively charged atom or molecule can also be mobile.
- There is a smallest unit of charge, e, which is e = 1.602×10^{-19} C. Charge can only come in units of e, so charge is *quantized*. The unit of charge is the Coulomb.
- Charge is *conserved*. Charge can be destroyed only in pairs (+e and –e can annihilate each other). Otherwise, it can only be moved from place to place. Like charges repel, opposite charges attract.
- The electric force is give by Coulomb's Law:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{|q_1||q_2|}{r^2}$$

- Materials can be either conductors or insulators. Conductors and insulators can both be charged by adding charge, but charge can also be *induced*.
- Spherical conductors act as if all of the charge on their surface were concentrated at their centers.

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

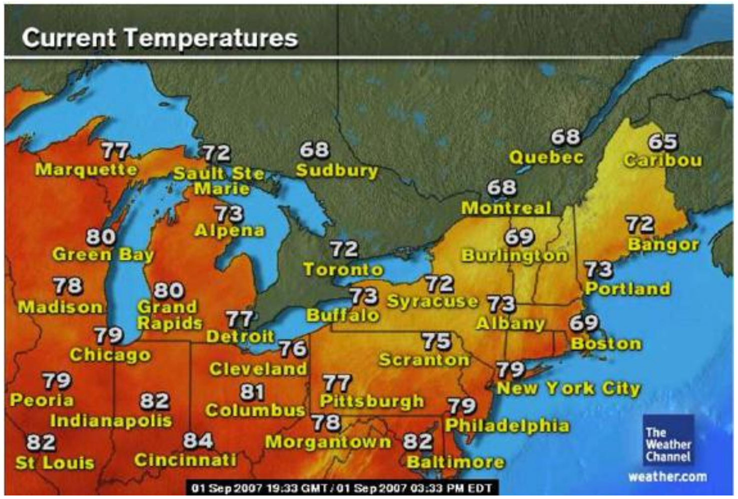
Electric Field

Electric Field

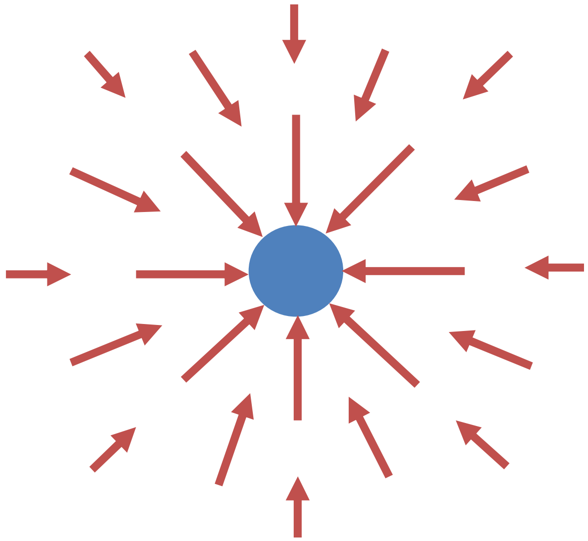
- Fields
- Electric field
- Electric field lines
- Electric field value
- Electric field due to
- Motion of a charged particle in a uniform electric field
- A dipole in an electric field

Fields

- Scalar Fields:
  - Temperature – T(r)
  - Pressure – P(r)
  - Potential energy – U(r)



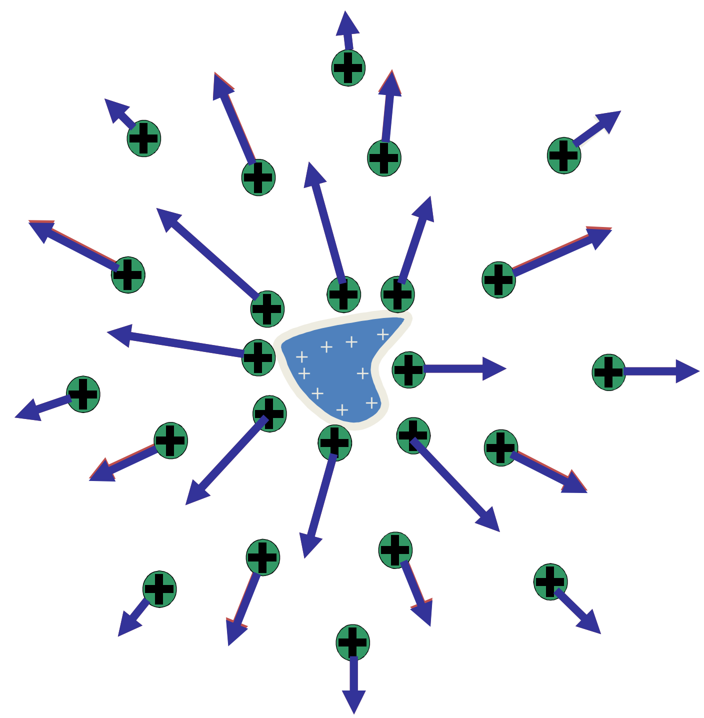
- Vector Fields:
  - Velocity field – $\vec{v}(\vec{r})$
  - Gravitational field – $\vec{g}(\vec{r})$
  - Electric field – $\vec{E}(\vec{r})$
  - Magnetic field – $\vec{B}(\vec{r})$



Electric Field

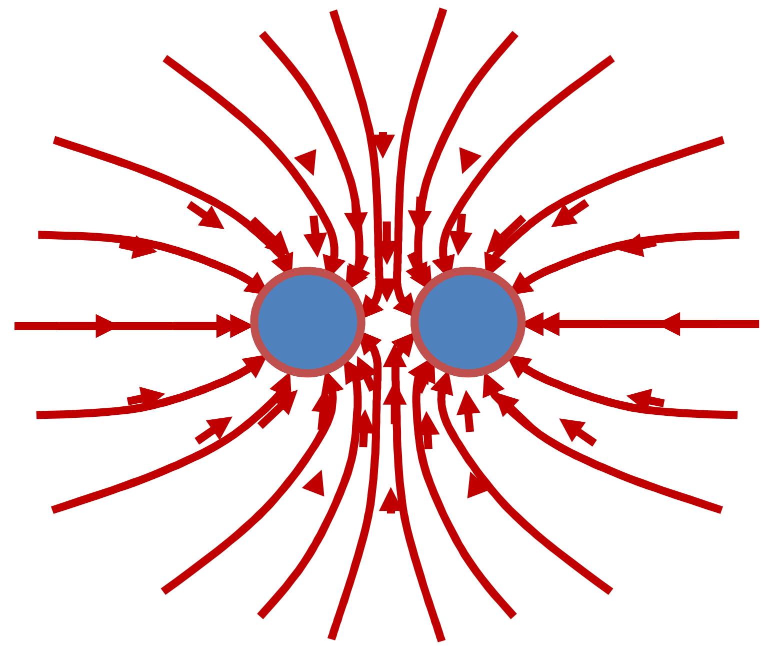
- Electric field is said to exist in the region of space around a charged object: the source charge.
- Concept of test charge:
  - Small and positive
  - Does not affect charge distribution
- Electric field:
  - Existence of an electric field is a property of its source;
  - Presence of test charge is not necessary for the field to exist;

$$\vec{E} = \frac{\vec{F}}{q_0}$$

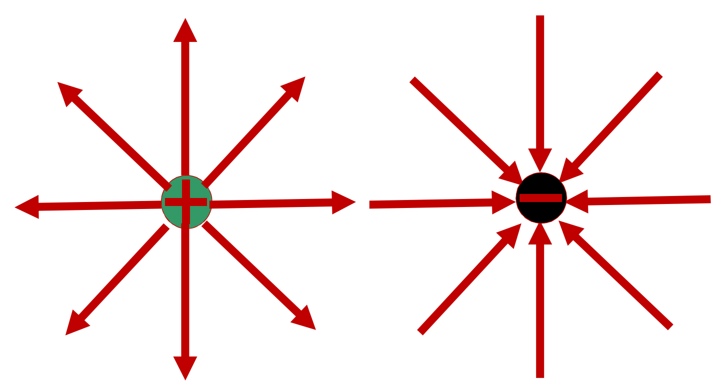


Electric Field Lines I

- The electric field vector is tangent to the electric field line at each point. The line has a direction, indicated by an arrowhead, that is the same as that of the electric field vector. The direction of the line is that of the force on a positive test charge placed in the field.

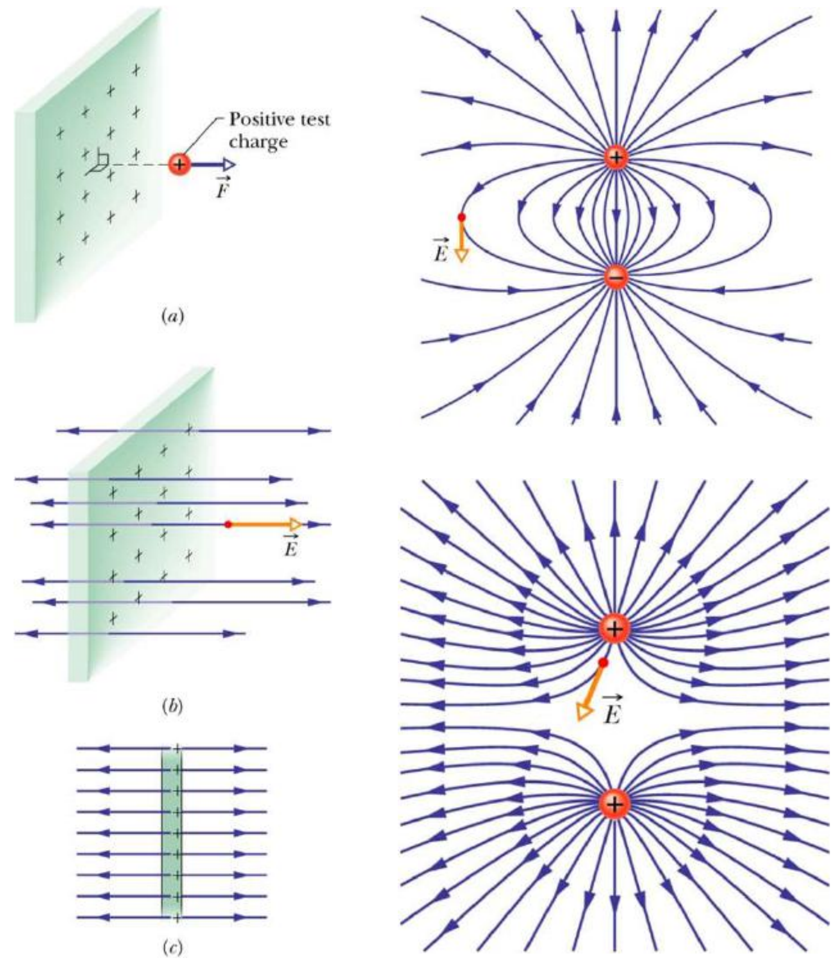


- The number of lines per unit area through a surface perpendicular to the lines is proportional to the magnitude of the electric field in that region. Thus, the field lines are close together where the electric field is strong and far apart where the field is weak.



Electric Field Lines II

- The lines must begin on a positive charge and terminate on a negative charge. In the case of an excess of one type of charge, some lines will begin or end infinitely far away.
- The number of lines drawn leaving a positive charge or approaching a negative charge is proportional to the magnitude of the charge.
- No two field lines can cross.



Electric Field Value

$$\vec{E} = \frac{\vec{F}}{q_0}$$

- Magnitude: $E=F/q_0$
- Direction: is that of the force that acts on the positive test charge
- SI unit: N/C

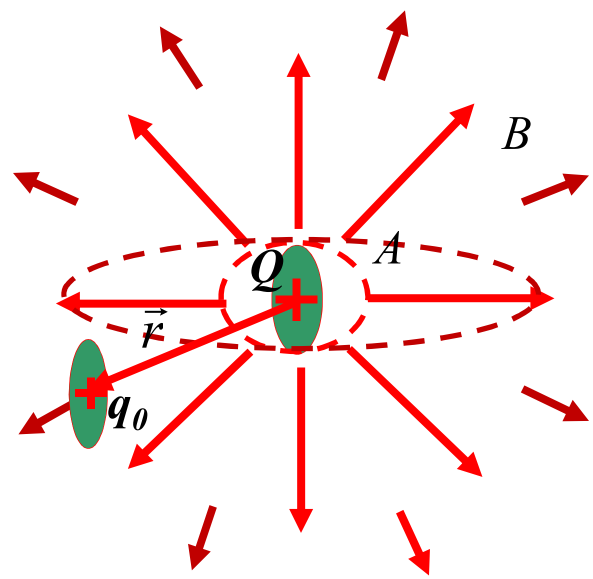
Situation	Value
Inside a copper wire of household circuits	10^{-2} N/C
Near a charged comb	10^{3} N/C
Inside a TV picture tube	10^{5} N/C
Near the charged drum of a photocopier	10^{5} N/C
Electric breakdown across an air gap	3×10^{6} N/C
At the electron's orbit in a hydrogen atom	5×10^{11} N/C
On the suface of a Uranium nucleus	3×10^{21} N/C

Electric Field due to a Point Charge Q

$$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{Qq_0}{r^2}\hat{r}$$

$$\vec{E} = \frac{\vec{F}}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}\hat{r}$$

- Direction is radial: outward for +|Q| inward for -|Q|
- Magnitude: constant on any spherical shell
- Flux through any shell enclosing Q is the same: $E_A A_A = E_B A_B$

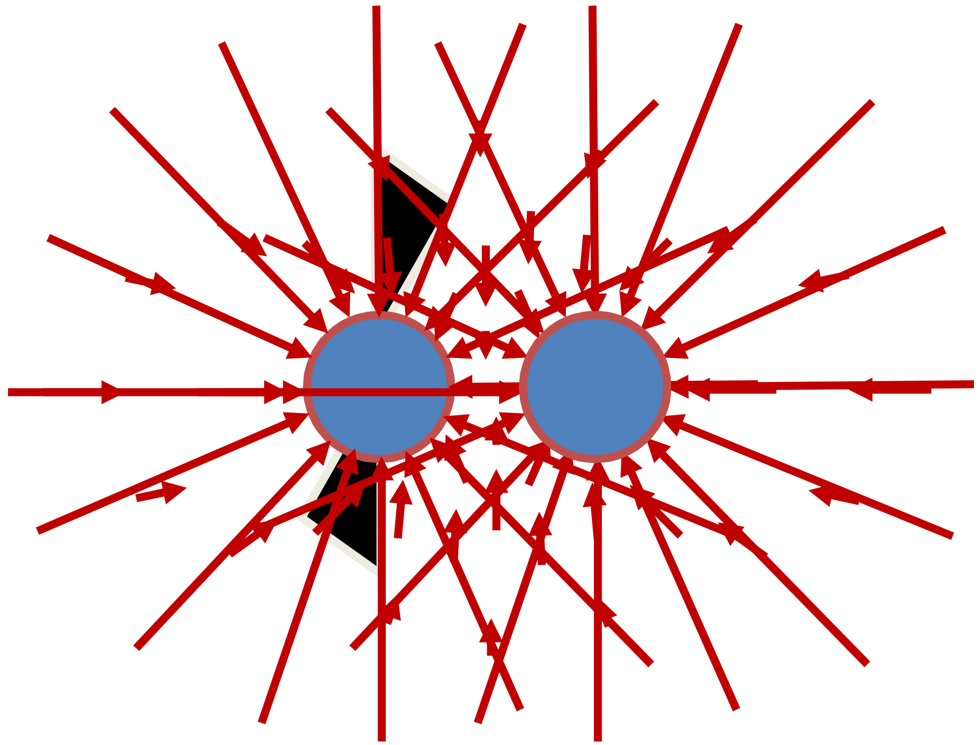


Electric Field Due To A Group of Individual Charge

$$\vec{F}_0 = \vec{F}_{01} + \vec{F}_{02} + \ldots + \vec{F}_{0n}$$

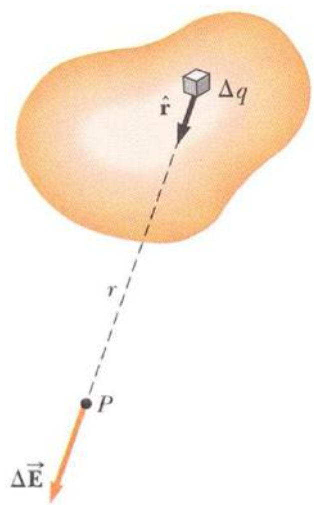
$$\vec{E} = \frac{\vec{F}_0}{q_0} = \frac{\vec{F}_{01}}{q_0} + \frac{\vec{F}_{02}}{q_0} + \ldots + \frac{\vec{F}_{0n}}{q_0}$$
$$= \vec{E}_1 + \vec{E}_2 + \ldots + \vec{E}_n$$

$$\vec{E} = \frac{1}{4\pi\varepsilon_0} \sum_i \frac{q_i}{r_i^{\,2}} \hat{r}_i$$



Electric Field of a Continuous Charge Distribution

$$\Delta\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{\Delta q}{r^2}\hat{r}$$



$$\vec{E} \approx \frac{1}{4\pi\varepsilon_0}\sum_i \frac{\Delta q_i}{r_i^2}\hat{r}_i$$

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\lim_{\Delta q\to 0}\sum_i \frac{\Delta q_i}{r_i^2}\hat{r}_i = \frac{1}{4\pi\varepsilon_0}\int\frac{dq}{r^2}\hat{r}$$

- Find an expression for dq:
  - dq = λdl for a line distribution
  - dq = σdA for a surface distribution
  - dq = ρdV for a volume distribution
- Represent field contributions at P due to point charges dq located in the distribution. Use symmetry
- Add up (integrate the contributions) over the whole distribution, varying the displacement as needed,

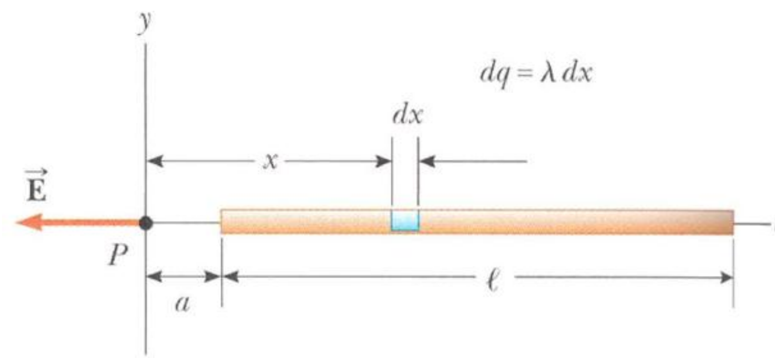
Example: Electric Field Due to a Charged Rod

A rod of length l has a uniform positive charge per unit length λ and a total charge Q. Calculate the electric field at a point P that is located along the long axis of the rod and a distance a from one end.

Start with

$$dq = \lambda dx$$

$$dE = \frac{1}{4\pi\varepsilon_0}\frac{dq}{x^2} = \frac{1}{4\pi\varepsilon_0}\frac{\lambda dx}{x^2}$$



then,

$$E = \int_a^{l+a} \frac{\lambda}{4\pi\varepsilon_0}\frac{dx}{x^2} = \frac{\lambda}{4\pi\varepsilon_0}\int_a^{l+a}\frac{dx}{x^2} = \frac{\lambda}{4\pi\varepsilon_0}\left[-\frac{1}{x}\right]_a^{l+a}$$

So

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{l}\left(\frac{1}{a} - \frac{1}{l+a}\right) = \frac{Q}{4\pi\varepsilon_0 a(l+a)}$$

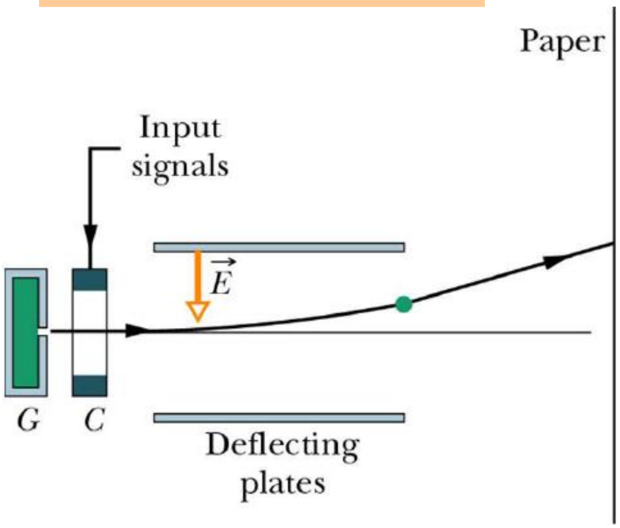
- Finalize
  - l => 0 ?
  - a >> l ?

Motion of a Charged Particle in a Uniform Electric Field

$$\vec{F} = q\vec{E}$$

$$\vec{F} = q\vec{E} = m\vec{a}$$

$$\vec{a} = \frac{q\vec{E}}{m}$$



- If the electric field E is uniform (magnitude and direction), the electric force F on the particle is constant.
- If the particle has a positive charge, its acceleration a and electric force F are in the direction of the electric field E.
- If the particle has a negative charge, its acceleration a and electric force F are in the direction opposite the electric field E.

A Dipole in An Electric Field I

Start with

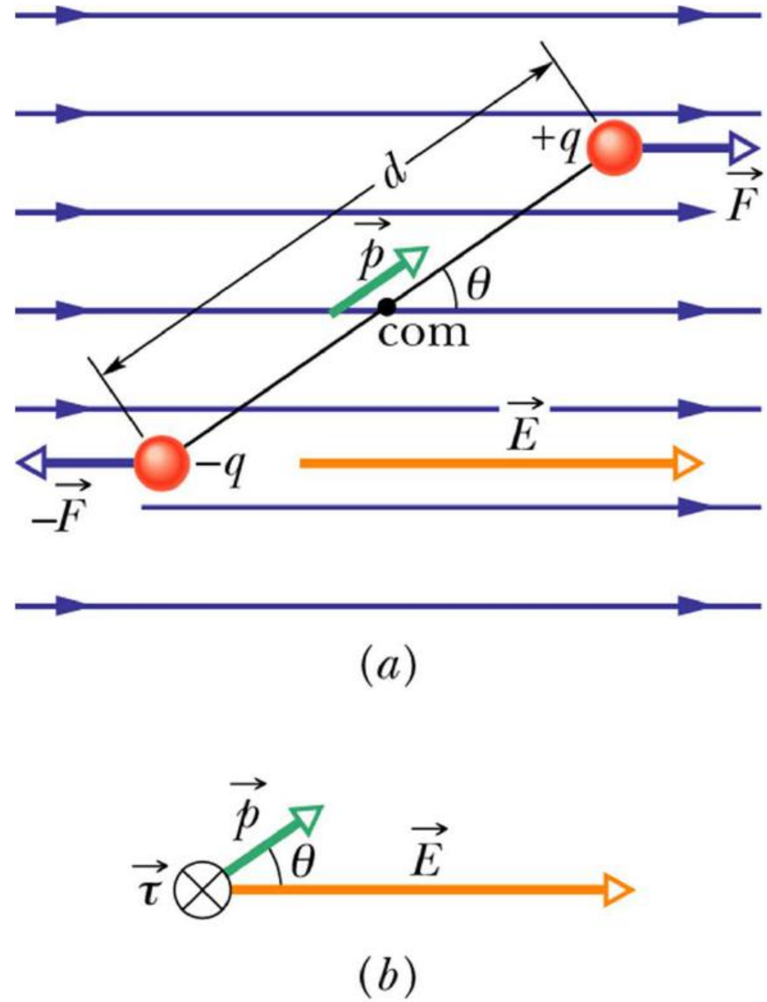
$$\tau = Fx\sin\theta + F(d-x)\sin\theta = Fd\sin\theta$$

Then $F = qE$ and $p = qd$

$$|\tau| = pE\sin\theta$$

So

$$\vec{\tau} = \vec{p}\times\vec{E}$$



A Dipole in An Electric Field II

Start with $$dW = \tau d\theta$$

Since

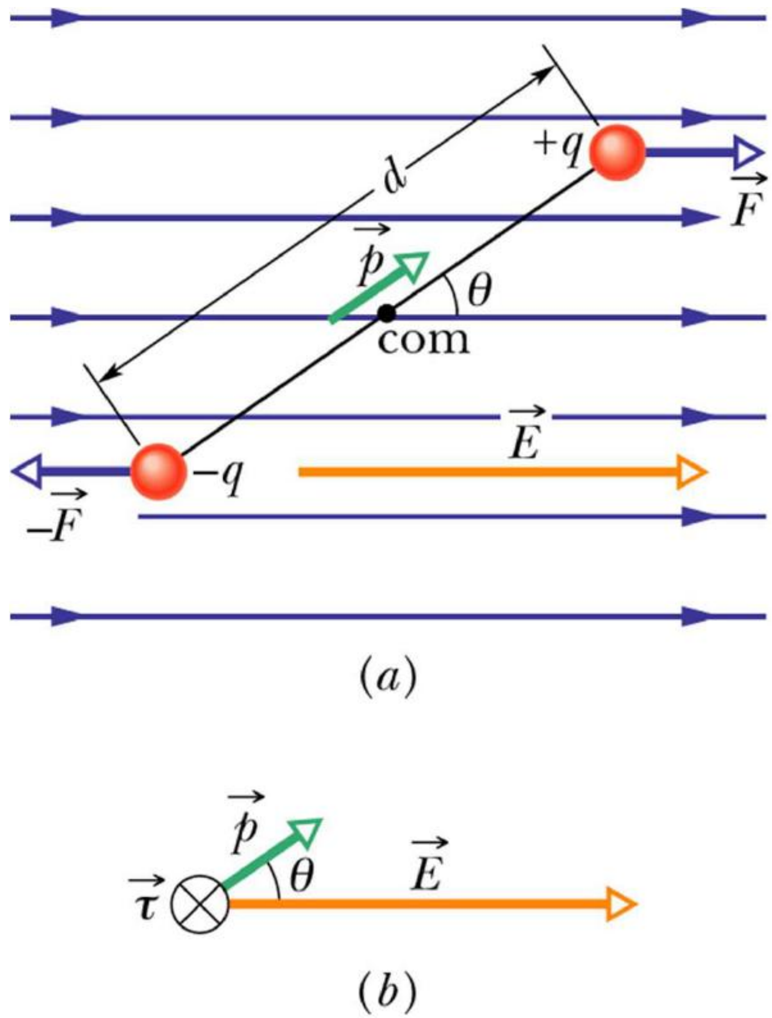
$$U_f - U_i = \int_{\theta_i}^{\theta_f} \tau d\theta = \int_{\theta_i}^{\theta_f} pE \sin\theta d\theta = pE \int_{\theta_i}^{\theta_f} \sin\theta d\theta$$

$$= pE[-\cos\theta]_{\theta_i}^{\theta_f} = pE(\cos\theta_i - \cos\theta_f)$$

Choose $U_i = 0 \quad \theta_i = 90°$

at $U = -pE\cos\theta$

So $$U = -\vec{p} \cdot \vec{E}$$



Summary

- Electric field E at any point is defined in terms of the electric force F that acts on a small positive test charge placed at that point divided by the magnitude q_0 of the test charge:
- Electric field lines provide a means for visualizing the direction and magnitude of electric fields. The electric field vector at any point is tangent to a field line through that point. The density of field lines in any region is proportional to the magnitude of the electric field in that region.
- Field lines originate on positive charge and terminate on negative charge.
- Field due to a point charge:

  The direction is away from the point charge if the charge is positive and toward it if the charge is negative.
- Field due to an electric dipole:
- Field due to a continuous charge distribution: treat charge elements as point charges and then summing via integration, the electric field vectors produced by all the charge elements.
- Force on a point charge in an electric field:
- Dipole in an electric field:
  - The field exerts a torque on the dipole
  - The dipole has a potential energy U associated with its orientation in the field

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Electric Potential

Electric Potential

- Electric potential energy
- Equipotential surface
- Potential due to point charge
- Potential due to a continuous charge distribution
- Potential due to a continuous charged rod
- Potential due to a continuous charged isolated conductor
- Calculating the field from the potential

Electric Potential Energy

- The potential energy of the system

$$\Delta U = U_f - U_i = -W$$

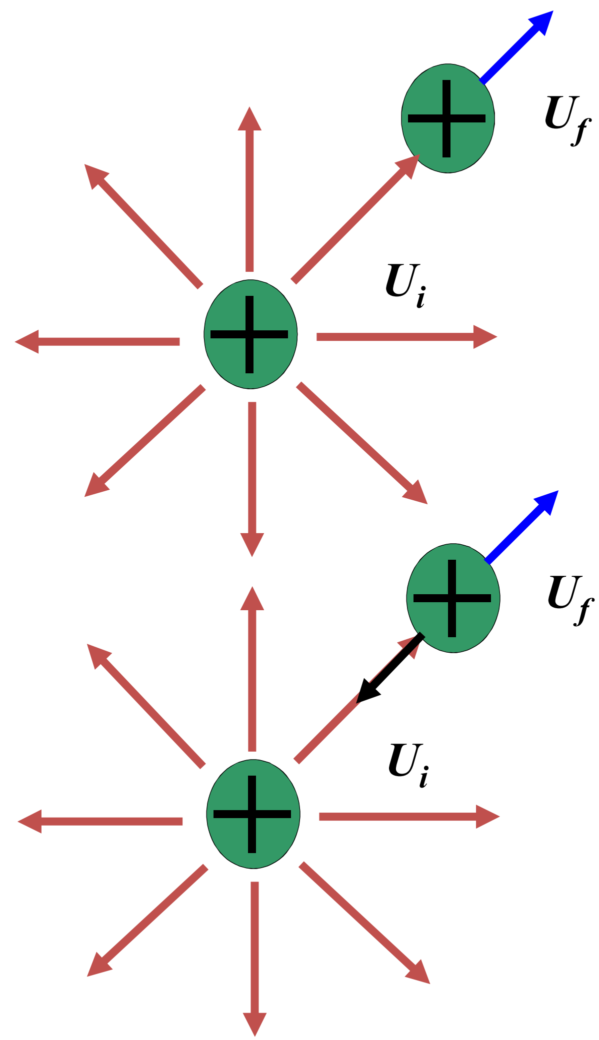
- The work done by the electrostatic force is path independent.
- Work done by a electric force or "field"

$$W = \vec{F} \cdot \Delta\vec{r} = q\vec{E} \cdot \Delta\vec{r}$$

- Work done by an Applied force

$$\Delta K = K_f - K_i = W_{app} + W$$

$$W_{app} = -W \qquad \Delta U = U_f - U_i = W_{app}$$



Electric Potential

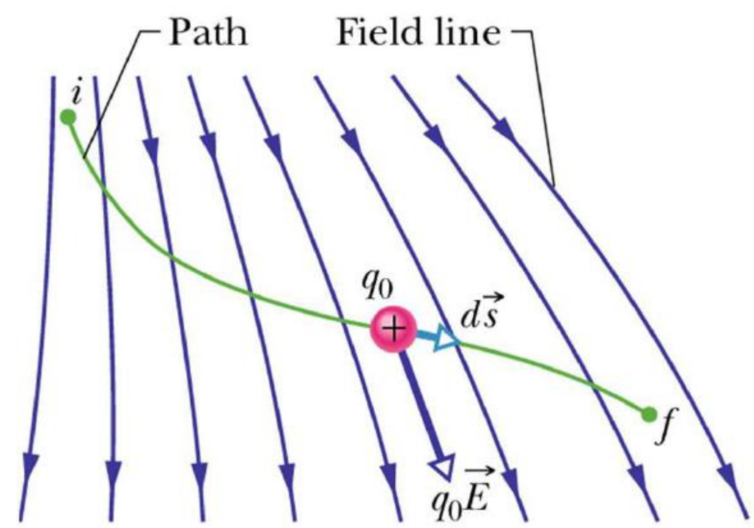
- The electric potential energy
  - Start $dW = \vec{F} \cdot d\vec{s}$
  - Then $dW = q_0 \vec{E} \cdot d\vec{s}$
  - So $W = q_0 \int_i^f \vec{E} \cdot d\vec{s}$

$$\Delta U = U_f - U_i = -W = -q_0 \int_i^f \vec{E} \cdot d\vec{s}$$

- The electric potential $V = \frac{U}{q}$

$$\Delta V = V_f - V_i = \frac{U_f}{q} - \frac{U_i}{q} = \frac{\Delta U}{q}$$

$$\Delta V \equiv \frac{\Delta U}{q_0} = -\int_i^f \vec{E} \cdot d\vec{s}$$



- Potential difference depends only on the source charge distribution (Consider points i and f without the presence of the test charge;

- The difference in potential energy exists only if a test charge is moved between the points.

Equipotential Surface

- The name equipotential surface is given to any surface consisting of a continuous distribution of points having the same electric potential.

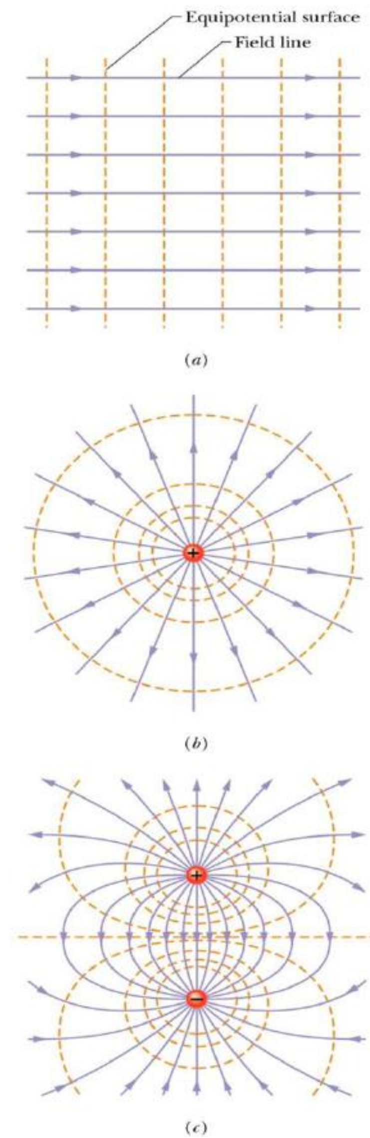
- Equipotential surfaces are always perpendicular to electric field lines.

- No work is done by the electric field on a charged particle while moving the particle along an equipotential surface.

Analogy to Gravity

- The equipotential surface is like the "height" lines on a topographic map.

- Following such a line means that you remain at the same height, neither going up nor going down—again, no work is done.



Potential Due to a Point Charge

Start with (set V_f=0 at ∞ and V_i=V at R)

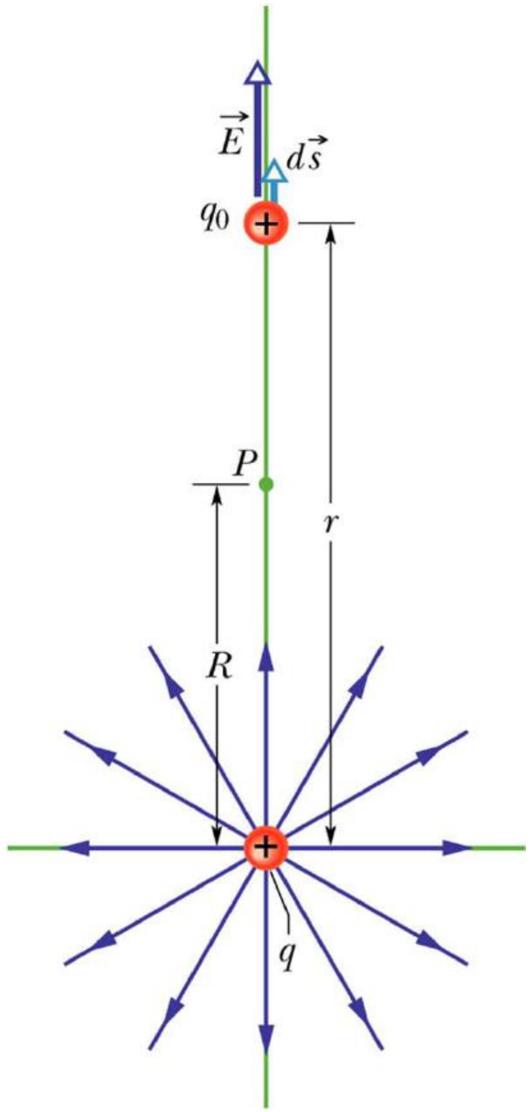
$$\Delta V = V_f - V_i = -\int_i^f \vec{E} \cdot d\vec{s} = -\int_i^f (E\cos 0°)ds = -\int_R^\infty E dr$$

We have $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$

Then $$0 - V = -\frac{q}{4\pi\varepsilon_0}\int_R^\infty \frac{1}{r^2}dr = \frac{q}{4\pi\varepsilon_0}\left[\frac{1}{r}\right]_R^\infty = -\frac{1}{4\pi\varepsilon_0}\frac{q}{R}$$

So $$V(r) = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

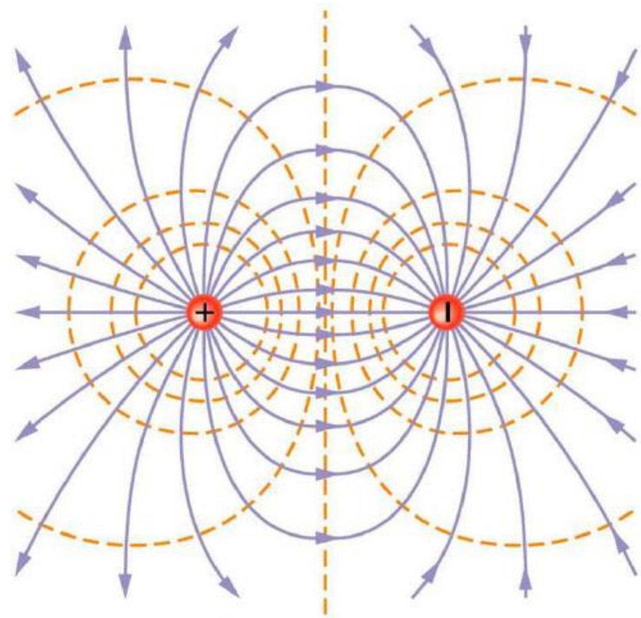
A positively charged particle produces a positive electric potential. A negatively charged particle produces a negative electric potential



Potential due to a group of point charges

Use superposition

$$V = -\int_{\infty}^{r} \vec{E} \cdot d\vec{s} = -\sum_{i=1}^{n} \int_{\infty}^{r} \vec{E}_i \cdot d\vec{s} = \sum_{i=1}^{n} V_i$$



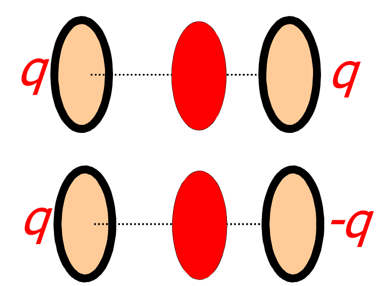
For point charges

$$V = \sum_{i=1}^{n} V_i = \frac{1}{4\pi\varepsilon_0} \sum_{i=1}^{n} \frac{q_i}{r_i}$$

The sum is an algebraic sum, not a vector sum.

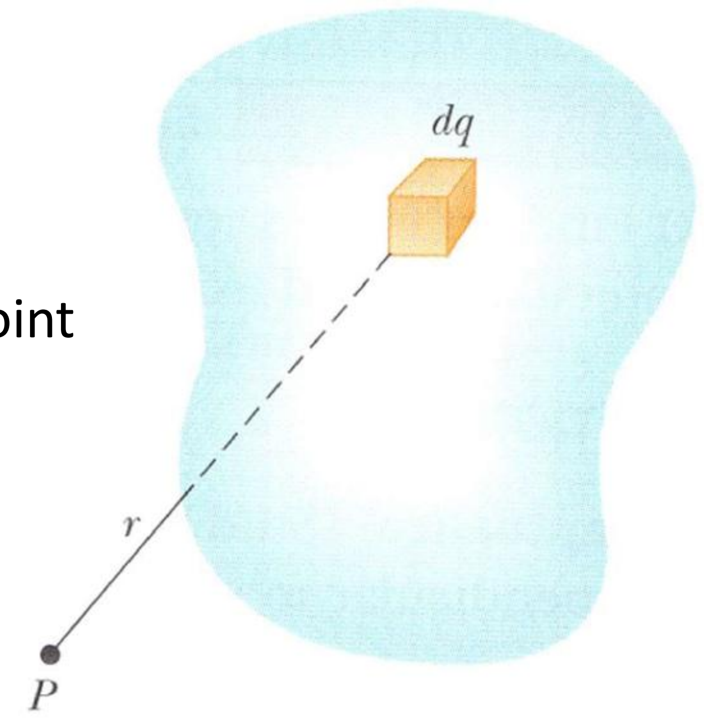
E may be zero where V does not equal to zero.

V may be zero where E does not equal to zero.



Potential due to a Continuous Charge Distribution

- Expression for dq:
  - $dq = \lambda dl$ for a line distribution
  - $dq = \sigma dA$ for a surface distribution
  - $dq = \rho dV$ for a volume distribution



- Represent field contributions at P due to point charges dq located in the distribution.

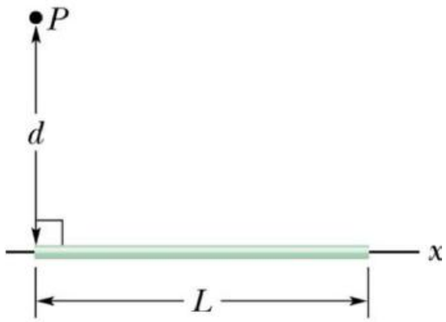
$$dV = \frac{1}{4\pi\varepsilon_0}\frac{dq}{r}$$

- Integrate the contributions over the whole distribution, varying the displacement as needed,

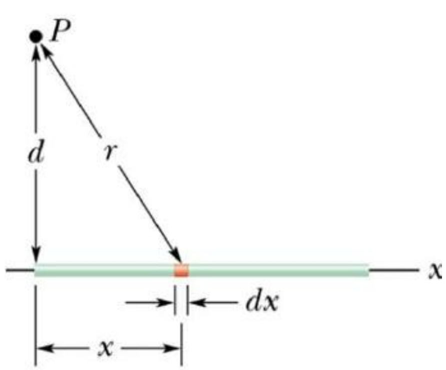
$$V = \int dV = \frac{1}{4\pi\varepsilon_0}\int\frac{dq}{r}$$

Example: Potential Due to a Charged Rod

- A rod of length L located along the x axis has a uniform linear charge density λ. Find the electric potential at a point P located on the y axis a distance d from the origin.



(a)



(b)

- Start with

$$dq = \lambda dx$$

$$dV = \frac{1}{4\pi\varepsilon_0}\frac{dq}{r} = \frac{1}{4\pi\varepsilon_0}\frac{\lambda dx}{(x^2+d^2)^{1/2}}$$

- then,

$$V = \int dV = \int_0^L \frac{\lambda}{4\pi\varepsilon_0}\frac{dx}{(x^2+d^2)^{1/2}} = \frac{\lambda}{4\pi\varepsilon_0}\left[\ln\left(x+(x^2+d^2)^{1/2}\right)\right]_0^L$$

$$= \frac{\lambda}{4\pi\varepsilon_0}\left[\ln\left(L+(L^2+d^2)^{1/2}\right) - \ln d\right]$$

- So

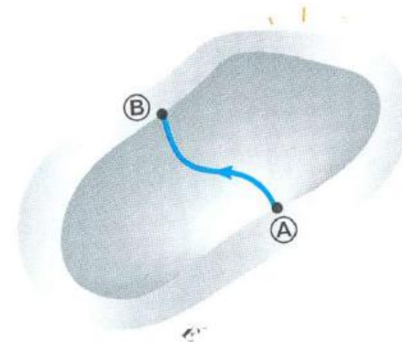
$$V = \frac{\lambda}{4\pi\varepsilon_0}\ln\left[\frac{L+(L^2+d^2)^{1/2}}{d}\right]$$

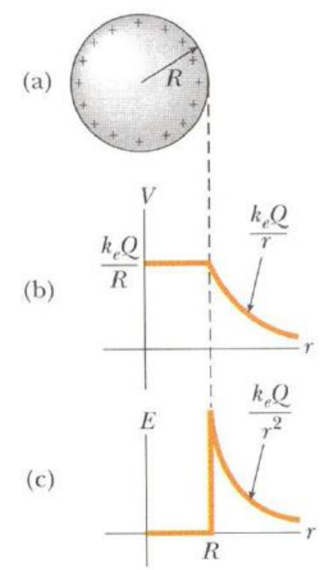
Potential Due to a Charged Isolated Conductor

- According to Gauss' law, the charge resides on the conductor's outer surface.
- Furthermore, the electric field just outside the conductor is perpendicular to the surface and field inside is zero.
- Since

$$V_B - V_A = -\int_A^B \vec{E} \cdot d\vec{s} = 0$$

- Every point on the surface of a charged conductor in equilibrium is at the same electric potential.
- Furthermore, the electric potential is constant everywhere inside the conductor and equal to its value to its value at the surface.





Calculating the Field from the Potential

- Suppose that a positive test charge q_0 moves through a displacement ds from on equipotential surface to the adjacent surface.
- The work done by the electric field on the test charge is W = -dU = -q_0 dV.
- The work done by the electric field may also be written as $W = q_0 \vec{E} \cdot d\vec{s}$
- Then, we have $-q_0 dV = q_0 E(\cos\theta) ds$ $\quad E\cos\theta = -\frac{dV}{ds}$
- So, the component of E in any direction is the negative of the rate at which the electric potential changes with distance in that direction. $E_s = -\frac{\partial V}{\partial s}$
- If we know V(x, y, z), $E_x = -\frac{\partial V}{\partial x}$ $\quad E_y = -\frac{\partial V}{\partial y}$ $\quad E_z = -\frac{\partial V}{\partial z}$

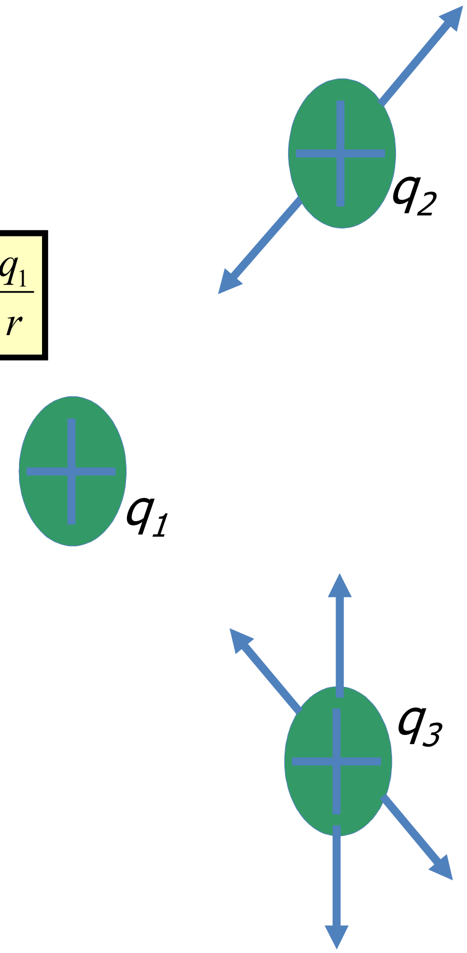
Electric Potential Energy of a System of Point Charges

$$\Delta U = U_f - U_i = -W$$

$$W = \vec{F} \cdot \Delta\vec{r} = q\vec{E} \cdot \Delta\vec{r}$$

$$W_{app} = -W$$

$$\Delta U = U_f - U_i = W_{app}$$



- Start with (set U_i=0 at ∞ and U_f=U at r)

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{r}$$

- We have

$$U = q_2 V = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r}$$

- If the system consists of more than two charged particles, calculate U for each pair of charges and sum the terms algebraically.

$$U = U_{12} + U_{13} + U_{23} = \frac{1}{4\pi\varepsilon_0}\left(\frac{q_1 q_2}{r_{12}} + \frac{q_1 q_3}{r_{13}} + \frac{q_2 q_3}{r_{23}}\right)$$

Summary

- Electric Potential Energy: a point charge moves from *i* to *f* in an electric field, the change in electric potential energy is $\Delta U = U_f - U_i = -W$
- Electric Potential Difference between two points *i* and *f* in an electric field: $\Delta V = V_f - V_i = \frac{U_f}{q} - \frac{U_i}{q} = \frac{\Delta U}{q}$
- Equipotential surface: the points on it all have the same electric potential. No work is done while moving charge on it. The electric field is always directed perpendicularly to corresponding equipotential surfaces.
- Finding V from E: $\Delta V \equiv \frac{\Delta U}{q_0} = -\int_i^f \vec{E} \cdot d\vec{s}$
- Potential due to point charges: $V(r) = \frac{1}{4\pi\varepsilon_0} \frac{q}{r}$
- Potential due to a collection of point charges: $V = \sum_{i=1}^{n} V_i = \frac{1}{4\pi\varepsilon_0} \sum_{i=1}^{n} \frac{q_i}{r_i}$
- Potential due to a continuous charge distribution: $V = \int dV = \frac{1}{4\pi\varepsilon_0} \int \frac{dq}{r}$
- Potential of a charged conductor is constant everywhere inside the conductor and equal to its value to its value at the surface.
- Calculatiing E from V: $E_s = -\frac{\partial V}{\partial s}$ $E_x = -\frac{\partial V}{\partial x}$ $E_y = -\frac{\partial V}{\partial y}$ $E_z = -\frac{\partial V}{\partial z}$
- Electric potential energy of system of point charges: $U = q_2 V = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r}$

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Magnetic Field

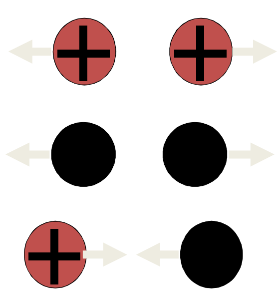
Magnetic Field

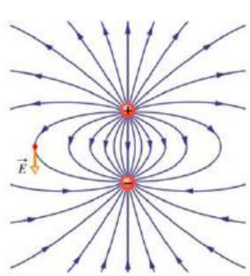
- Preface
- Magnetic force
- Magnetic field
- Force between two parallel current
- Ampere’s law
- Selenoids
- Toroid

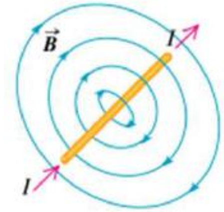
Preface: Electric Field & Magnetic Field

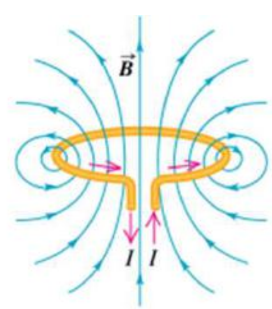
- Electric forces acting at a distance through electric field.
- Vector field, **E**.
- Source: electric charge.
- Positive charge (+) and negative charge (-).
- Opposite charges attract, like charges repel.
- Electric field lines visualizing the direction and magnitude of **E**.

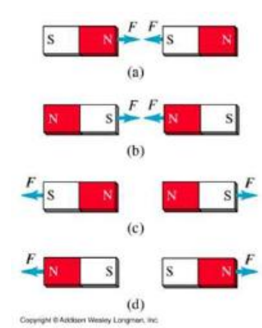
- Magnetic forces acting at a distance through Magnetic field.
- Vector field, **B**
- Source: **moving** electric charge (current or magnetic substance, such as permanent magnet).
- North pole (N) and south pole (S)
- Opposite poles attract, like poles repel.
- Magnetic field lines visualizing the direction and magnitude of **B**.

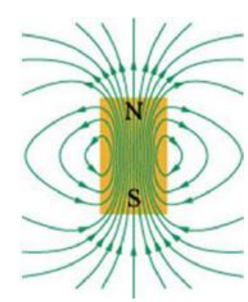












Definition of $\vec{B}$

- Test charge and electric field

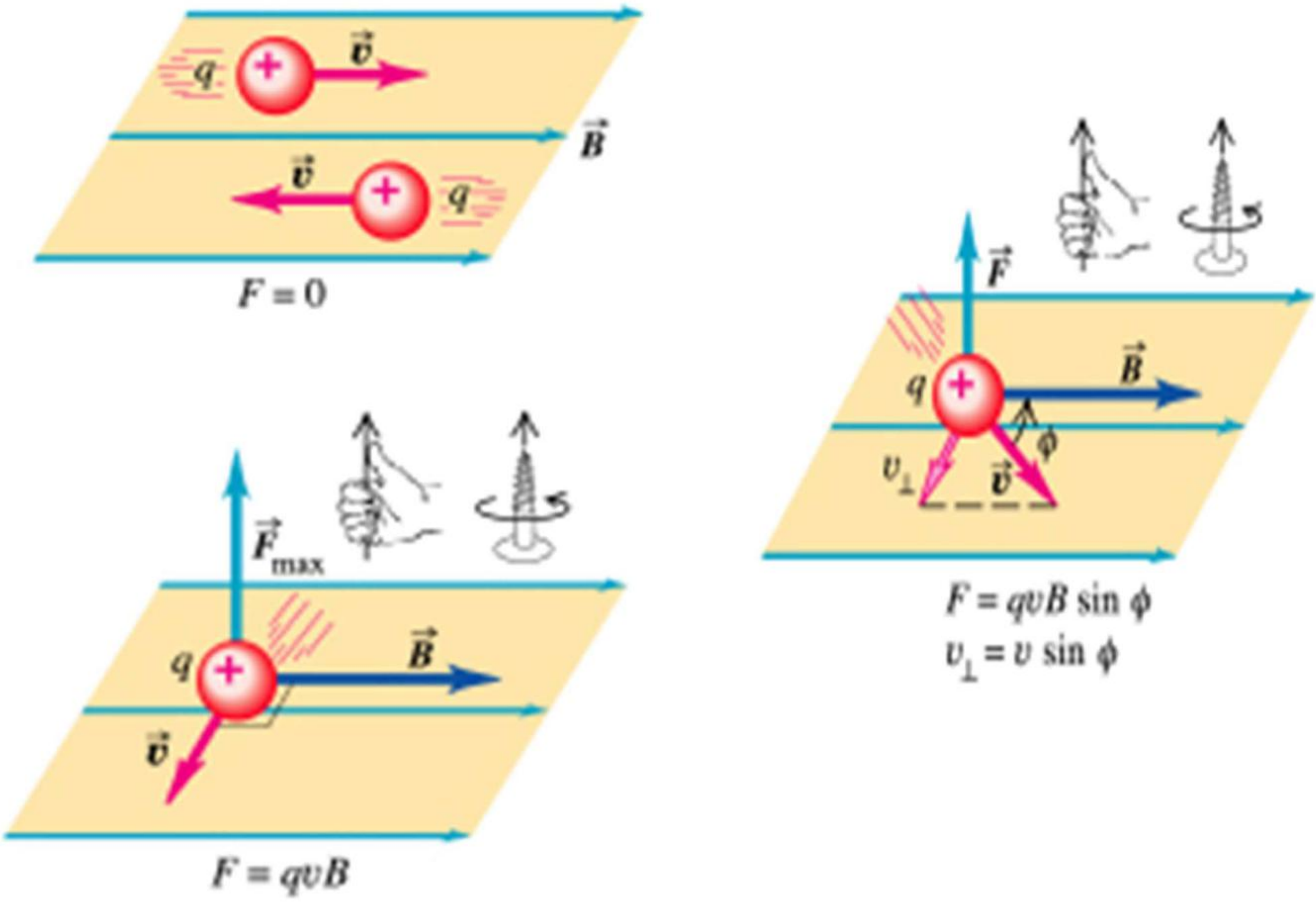
$$\vec{E} = \frac{\vec{F}_E}{q}$$

- Test monopole and magnetic field ?

~~$$\vec{B} = \frac{\vec{F}_B}{p}$$~~

Magnetic poles are always found in pairs. A single magnetic pole has never been isolated.

Define ***B*** at some point in space in terms of the magnetic force $\boldsymbol{F_B}$ that the field exerts on a ***charged*** particle ***moving*** with a velocity ***v***: The magnitude F_B is proportional to the charge q and to the speed v of the particle. $F_B = 0$ when the charged particle moves parallel to the magnetic field vector. When velocity vector makes any angle $\theta \neq 0$ with the magnetic field, $\boldsymbol{F_B}$ is perpendicular to both ***B*** and ***v***. F_B on a positive charge is opposite on a negative charge. The magnitude F_B is proportional to $\sin\theta$.


q
+
v
B
F = 0
F
F max
F = qvB
v⊥
φ
F = qvB sin φ
v⊥ = v sin φ

Magnetic Force

- Magnetic force $$\vec{F}_B = q\,\vec{v} \times \vec{B}$$

- Right-hand rule determine the direction of magnetic force. So the magnetic force is always perpendicular to **v** and **B**.
- The magnitude of the magnetic force is

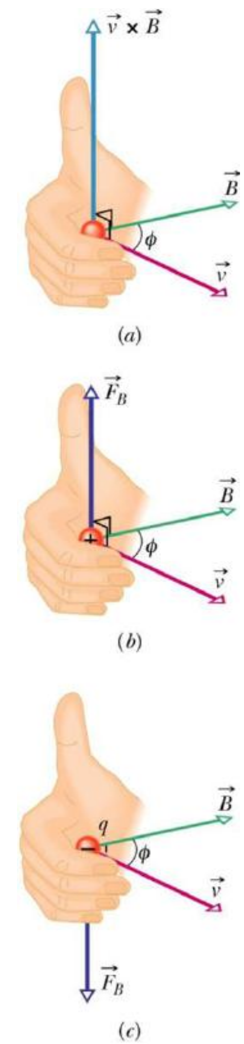
$$F_B = |q| vB \sin\theta$$

$$\vec{F}_E = q\,\vec{E} \quad \Longleftrightarrow \quad \vec{F}_B = q\,\vec{v} \times \vec{B}$$

The electric force is along the direction of the electric field, the magnetic force is perpendicular to the magnetic field.

The electric force acts on a charged particle regardless of whether the particle is moving, the magnetic force acts on a charged particle only when the particle is in motion.

The electric force does work in displacing a charged particle, the magnetic force does no work when a particle is displaced.



Magnetic Fields

Magnetic field: $B = \frac{F_B}{|q|v}$

SI unit of magnetic field: tesla (T)

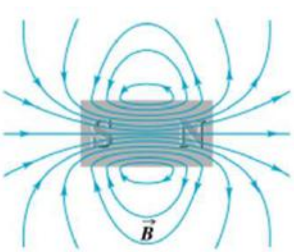
1T = 1 N/[Cm/s] = 1 N/[Am] = 10^4 gauss

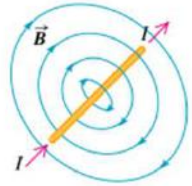
Magnetic field lines with similar rules:

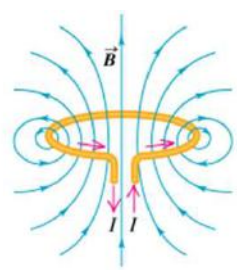
The direction of the tangent to a magnetic field line at any point gives the direction of **B** at that point;

The spacing of the lines represents the magnitude of **B** – the magnetic field is stronger where the lines are closer together, and conversely.

At surface of neutron star	10^8 T
Near big electromagnet	1.5 T
Inside sunspot	10^{-1} T
Near small bar magnet	10^{-2} T
At Earth's surface	10^{-4} T
In interstellar space	10^{-10} T

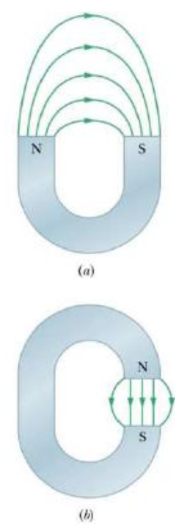


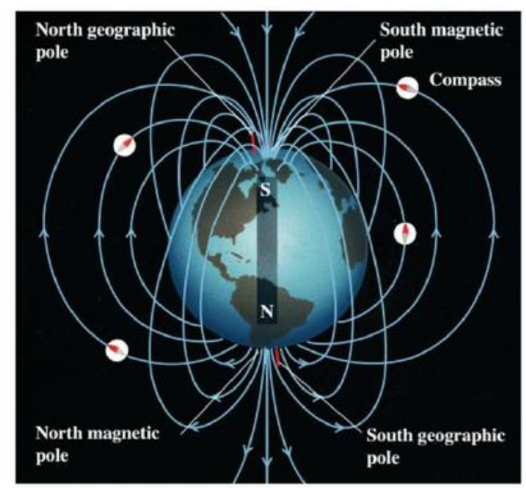




CONVENTION

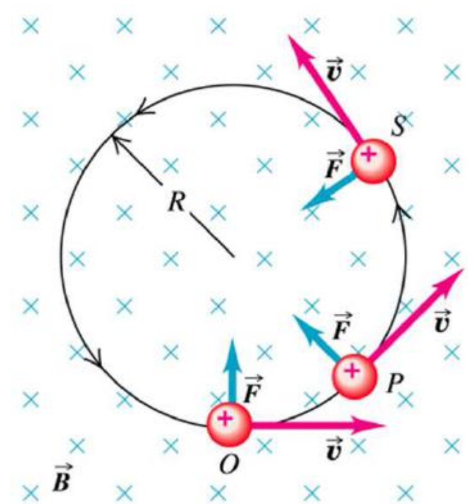
● OUT ✕ IN





Motion of a Charged Particle in a Uniform Magnetic Field

F_B never has a component parallel to **v** and can't change the particle's kinetic energy. The force can change only the direction of **v**.



Charged particle moves in a circle in a plane perpendicular to the magnetic field.

Start with $\sum F = F_B = ma$

Then, we have $F_B = qvB = \frac{mv^2}{r}$

The radius of the circular path: $r = \frac{mv}{qB}$

The angular speed: $\omega = \frac{v}{r} = \frac{qB}{m}$

The period of the motion:

$$T = \frac{2\pi r}{v} = \frac{2\pi}{\omega} = \frac{2\pi m}{qB}$$

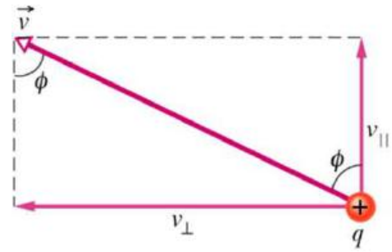
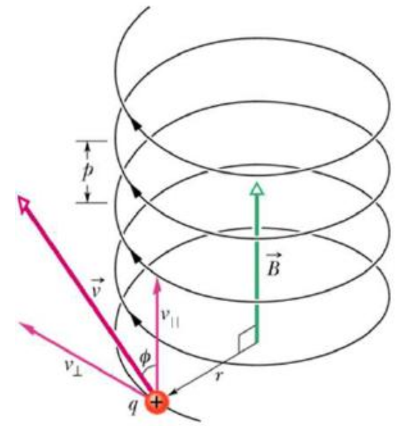
T and ω do not depend on v of the particle. Fast particles move in large circles and slow ones in small circles, but all particles with the same charge-to-mass ratio take the same time T to complete one round trip.

The direction of rotation for a positive particle is always counterclockwise, and the direction for a negative particle is always clockwise.

Motion of a Charged Particle in Magnetic Field

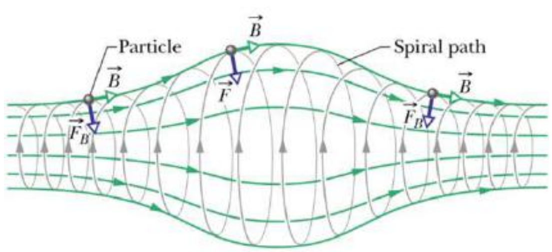
Circle Paths: **v** is perpendicular to **B** (uniform);
Helical Paths: v has a component parallel to B.

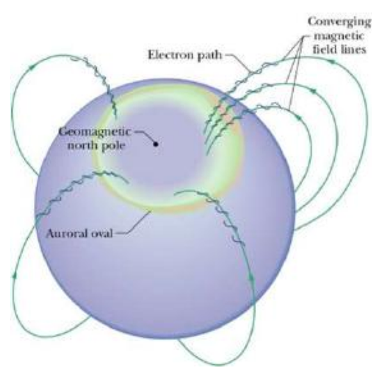
$$v_{\parallel} = v\cos\phi$$
$$v_{\perp} = v\sin\phi$$

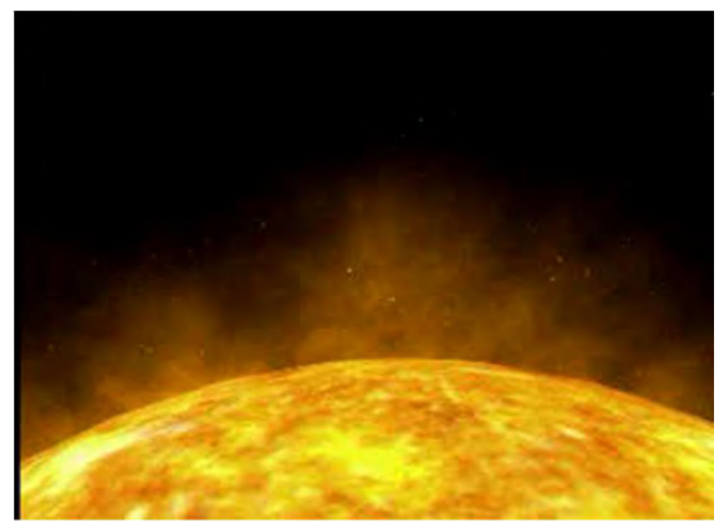



Motion in a nonuniform magnetic field: strong at the ends and weak in the middle;

- Magnetic bottle
- Aurora







Motion of a Charged Particle in a Uniform Electric Field and Magnetic Field

Charged particle in both electric field and magnetic field

$$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

Velocity Selector:

$$qE = qvB \qquad v = \frac{E}{B}$$

The Mass Spectrometer:

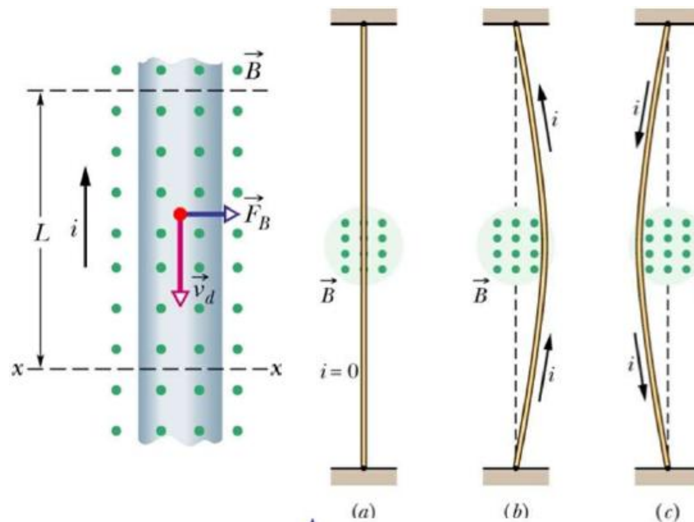
$$r = \frac{mv}{qB} \qquad \frac{m}{q} = \frac{rB_0}{v} \qquad \frac{m}{q} = \frac{rB_0B}{E}$$

The Cyclotron:

$$T = \frac{2\pi m}{|q|B} \qquad f = f_{osc} = \frac{1}{T} \quad |q|B = 2\pi m f_{osc}$$

Magnetic Force on a Current-Carrying Wire

Free electrons (negative charges) move with drift velocity v_d opposite to the current.

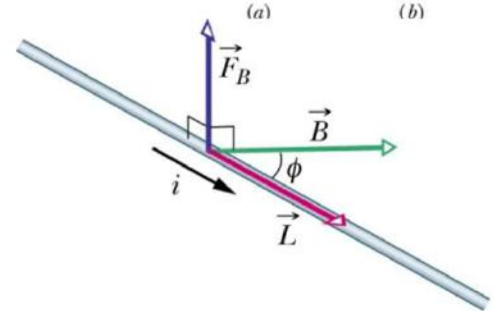


Electrons in this section feel Lorentz force:

We have $\vec{F}_B = (q\vec{v}_d \times \vec{B})nAL$

So, $i = nqv_d A$ $\quad$ $\vec{F}_B = i\vec{L} \times \vec{B}$

Wire is pushed/pulled by the charges. **L** is a length vector that points in the direction of *i* and has a magnitude equal to the length.



Arbitrarily shaped wire segment of uniform cross section in a magnetic field. $d\vec{F}_B = I\,d\vec{s} \times \vec{B}$

$$\vec{F}_B = I\int_a^b d\vec{s} \times \vec{B}$$

Torque on a Current Loop

- Loop rotates. Calculate force for each side of the loop:

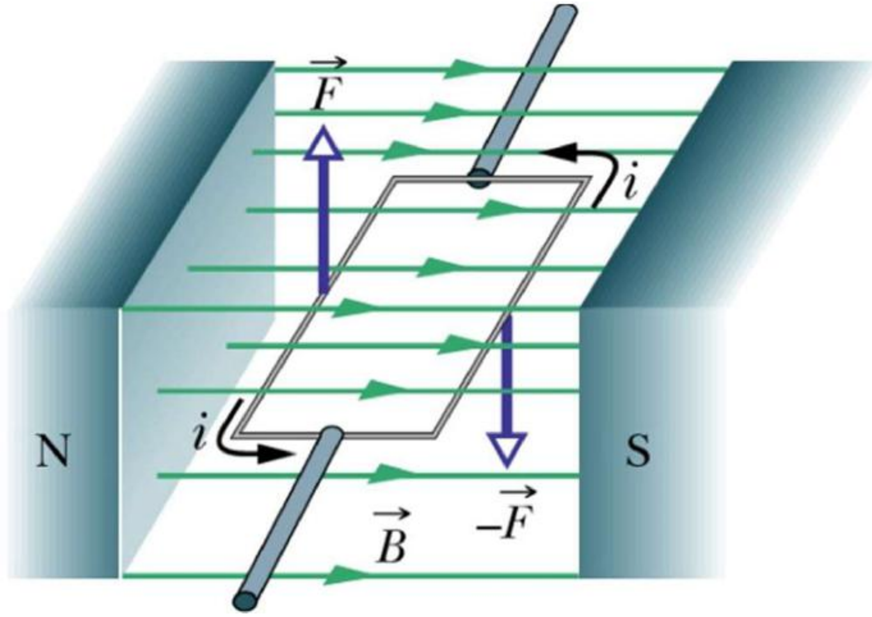
$$F_2 = F_4 = iaB$$

- Torque:

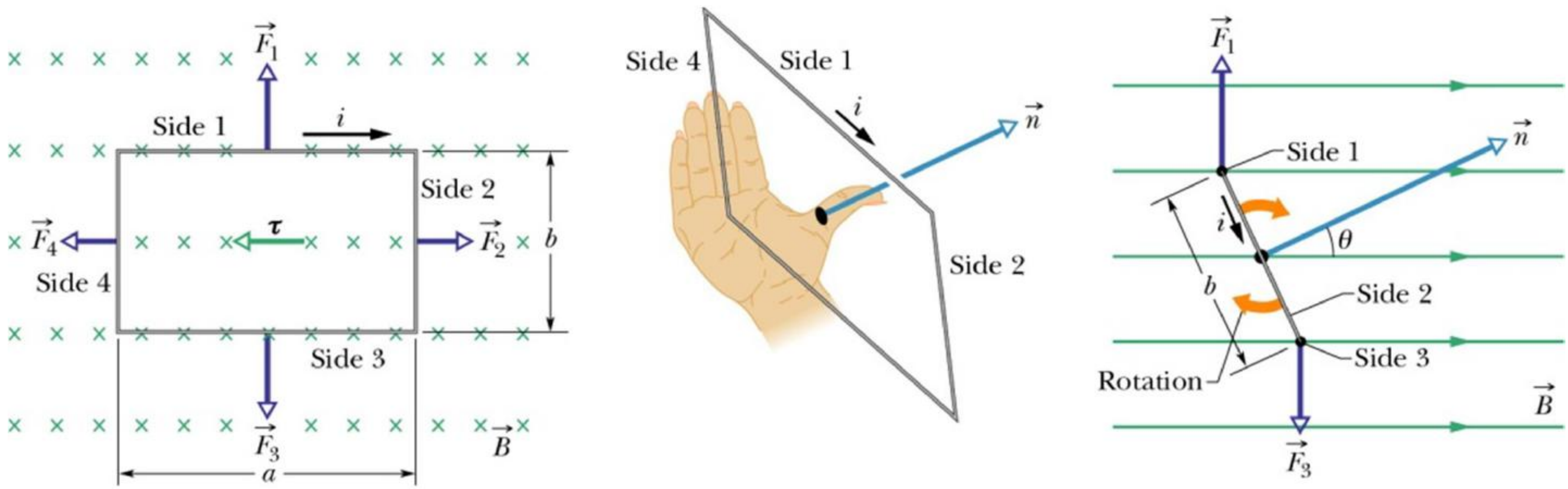
$$\begin{aligned}\tau &= F_2 \frac{b}{2}\sin\theta + F_4 \frac{b}{2}\sin\theta \\ &= iaB(\frac{b}{2}\sin\theta) + iaB(\frac{b}{2}\sin\theta) \\ &= iabB\sin\theta = iAB\sin\theta\end{aligned}$$

$$\vec{\tau} = i\,\vec{A} \times \vec{B}$$

- Maximum torque $\tau_{\max} = iAB$
- Sinusoidal variation $\tau(\theta) = \tau_{\max}\sin\theta$
- Stable when n parallels B.
- Restoring torque: oscillations.



$\vec{F}$
i
N
i
S
$\vec{B}$
$-\vec{F}$



$\vec{F}_1$
Side 1
i
Side 2
$\vec{F}_4$
τ
$\vec{F}_2$
b
Side 4
Side 3
$\vec{F}_3$
$\vec{B}$
a
Side 4
Side 1
i
$\vec{n}$
Side 2
$\vec{F}_1$
$\vec{n}$
Side 1
i
θ
b
Side 2
Side 3
Rotation
$\vec{B}$
$\vec{F}_3$

(a) (b) (c)

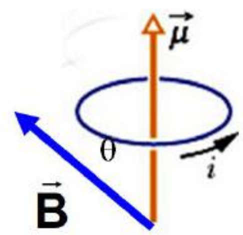
The Magnetic Dipole Moment

- Magnetic dipole moment $\vec{\mu} = i\vec{A}$
- SI unit: Am^2, Nm/T = J/T
- A coil of wire has N loops of the same area:

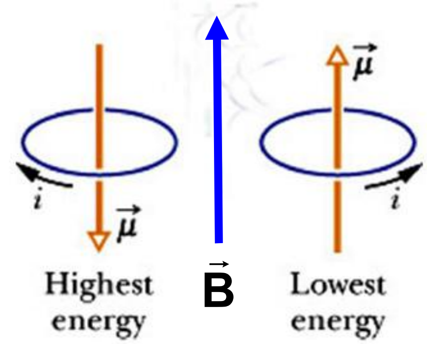
$$\vec{\mu}_{coil} = Ni\vec{A}$$

- Torque $\vec{\tau} = \vec{\mu} \times \vec{B}$
- Magnetic potential $U = -\vec{\mu} \cdot \vec{B}$
- Electric dipole and magnetic dipole

	Electric Dipole	Magnetic Dipole
Moment	$p = qd$	
Torque	$\vec{\tau} = \vec{p} \times \vec{E}$	$\vec{\tau} = \vec{\mu} \times \vec{B}$
Potential Energy	$U = -\vec{p} \cdot \vec{E}$	$U = -\vec{\mu} \cdot \vec{B}$



Small bar magnet	5 J/T
Earth	8.0×10^{22} J/T
Proton	1.4×10^{-26} J/T
Electron	9.3×10^{-24} J/T

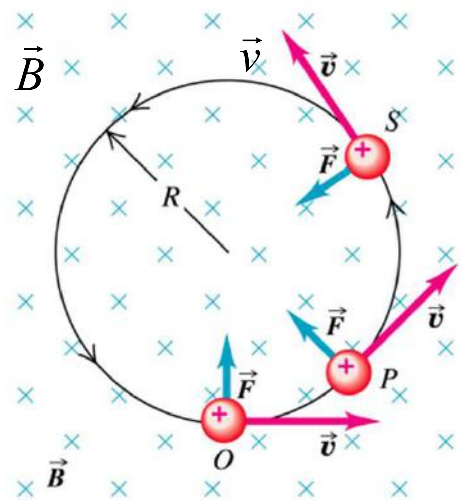


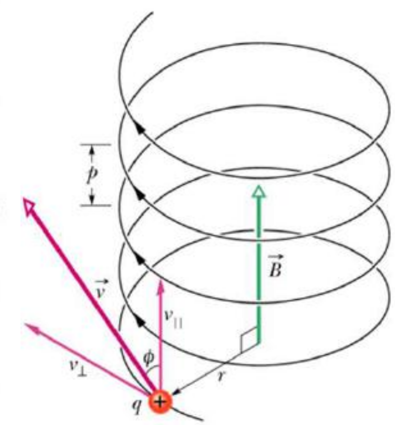
$$U = -p \cdot E$$

Magnetic Field Review

- Magnets only come in pairs of N and S poles (no monopoles).
- Magnetic field exerts a force on *moving* charges (i.e. on currents).
- The force is perpendicular to both and the direction of motion (i.e. must use cross product).
- Because of this perpendicular direction of force, a moving charged particle in a uniform magnetic field moves in a circle or a spiral.
- Because a moving charge is a current, we can write the force in terms of current, but since current is not a vector, it leads to a kind of messy way of writing the equation:

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

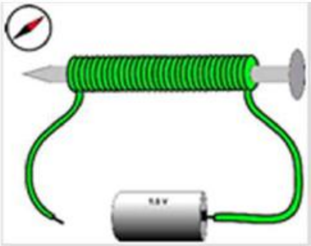




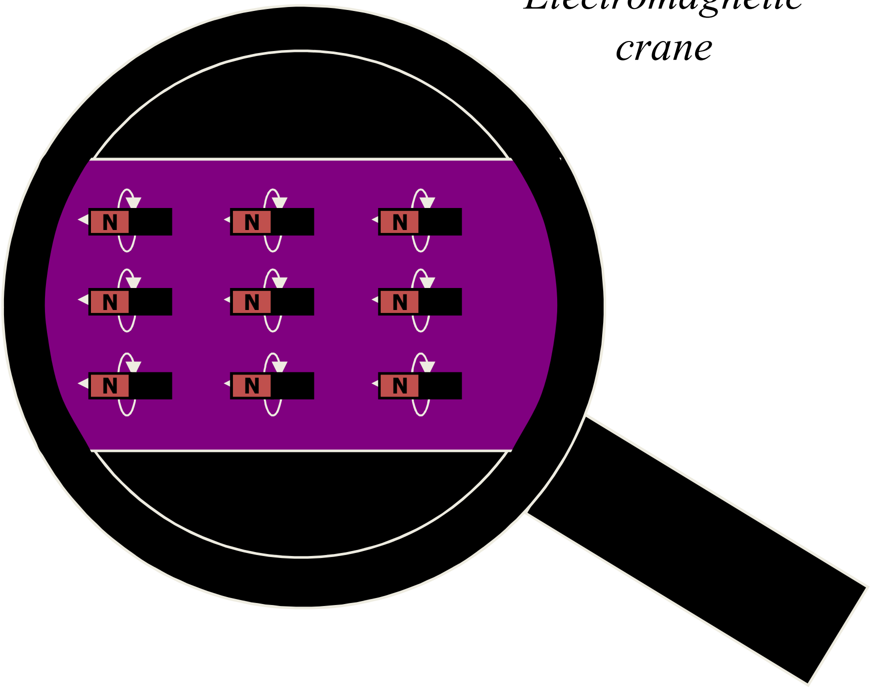
$$\vec{F}_B = i\vec{L} \times \vec{B}$$

Magnetic Field Caused by Current

- As you may know, it is possible to make a magnet by winding wire in a coil and running a current through the wire.
- From this and other experiments, it can be seen that currents *create* magnetic fields.
- In fact, that is the *only* way that magnetic fields are created.
- If you zoom in to a permanent magnet, you will find that it contains a tremendous number of atoms whose charges whiz around to create a current.
- The strength of the magnetic field created by a current depends on the current, and falls off as $1/r^2$.



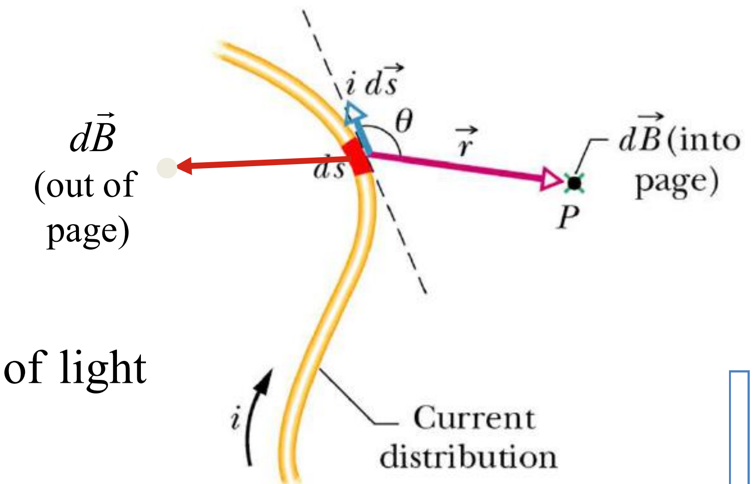
Electromagnetic crane



Biot-Savart Law

- The magnetic field due to an element of current $i\,d\vec{s}$ is

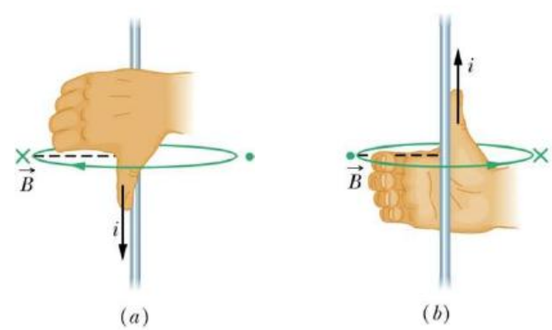
$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\,d\vec{s}\times\hat{r}}{r^2} = \frac{\mu_0}{4\pi}\frac{i\,d\vec{s}\times\vec{r}}{r^3}$$

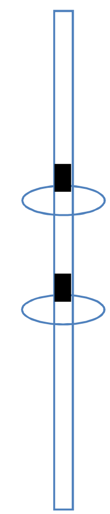


μ_0 = permeability constant exactly $4\pi\times10^{-7}\ \mathrm{T\cdot m/A}$

$$\frac{1}{\sqrt{\varepsilon_0\mu_0}} = c = \text{speed of light}$$

- The magnetic field wraps in circles around a wire. The direction of the magnetic field is easy to find using the right-hand rule.
- Put the thumb of your right hand in the direction of the current, and your fingers curl in the direction of B.





Biot-Savart sounds like "Leo Bazaar"

B due to a Long Straight Wire

Just add up all of the contributions ds to the current, keeping track of distance r.

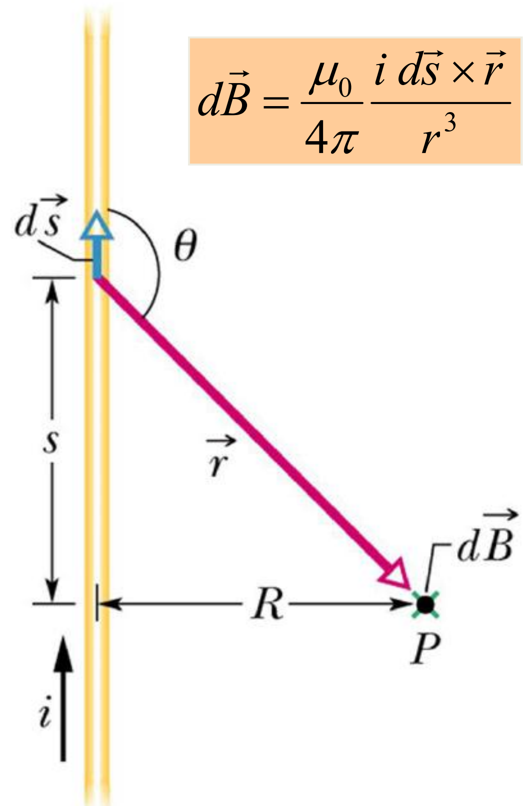
$$B = 2\int_0^\infty dB = \frac{\mu_0 i}{2\pi}\int_0^\infty \frac{r\sin\theta\, ds}{r^3}$$

Notice that $r = \sqrt{R^2 + s^2}$. And $r\sin\theta = R$, So the integral becomes

$$B = \frac{\mu_0 i}{2\pi}\int_0^\infty \frac{R\, ds}{(R^2+s^2)^{3/2}}$$

The integral is a little tricky, but is

$$B = \frac{\mu_0 i}{2\pi R}\left[\frac{s}{\sqrt{R^2+s^2}}\right]_0^\infty = \frac{\mu_0 i}{2\pi R}$$



$$B = \frac{\mu_0 i}{2\pi R}$$

B due to current in a long straight wire

B at Center of a Circular Arc of Wire

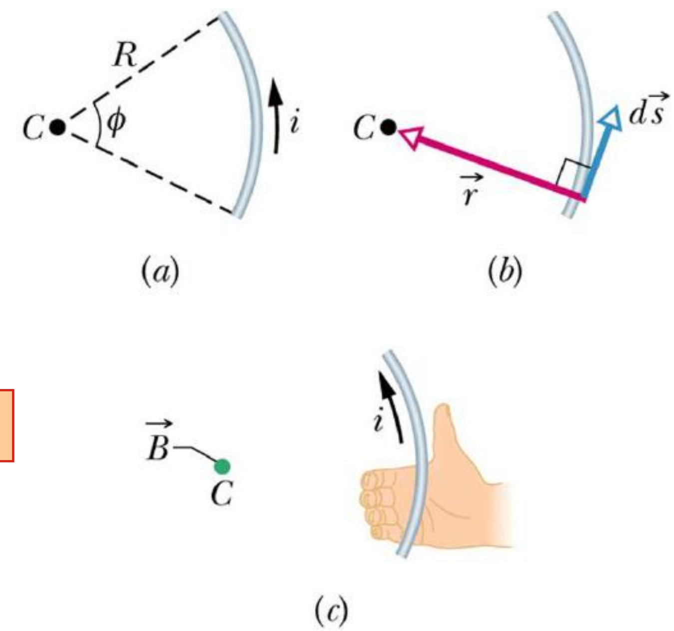
Just add up all of the contributions ds to the current, but now distance $r=R$ is constant, and $\vec{r} \perp d\vec{s}$

$$B = \int_0^{\phi} dB = \frac{\mu_0 i}{4\pi R^2}\int_0^{\phi} ds$$

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\, d\vec{s} \times \vec{r}}{r^3}$$

Notice that $ds = Rd\phi$. So the integral becomes

$$B = \frac{\mu_0 i}{4\pi R^2}\int_0^{\phi} Rd\phi = \frac{\mu_0 i\phi}{4\pi R}$$



For a complete loop, $\phi = 2\pi$, so

$$B = \frac{\mu_0 i\phi}{4\pi R}$$

B due to current in circular arc

$$B = \frac{\mu_0 i}{2R}$$

B at center of a full circle

B for Lines and Arcs

How would you determine B in the center of this loop of wire?

Say $R = 10$ cm, $i = 2.43$ A. Since $95^\circ = 1.658$ radians, $90^\circ = 1.571$ radians, $70^\circ = 1.222$ radians, $105^\circ = 1.833$ radians, we have

$$B = 10^{-7}(2.43)\left[\frac{1.658}{3R} + \frac{1.833}{2R} + \frac{1.571}{3R} + \frac{1.222}{R}\right]$$

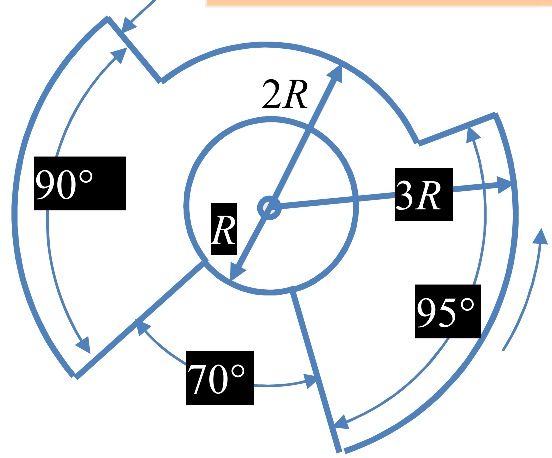
$$= \frac{7.812\times 10^{-7}}{0.1}\text{T} = 7.812\ \mu\text{T}$$ (out of page)

$$B = 10^{-7}(2.43)\left[\frac{1.658}{3R} + \frac{1.833}{2R} + \frac{1.571}{3R} - \frac{5.062}{R}\right]$$

$$= -\frac{7.458\times 10^{-7}}{0.1}\text{T} = -7.458\ \mu\text{T}$$ (into page)

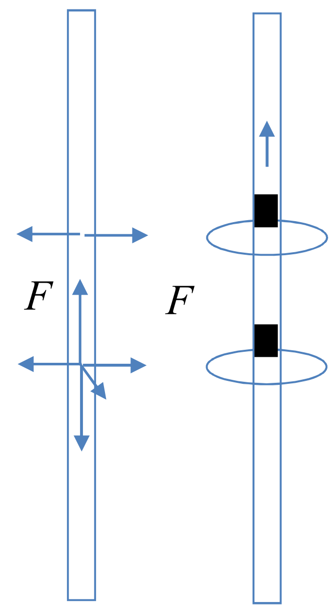
$$B = \frac{\mu_0 i \phi}{4\pi R}$$ circular arc

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\, d\vec{s}\times\vec{r}}{r^3} = 0$$



Force Between Two Parallel Currents

- Recall that a wire carrying a current in a magnetic field feels a force.
- When there are two parallel wires carrying current, the magnetic field from one causes a force on the other.
- When the currents are parallel, the two wires are pulled together.
- When the currents are anti-parallel, the two wires are forced apart.



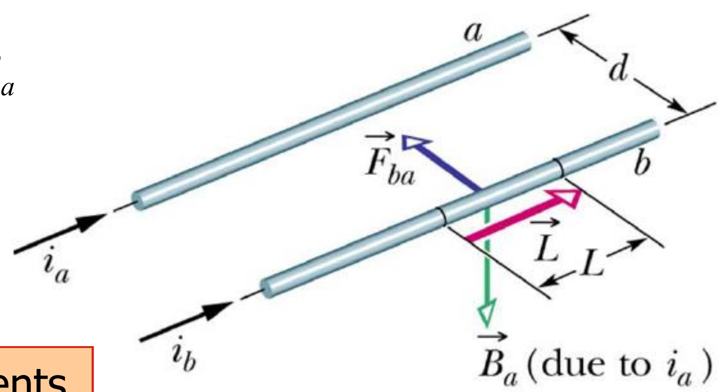
$$\vec{F}_B = i\vec{L}\times\vec{B}$$

To calculate the force on b due to a, $\vec{F}_{ba} = i_b\vec{L}\times\vec{B}_a$

$$B = \frac{\mu_0 i}{2\pi R} = \frac{\mu_0 i_a}{2\pi\, d}$$

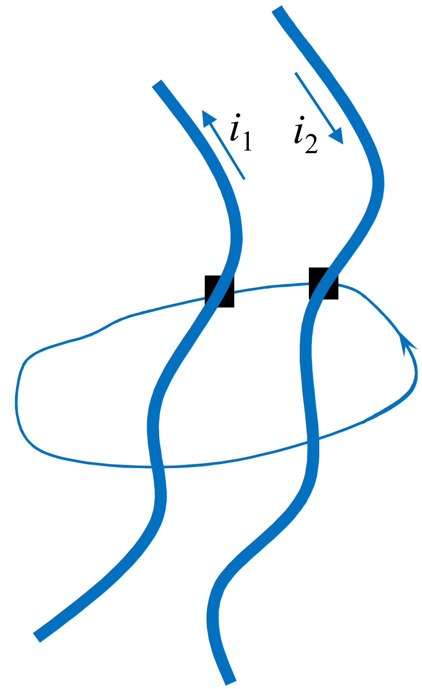
$$F_{ba} = \frac{\mu_0 i_a i_b L}{2\pi d}$$

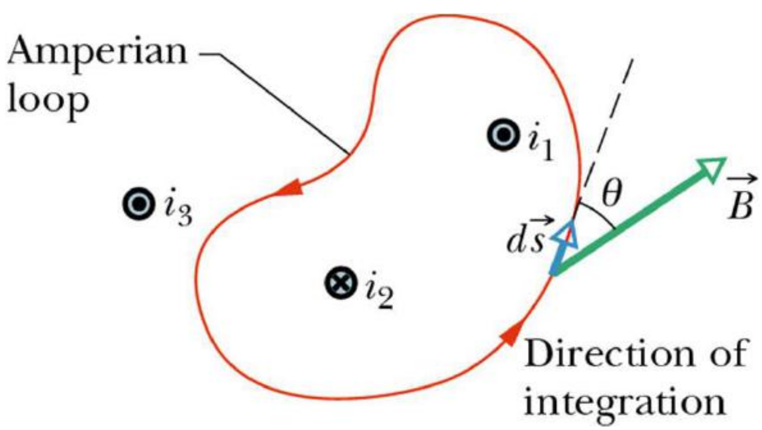
Force between two parallel currents



Ampere's Law

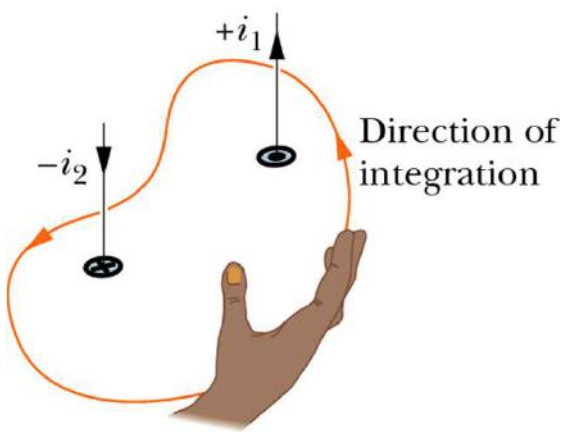
- Another way to calculate B is using Ampere's Law (integrate B around closed Amperian loops)
- Ampere's Law for magnetic fields is analogous to Gauss' Law for electric fields.
- Draw an "amperian loop" around a system of currents (like the two wires at right). The loop can be any shape, but it must be *closed*.
- Add up the component of $\vec{B}$ along the loop, for each element of length *ds* around this closed loop.
- The value of this integral is proportional to the current enclosed:





$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc}$$

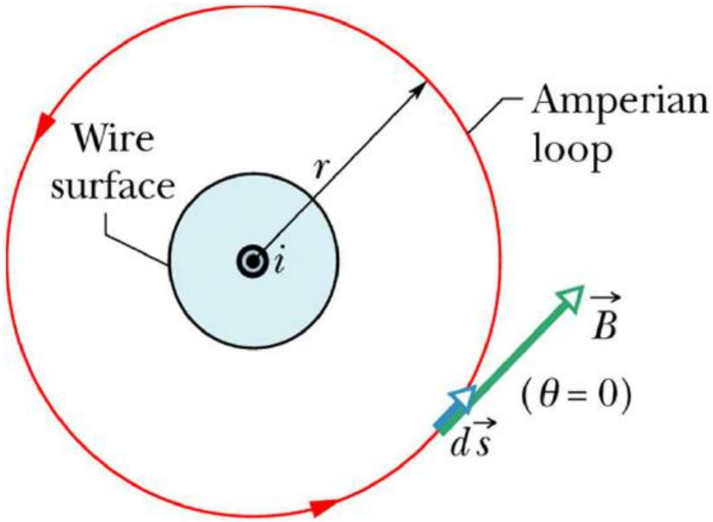
Ampere's Law



Magnetic Field Outside a Long Straight Wire with Current

- We already used the Biot-Savart Law to show that, for this case,

$$B = \frac{\mu_0 i}{2\pi r}$$



- Let's show it again, using Ampere's Law:
- First, we are free to draw an Amperian loop of any shape, but since we know that the magnetic field goes in circles around a wire, let's choose a circular loop (of radius *r*).
- Then *B* and *ds* are parallel, and *B* is constant on the loop, so

$$\oint \vec{B} \cdot d\vec{s} = B 2\pi r = \mu_0 i_{enc}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc}$$

Ampere's Law

- And solving for B gives our earlier expression.

$$B = \frac{\mu_0 i}{2\pi r}$$

Magnetic Field Inside a Long Straight Wire with Current

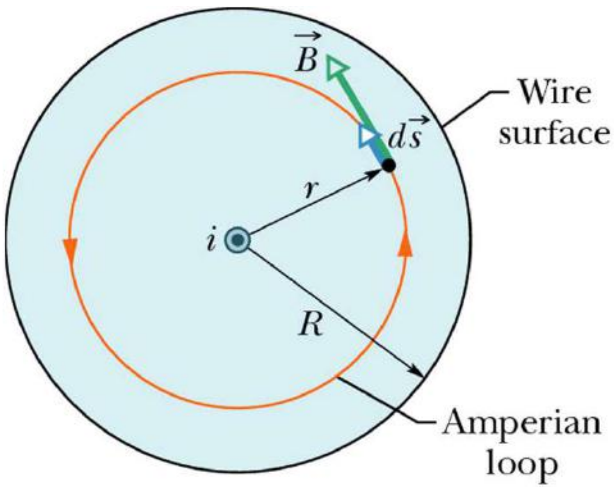
- Now we can even calculate B inside the wire.
- Because the current is evenly distributed over the cross-section of the wire, it must be cylindrically symmetric.
- So we again draw a circular Amperian loop around the axis, of radius *r* < *R*.
- The enclosed current is less than the total current, because some is outside the Amperian loop. The amount enclosed is

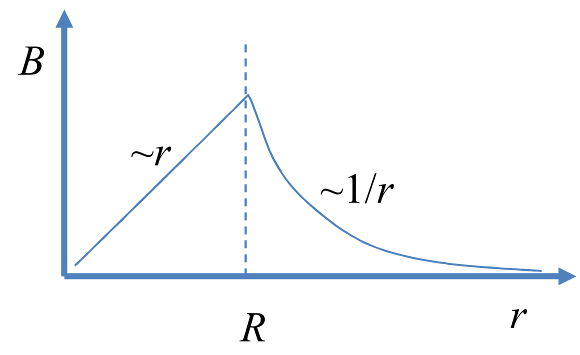
$$i_{enc} = i\frac{\pi r^2}{\pi R^2}$$

- so $\oint \vec{B}\cdot d\vec{s} = B2\pi r = \mu_0 i_{enc} = \mu_0 i\frac{r^2}{R^2}$

$$B = \left(\frac{\mu_0 i}{2\pi R^2}\right)r$$

inside a straight wire



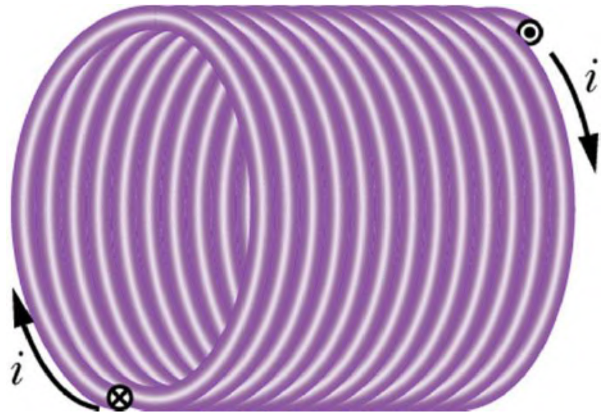


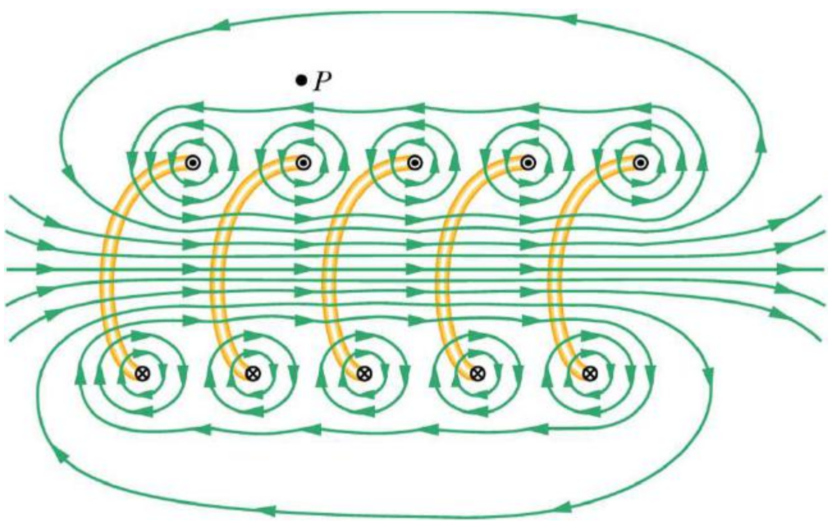
Solenoids

- We saw earlier that a complete loop of wire has a magnetic field at its center:

$$B = \frac{\mu_0 i}{2R}$$

- We can make the field stronger by simply adding more loops. A many turn coil of wire with current is called a solenoid.
- We can use Ampere's Law to calculate B inside the solenoid.
- The field near the wires is still circular, but farther away the fields blend into a nearly constant field down the axis.





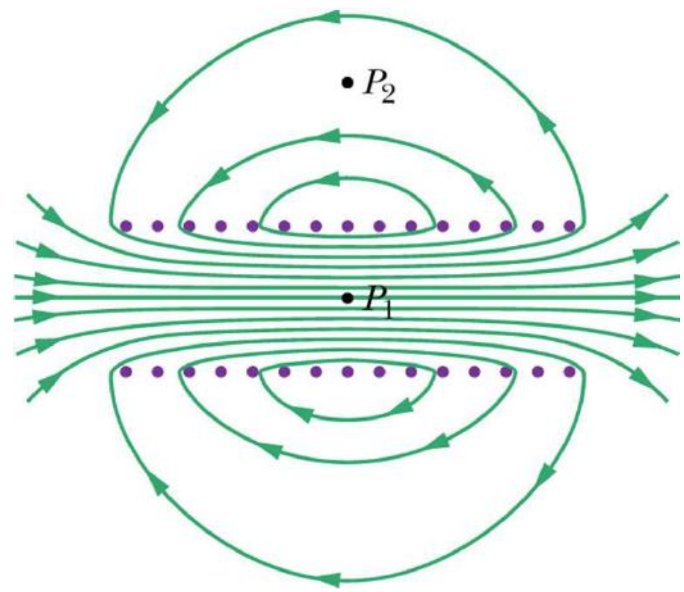
Actual Field of Solenoids

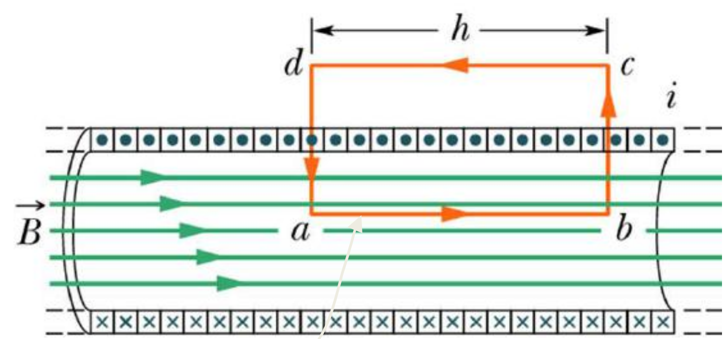
The actual field looks more like this:

- Compare with electric field in a capacitor.
- Like a capacitor, the field is uniform inside (except near the ends), but the direction of the field is different.
- Approximate that the field is constant inside and zero outside (just like capacitor).
- Characterize the windings in terms of number of turns per unit length, n. Each turn carries current i, so total current over length h is inh.

$$\oint \vec{B} \cdot d\vec{s} = Bh = \mu_0 i_{enc} = \mu_0 inh$$

$B = \mu_0 in$ ideal solenoid





only section that has non-zero contribution

Toroid

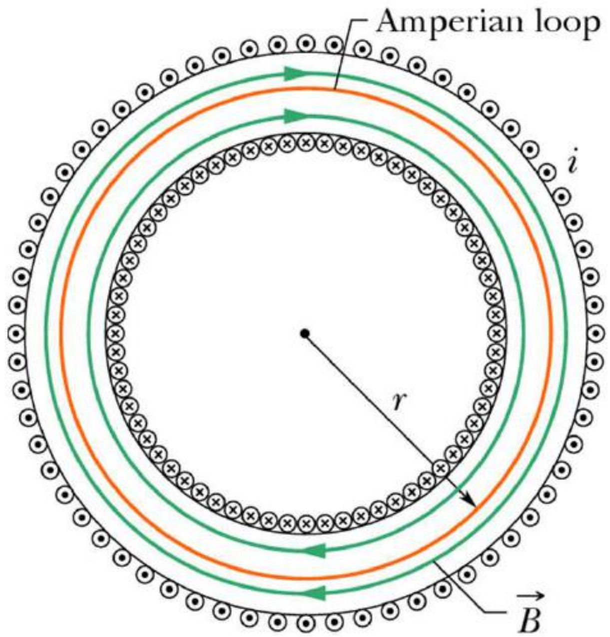
- Notice that the field of the solenoid sticks out both ends, and spreads apart (weakens) at the ends.
- We can wrap our coil around like a doughnut, so that it has no ends. This is called a toroid.
- Now the field has no ends, but wraps uniformly around in a circle.
- What is B inside? We draw an Amperian loop parallel to the field, with radius *r*. If the coil has a total of *N* turns, then the Amperian loop encloses current *Ni*.

$$\oint \vec{B} \cdot d\vec{s} = B 2\pi r = \mu_0 i_{enc} = \mu_0 i N$$

$$B = \frac{\mu_0 i N}{2\pi r}$$

inside toroid

(a)



(b)

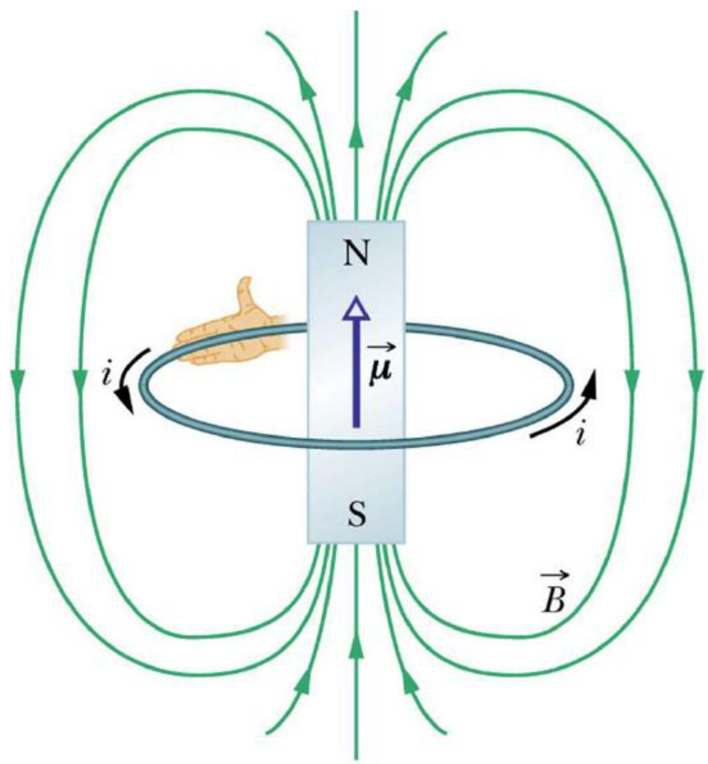
Current-Carrying Coils

- Last week we learned that a current-carrying coil of wire acts like a small magnet, and we defined the "dipole moment" (a vector) as

$$\left|\vec{\mu}\right| = NiA$$

N is number of turns, A is area of loop

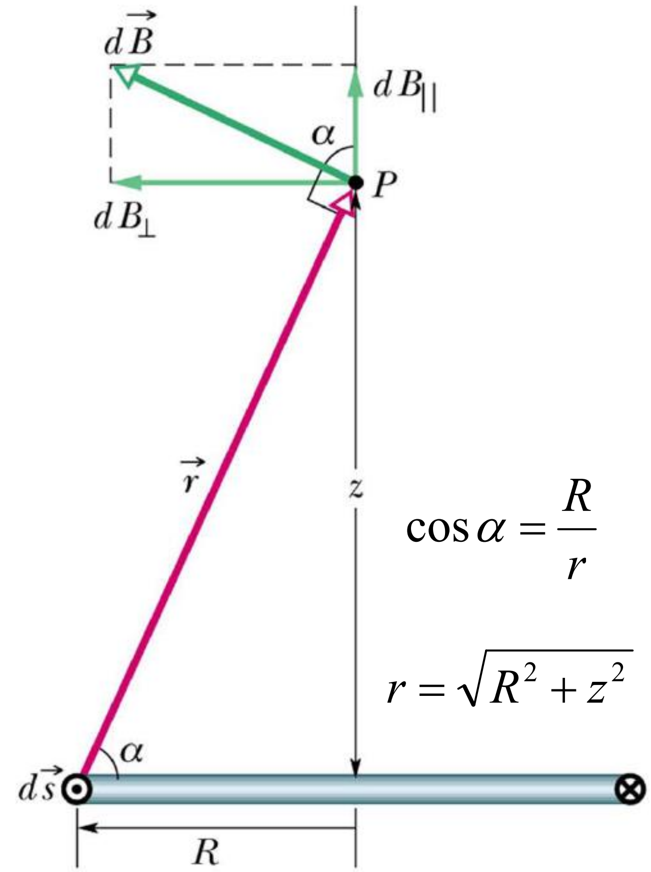
- The direction is given by the right-hand rule. Let your fingers curl around the loop in the direction of *i*, and your thumb points in the direction of *B*. Notice that the field lines of the loop look just like they would if the loop were replaced by a magnet.
- We are able to calculate the field in the center of such a loop, but what about other places. In general, it is hard to calculate in places where the symmetry is broken.
- But what about along the *z* axis?



B on Axis of Current-Carrying Coil

- What is B at a point P on the z axis of the current loop?
- We use the Biot-Savart Law $d\vec{B} = \frac{\mu_0}{4\pi}\frac{i\, d\vec{s} \times \vec{r}}{r^3}$

  to integrate around the current loop, noting that the field is perpendicular to r.
- By symmetry, the perpendicular part of B is going to cancel around the loop, and only the parallel part will survive.



$$\cos\alpha = \frac{R}{r}$$

$$r = \sqrt{R^2 + z^2}$$

$$dB_{\parallel} = dB\cos\alpha = \frac{\mu_0}{4\pi}\frac{i\,ds}{r^2}\cos\alpha = \frac{\mu_0}{4\pi}\frac{i\,ds}{(R^2+z^2)^{3/2}}R$$

$$B = \int dB_{\parallel} = \frac{\mu_0}{4\pi}\frac{iR}{(R^2+z^2)^{3/2}}\int ds$$

$$B(z) = \frac{\mu_0 i R^2}{2(R^2+z^2)^{3/2}}$$

$$B(0) = \frac{\mu_0 i}{2R}$$

Summary

- Calculate the B field due to a current using Biot-Savart Law $d\vec{B} = \frac{\mu_0}{4\pi} \frac{i\, d\vec{s} \times \vec{r}}{r^3}$
- Permiability constant μ_0 : $4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$
- B due to long straight wire: $B = \frac{\mu_0 i}{2\pi r}$ circular arc: $B = \frac{\mu_0 i \phi}{4\pi R}$ complete loop: $B = \frac{\mu_0 i}{2R}$
- Force between two parallel currents $F_{ba} = \frac{\mu_0 i_a i_b L}{2\pi d}$
- Another way to calculate B is using Ampere's Law (integrate B around closed Amperian loops): $\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc}$
- B inside a long straight wire: $B = \left(\frac{\mu_0 i}{2\pi R^2} \right) r$ a solenoid: $B = \mu_0 i n$ a torus: $B = \frac{\mu_0 i N}{2\pi\, r}$
- B on axis of current-carrying coil: $B(z) = \frac{\mu_0 i R^2}{2(R^2 + z^2)^{3/2}}$

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

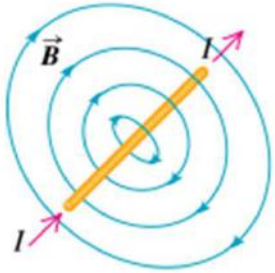
Induction 1

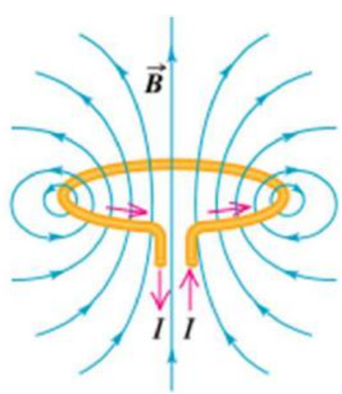
Induction 1

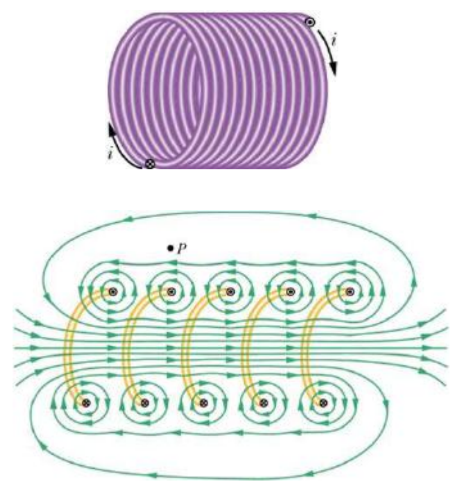
- Induced EMF and current
- Faraday’s law
- Induction and Energy Transfers
- Lenz’s law
- Induced electric field

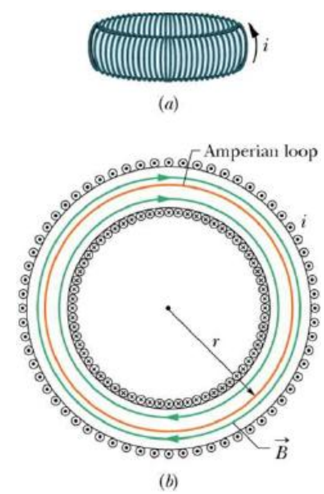
Currents Create Magnetic Fields

- B due to long straight wire carrying a current i: $B = \dfrac{\mu_0 i}{2\pi r}$
- B due to complete loop carrying a current i : $B = \dfrac{\mu_0 i}{2R}$
- B inside a solenoid: $B = \mu_0 i n$ a torus carrying a current i : $B = \dfrac{\mu_0 i N}{2\pi\, r}$





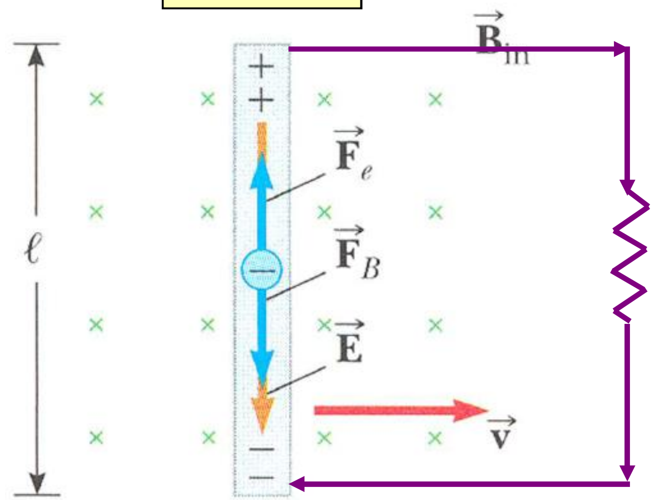




Induced EMF and Current

- A wire of length l is moving through a uniform magnetic field directed into the board.
- Moving in a direction perpendicular to the field with constant velocity **v**.
- Electrons feel a magnetic force and migrate, producing an induced electric field **E**.
- Charges come to equilibrium when the forces on charges balance: $qE = qvB \quad \text{or} \quad E = vB$
- Electric field is related to potential difference across the ends of wire: $V = El = Blv$
- A potential difference is maintained between the ends of the wire as long as the wire continues to move through the magnetic field.

$$\vec{F}_E = q\vec{E}$$



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

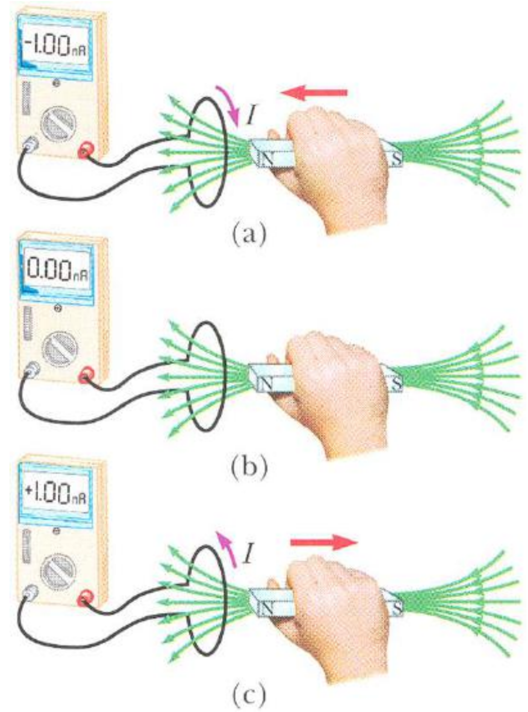
A current is set up even through no batteries are present in the circuit. Such a current is an induced current. It is produced by an induced EMF.

Faraday’s Law: Experiments

- A current appears only if there is relative motion between the loop and the magnet; the current disappears when the relative motion between them ceases.

- Faster motion produces a greater current.

- If moving the magnet’s north pole toward the loop causes, say, clockwise current, then moving the north pole away causes counterclockwise current. Moving the south pole toward or away from the loop also causes currents, but in the reversed directions.

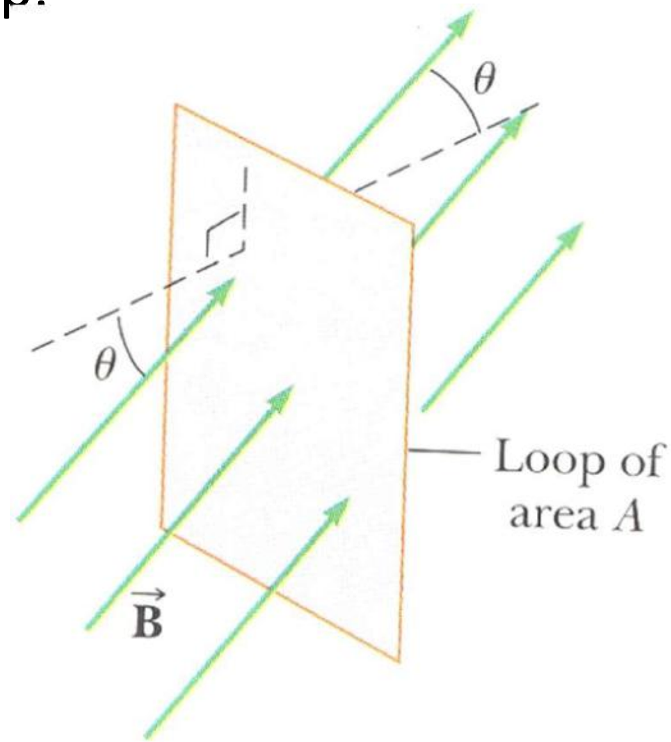


An EMF is induced in the loop when the number of magnetic field lines that pass through the loop is changing.

Flux of Magnetic Field

- We need a way to calculate the *amount of magnetic field* that passes through a loop.
- Similar to the definition of electric flux, we define a magnetic flux

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$



- Magnetic flux is a scalar.
- In uniform magnetic field, the magnetic flux can be expressed as

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

- SI unit is the weber (Wb):
  1 weber = 1 Wb = 1 T m^2

Faraday's Law of Induction

- The magnitude of the EMF induced in a conducting loop is equal to the rate at which the magnetic flux through that loop changes with time,

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

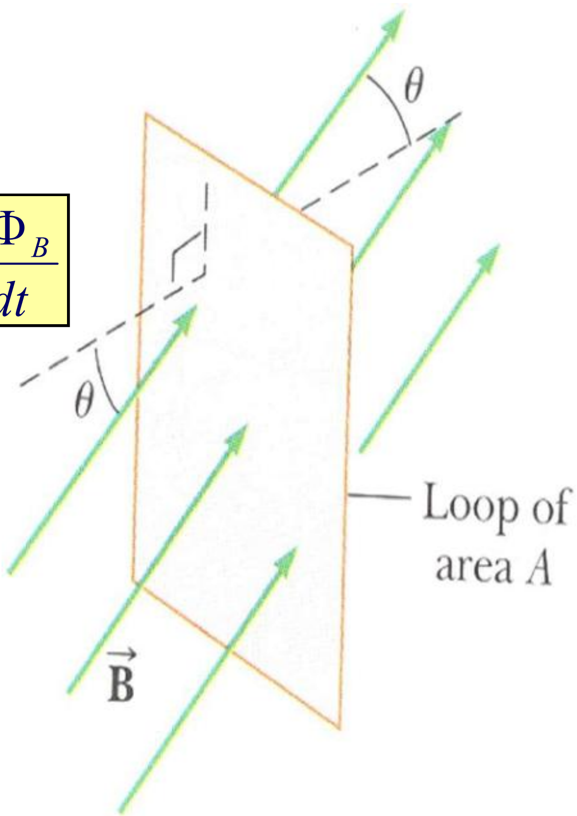
- If a coil consists of N loops with the same area, the total induced EMF in the coil is given by

$$\varepsilon = -N\frac{d\Phi_B}{dt}$$

- In uniform magnetic field, the induced EMF can be expressed as

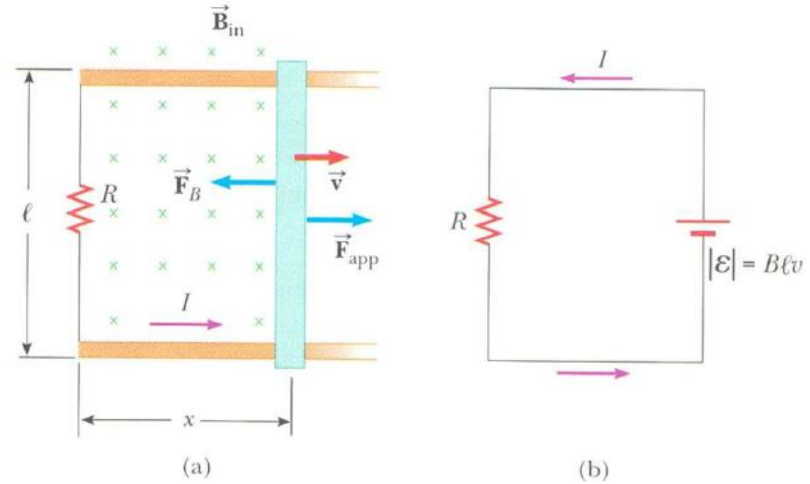
$$\varepsilon = -\frac{d}{dt}(BA\cos\theta)$$

- EMF can be induced in several ways,
  - The magnitude of B can change with time.
  - The area enclosed by the loop can change with time.
  - The angle between B and the normal to the loop can change with time.
  - Any combination of the above can occur.



Induction and Energy Transfers

A conducting bar of length l sliding along two fixed parallel conducting rails. Free charges feel a magnetic force along the length of the bar, producing an induced current I.



Start with magnetic flux

$$\Phi_B = Blx$$

$$\varepsilon = \frac{d\Phi_B}{dt} = \frac{d}{dt}(Blx) = Bl\frac{dx}{dt} = Blv$$

Follow Faraday's law, we have $I = \frac{\varepsilon}{R} = \frac{Blv}{R}$

Then $P = I^2 R = \left(\frac{Blv}{R}\right)^2 R = \frac{B^2 l^2 v^2}{R}$

Origin of the induced current and the energy dissipated by the resistor?

The change in energy in the system must equal to the transfer of energy into the system by work.

$$F_{app} = F_B = IlB\sin\theta = IlB$$

Moving with constant velocity, Power by the applied force is

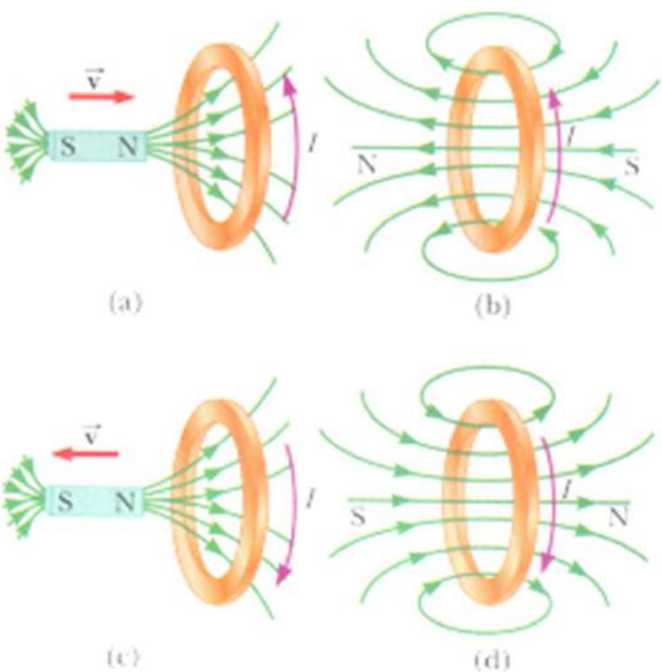
$$P = F_{app}v = (IlB)v = \frac{B^2 l^2 v^2}{R}$$

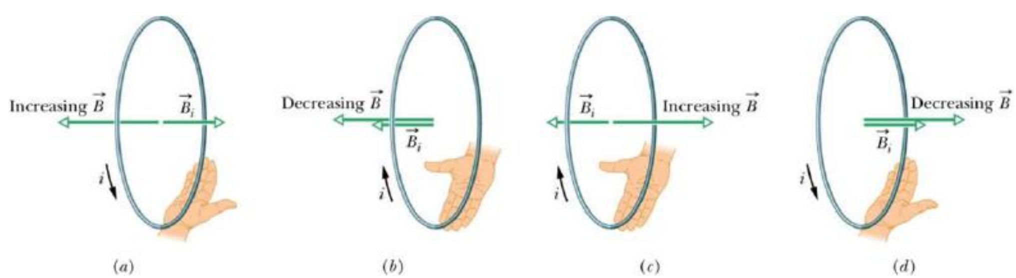
Lenz's Law

- Lenz's law for determining the direction of an induced current in a loop.
- The induced current in a loop is in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop. The direction of an induced EMF is that of the induced current.
- *The induced current tends to keep the original magnetic flux through the loop from changing.*

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

Work by external agent induces current. Induced **Bi** does not always opposes **B**.





A Loop Moving Through a Magnetic Field

A rectangular metallic loop of dimensions l and w and resistance R moves with constant speed v to the right. It passes through a uniform magnetic field **B** directed into the page and extending a distance 3w along the x axis. Define x as the position of the right side of the loop along the x axis. Plot as a function of x the magnetic flux, the induced EMF, the external applied force necessary to keep v constant.

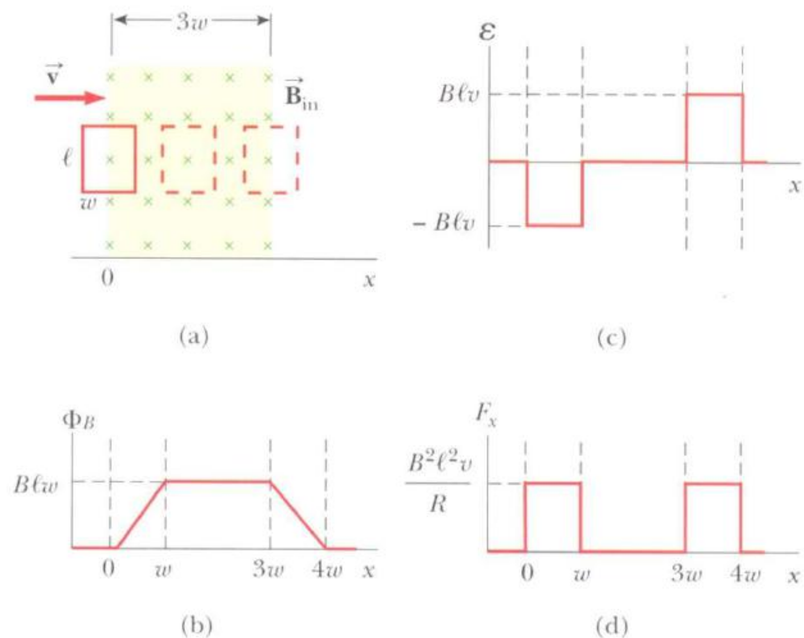
Definitions:

$$\Phi_B = Blx$$

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

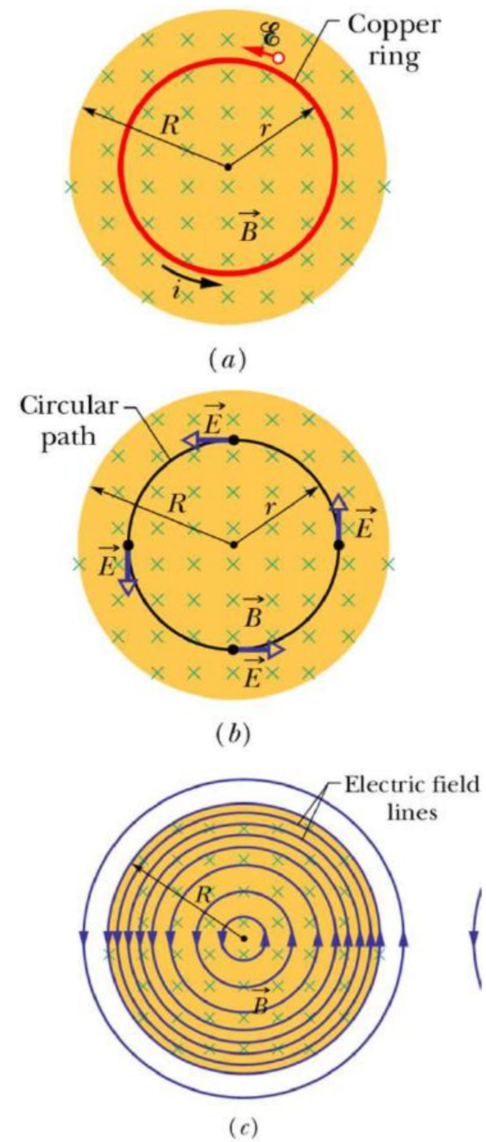
$$\varepsilon = -\frac{d\Phi_B}{dt} = -Bl\frac{dx}{dt} = -Blv$$

$$F_{app} = F_B = IlB = \frac{B^2 l^2 v}{R}$$



Induced Electric Fields

- A uniform field fills a cylindrical volume of radius R. Suppose that we increase the strength of this field at a steady rate by increasing.
- Copper ring: A changing magnetic field produces an electric field.
  - By Faraday's law, an induced EMF and current will appear in the ring;
  - From Lenz's law, the current flow counterclockwise;
  - An induced electric field must be present along the ring;
- The existence of an electric field is independent of the presence of any test charges. Even in the absence of the copper ring, a changing magnetic field generates an electric field in empty space.
- Hypothetical circle path: the electric field induced at various points around the circle path must be tangent to the circle.
- The electric field lines produced by the changing magnetic field must be a set of concentric circles.
- A changing magnetic field produces an electric field.



A Reformulation of Faraday's Law

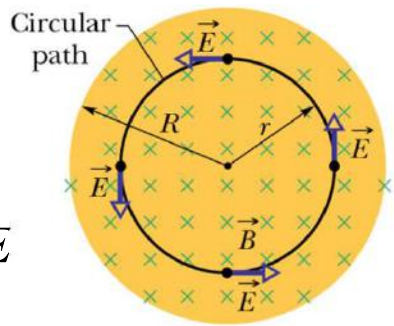
- A charge q_0 moving around the circular path.
- The work W done by the induced electric field, $W = q_0 \varepsilon$
- The work done in moving the test charge around the path,

$$W = \int \vec{F} \cdot \vec{ds} = (q_0 E)(2\pi r)$$

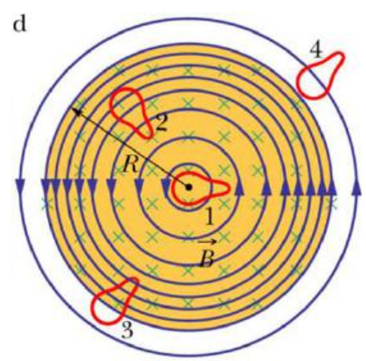
- Two expressions for W equal to each other, we find, $\varepsilon = 2\pi r E$
- A more general expression for the work done on a charge q_0 moving along any closed path,

$$W = \oint \vec{F} \cdot \vec{ds} = q_0 \oint \vec{E} \cdot \vec{ds}$$

- So, $\varepsilon = \oint \vec{E} \cdot \vec{ds}$
- Combined with Faraday's law, $\oint \vec{E} \cdot \vec{ds} = -\dfrac{d\Phi_B}{dt}$
- Electric potential has meaning only for electric fields produced by static charges; it has no meaning for that by induction.



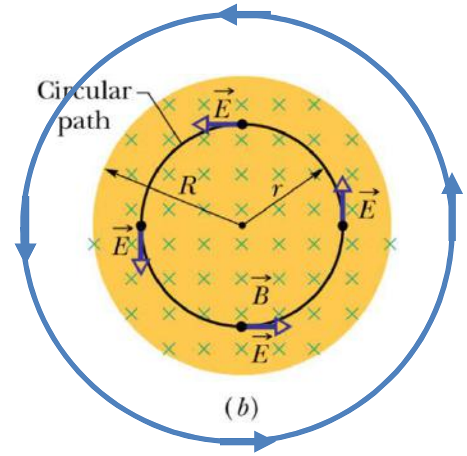
(b)

d


(d)

Find Induced Electric Field

In the right figure, dB/dt = constant, find the expression for the magnitude E of the induced electric field at points within and outside the magnetic field.



Due to symmetry, $\oint \vec{E}\cdot d\vec{s} = \oint E ds = E\oint ds = E(2\pi r)$

r < R: So, $\Phi_B = BA = B(\pi r^2)$

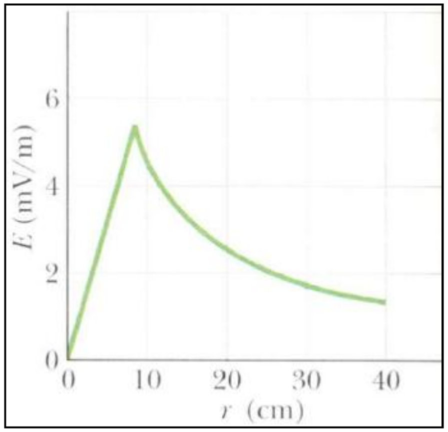
$$E(2\pi r) = (\pi r^2)\frac{dB}{dt}$$

$$E = \frac{r}{2}\frac{dB}{dt}$$

r > R: So, $\Phi_B = BA = B(\pi R^2)$

$$E(2\pi r) = B(\pi R^2)$$

$$E = \frac{R^2}{2r}\frac{dB}{dt}$$



The magnitude of electric field induced inside the magnetic field increases linearly with r.

Summary

- The magnetic flux Φ_B through an area A in a magnetic field B is defined as
- The SI unit of magnetic flux is the weber (Wb): 1Wb = 1Tm^2.
- If the magnetic flux Φ_B through an area bounded by a closed conducting loop changes with time, a current and an EMF are produced in the loop; this process is called induction. The induced EMF is
- If the loop is replaced by a closely packed coil of N turns, the induced EMF is
- An induced current has a direction such that the magnetic field due to the current opposes the change in the magnetic flux that induces the current. The induce EMF has the same direction as the induce current.
- An EMF is induce by a changing magnetic flux even if the loop through which the flux is changing is not a physical conductor but an imaginary line. The changing magnetic field induces an electric field E at every point of such a loop; the induced EMF is related to E by

$$\oint \vec{E} \cdot \vec{ds} = -\frac{d\Phi_B}{dt}$$

  where the integration is taken around the loop. We can write Faraday's lawin its most general form,
- The essence of this law is that *a changing magnetic field induces an electric field **E**.*

$$\Phi_B = \int \vec{B} \cdot \vec{dA}$$

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

$$\varepsilon = -N\frac{d\Phi_B}{dt}$$

$$\varepsilon = \oint \vec{E} \cdot \vec{ds}$$

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

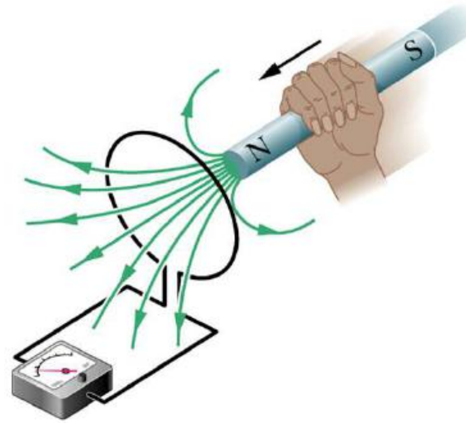
Induction 2

Induction 2

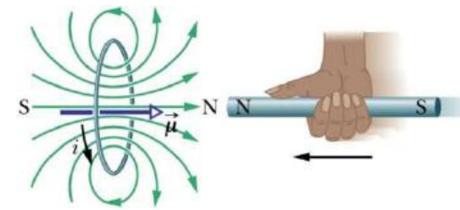
- Induction 1 review
- Induction and inductance
- Inductance of selenoid
- Self induction
- Inductors in circuits: The RL circuit
- Energy stored in magnetic field
- Electromagnetic oscillations

Induction 1 Review

- Faraday's Law: A changing magnetic flux through a coil of wire induces an EMF in the wire, proportional to the number of turns, *N*.
- Lenz's Law: The direction of the current driven by the EMF is such that it creates a magnetic field to oppose the flux change.
- Induction and energy transfer: The forces on the loop oppose the motion of the loop, and the power required to move the loop provides the electrical power in the loop.
- A changing magnetic field creates and electric field.



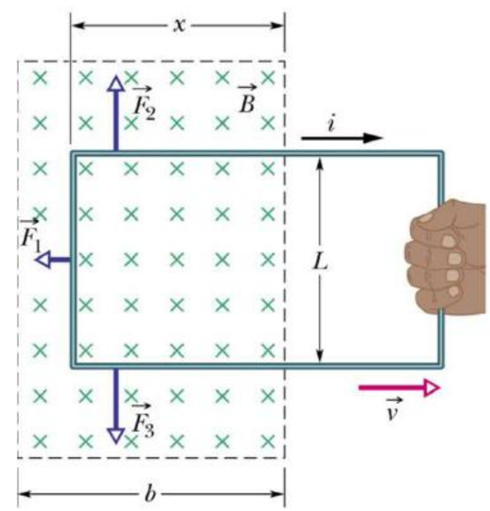
$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$



$$P = \vec{F}\cdot\vec{v} = Fv$$

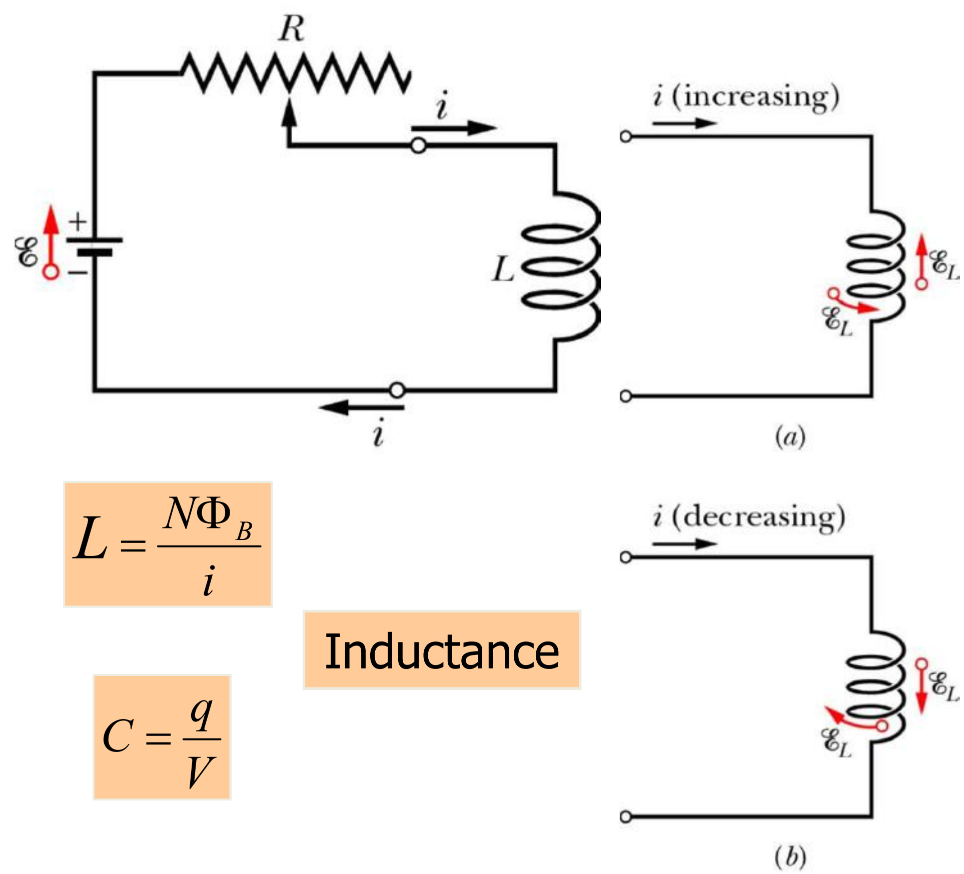
$$P = i\mathcal{E}$$

$$\mathcal{E} = \int \vec{E}\cdot d\vec{s} = -N\frac{d\Phi_B}{dt}$$



Induction and Inductance

- When we try to run a current through a coil of wire, the *changing* current induces a "back-EMF" that opposes the current.
- That is because the changing current creates a changing magnetic field, and the increasing magnetic flux through the coils of wire induce an opposing EMF.
- We seek a description of this that depends only on the geometry of the coils (i.e., independent of the current through the coil).
- We call this the inductance (c.f. capacitance). It describes the proportionality between the current through a coil and the magnetic flux induced in it.



$$L = \frac{N\Phi_B}{i}$$

Inductance

$$C = \frac{q}{V}$$

Inductance units: henry (H), 1 H = 1 T-m^2/A

Inductance of a Solenoid

- Consider a solenoid. Recall that the magnetic field inside a solenoid is

$$B = \mu_0 i n$$

- The magnetic flux through the solenoid is then $\Phi_B = \int B \cdot dA = \mu_0 i n A$

  Number of turns per unit length $n = N/l$.

- The inductance of the solenoid is then: $L = \frac{N\Phi_B}{i} = \frac{N\mu_0 i n A}{i} = nl\mu_0 n A = \mu_0 n^2 l A$

- Note that this depends only on the geometry. Since $N = nl$, this can also be written

$$L = \frac{\mu_0 N^2 A}{l}$$

Compare with capacitance of a capacitor $C = \frac{\varepsilon_0 A}{l}$

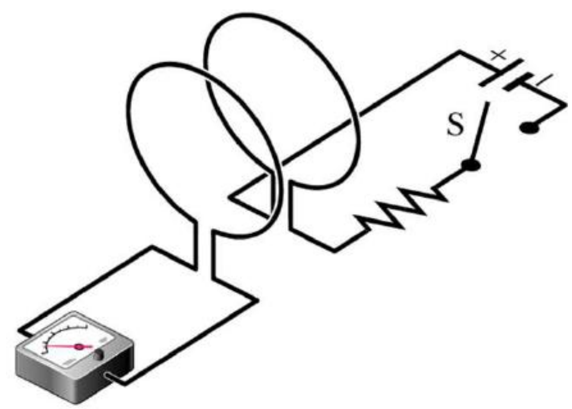
Can also write $\mu_0 = 4\pi \times 10^{-7}$ H/m $= 1.257$ μH/m

Compare with $\varepsilon_0 = 8.85$ pF/m

Self-Induction

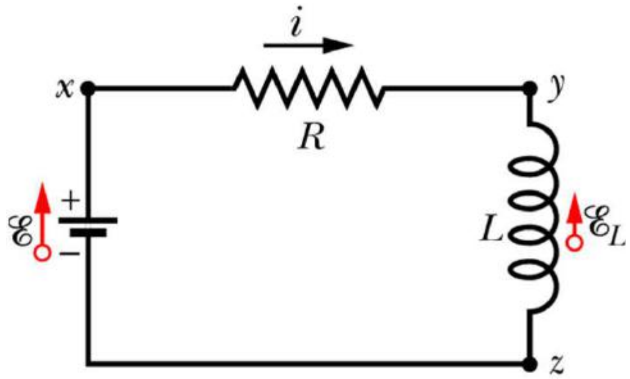
- You should be comfortable with the notion that a changing current in one loop induces an EMF in other loop.
- You should also be able to appreciate that if the two loops are part of the same coil, the induction still occurs—a changing current in one loop of a coil induces a back-EMF in another loop of the same coil.
- In fact, a changing current in a *single loop* induces a back-EMF in *itself*. This is called self-induction.
- Since for any inductor $L = \frac{N\Phi_B}{i}$ then $iL = N\Phi_B$, $L\frac{di}{dt} = N\frac{d\Phi_B}{dt}$
- But Faraday's Law says $\mathcal{E}_L = -N\frac{d\Phi_B}{dt} = -L\frac{di}{dt}$

The self-induced EMF is opposite to the direction of change of current



Inductors in Circuits: The RL Circuit

- Inductors, or coils, are common in electrical circuits.
- They are made by wrapping insulated wire around a core, and their main use is in resonant circuits, or filter circuits.
- Consider the RL circuit, where a battery with EMF ε drives a current around the loop, producing a back EMF ε_L in the inductor.
- Kirchoff's loop rule gives $$\mathcal{E} - iR - L\frac{di}{dt} = 0$$
- Solving this *differential equation* for i gives $$i = \frac{\mathcal{E}}{R}(1 - e^{-Rt/L})$$ Rise of current



RL Circuits

- When t is large: $i = \frac{\mathcal{E}}{R}$ Inductor acts like a wire.
- When t is small (zero), $i = 0$. Inductor acts like an open circuit.
- The current starts from zero and increases up to a maximum of $i = \mathcal{E}/R$ with a time constant given by

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

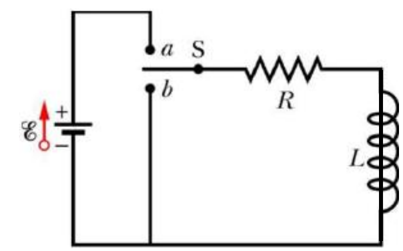
Inductor time constant

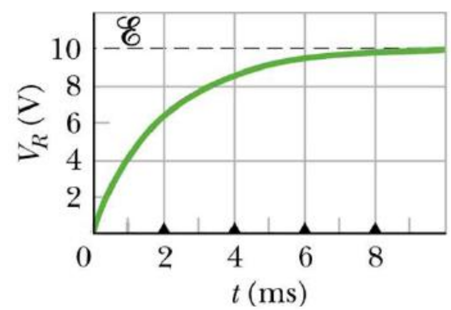
Compare: $\tau_C = RC$ Capacitor time constant

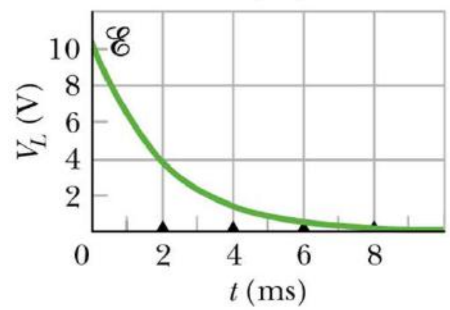
- The voltage across the resistor is $V_R = iR = \mathcal{E}(1 - e^{-Rt/L})$
- The voltage across the inductor is

$$V_L = \mathcal{E} - V_R = \mathcal{E} - \mathcal{E}(1 - e^{-Rt/L}) = \mathcal{E}\ e^{-Rt/L}$$

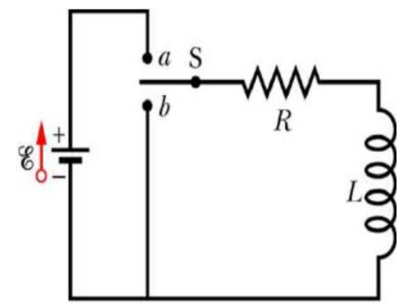
$$i = \frac{\mathcal{E}}{R}(1 - e^{-Rt/L})$$



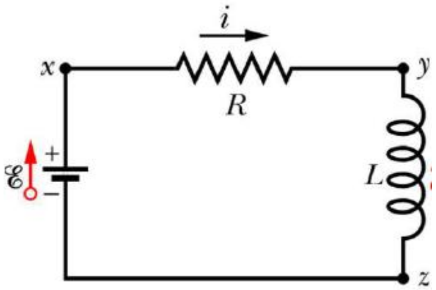




RL Circuits



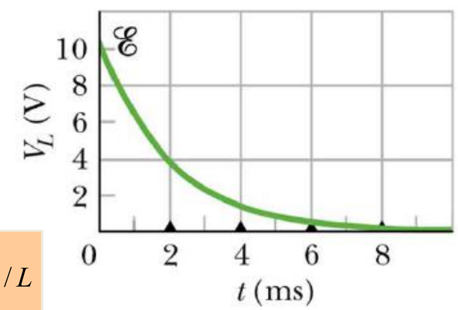
- What happens when the switch is thrown from *a* to *b*?
- Kirchoff's Loop Rule was: $\mathcal{E} - iR - L\dfrac{di}{dt} = 0$
- Now it is: $iR + L\dfrac{di}{dt} = 0$



- The decay of the current, then, is given by

$$i = \frac{\mathcal{E}}{R} e^{-Rt/L}$$

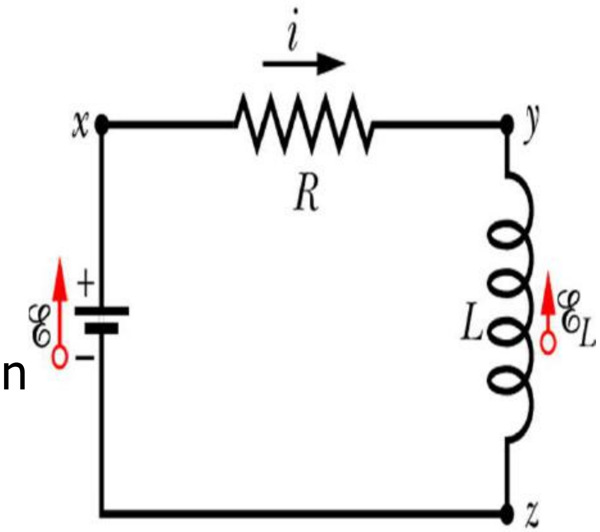
Decay of current



- Voltage across resistor: $V_R = iR = \mathcal{E}\ e^{-Rt/L}$
- Voltage across inductor: $V_L = L\dfrac{di}{dt} = L\dfrac{\mathcal{E}}{R}\dfrac{d}{dt}e^{-Rt/L} = -\mathcal{E}\ e^{-Rt/L}$

Energy Stored in Magnetic Field

- By Kirchoff's Loop Rule, we have $\mathcal{E} = iR + L\dfrac{di}{dt}$



- We can find the power in the circuit by multiplying by i.

$$\mathcal{E}i = i^2R + Li\frac{di}{dt}$$

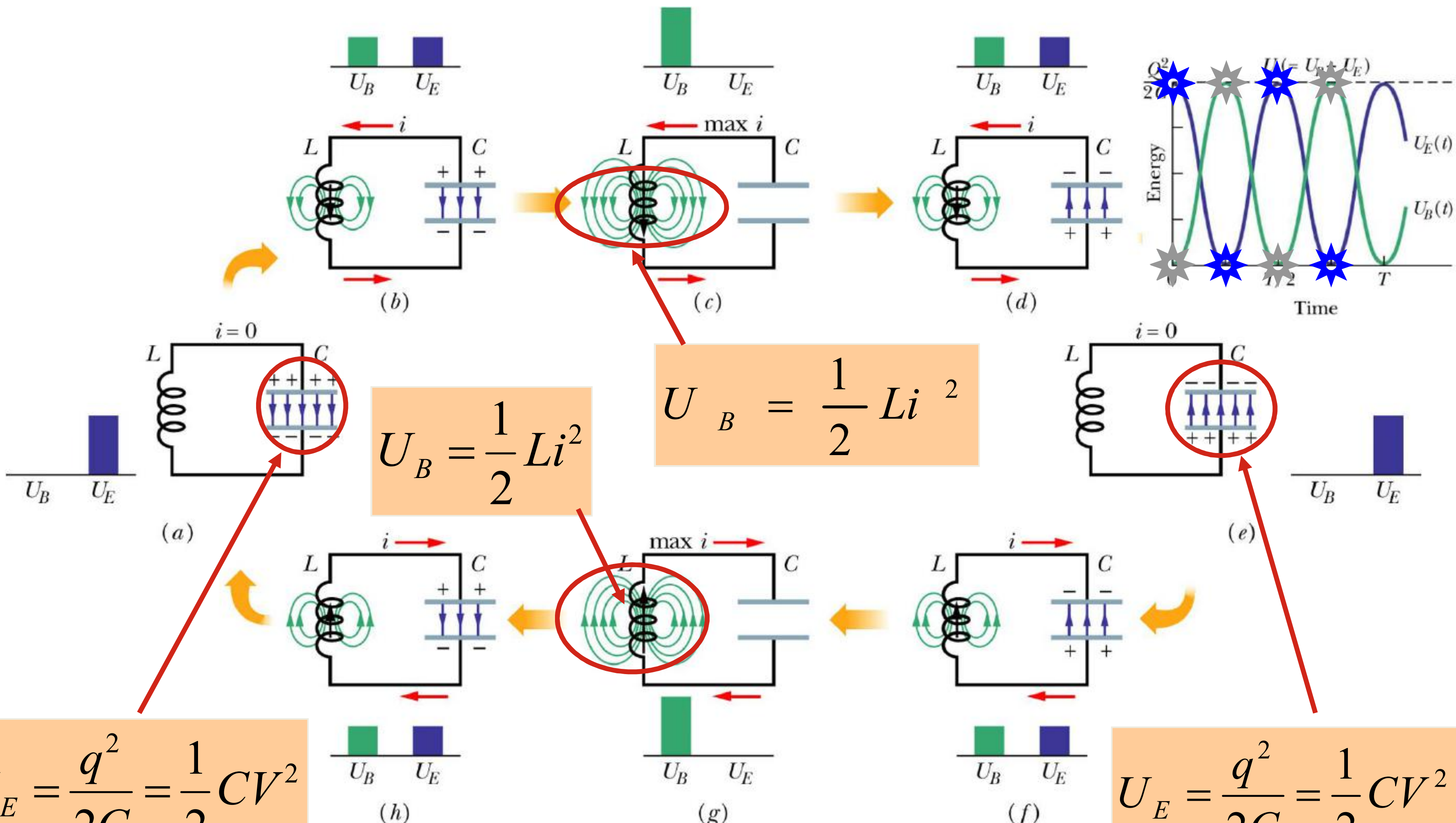
power provided by battery — power dissipated in resistor — power stored in magnetic field

- Power is rate that work is done, i.e. $P = \dfrac{dU_B}{dt} = Li\dfrac{di}{dt}$

- So $dU_B = Li\,di$ after integration $U_B = \dfrac{1}{2}Li^2$ Energy in magnetic field

Recall for electrical energy in a capacitor: $U_E = \dfrac{q^2}{2C} = \dfrac{1}{2}CV^2$

Electromagnetic Oscillations



$$U_B = \frac{1}{2} L i^2$$

$$U_B = \frac{1}{2} L i^2$$

$$U_E = \frac{q^2}{2C} = \frac{1}{2} C V^2$$

$$U_E = \frac{q^2}{2C} = \frac{1}{2} C V^2$$

Derivation of Oscillation Frequency

- We have shown qualitatively that LC circuits act like an oscillator.
- We can discover the frequency of oscillation by looking at the equations governing the total energy.

$$U = U_E + U_B = \frac{q^2}{2C} + \frac{1}{2}Li^2$$

- Since the total energy is constant, the time derivative should be zero:

$$\frac{dU}{dt} = \frac{q}{C}\frac{dq}{dt} + Li\frac{di}{dt} = 0$$

- But $i = \frac{dq}{dt}$ and $\frac{di}{dt} = \frac{d^2q}{dt^2}$, so making these substitutions: $L\frac{d^2q}{dt^2} + \frac{q}{C} = 0$
- This is a second-order, homogeneous differential equation, whose solution is
- i.e. the charge varies according to a cosine wave with amplitude Q and frequency ω. Check by taking $q = Q\cos(\omega t + \phi)$ two time derivatives of charge:

$$\frac{dq}{dt} = -Q\omega\sin(\omega t + \phi)$$

$$\frac{d^2q}{dt^2} = -Q\omega^2\cos(\omega t + \phi)$$

- Plug into original equation:

$$L\frac{d^2q}{dt^2} + \frac{q}{C} = -LQ\omega^2\cos(\omega t + \phi) + \frac{Q}{C}\cos(\omega t + \phi) = 0$$

$$-L\omega^2 + \frac{1}{C} = 0$$

$$\omega = \frac{1}{\sqrt{LC}}$$

Ideal vs. Non-Ideal Oscillation

- In an ideal situation (no resistance in circuit), these oscillations will go on forever.
- In fact, no circuit is ideal, and all have at least a little bit of resistance.
- In that case, the oscillations get smaller with time. They are said to be "damped oscillations."
- This is just like the situation with a pendulum, which is another kind of oscillator.
- There, the energy oscillation is between potential energy and kinetic energy.

Summary

- Inductance (units, henry H) is given by $L = \frac{N\Phi_B}{i}$
- Inductance of a solenoid is: $L = \frac{\mu_0 N^2 A}{l}$ (depends only on geometry)
- EMF, in terms of inductance, is: $\varepsilon_L = -N\frac{d\Phi_B}{dt} = -L\frac{di}{dt}$
- RL circuits

Rise of current	Decay of current	Inductor time constant
$i = \frac{\varepsilon}{R}(1 - e^{-Rt/L})$	$i = \frac{\varepsilon}{R}e^{-Rt/L}$	$\tau_L = \frac{L}{R}$

- Energy in inductor: $U_B = \frac{1}{2}Li^2$ Energy in magnetic field $U = U_E + U_B = \frac{q^2}{2C} + \frac{1}{2}Li^2$
- LC circuits: total electric + magnetic energy is conserved

Charge equation	Current equation	Oscillation frequency
$q = Q\cos(\omega t + \phi)$	$i = -Q\omega\sin(\omega t + \phi)$	$\omega = \frac{1}{\sqrt{LC}}$

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Maxwell’s Laws

Maxwell’s Laws

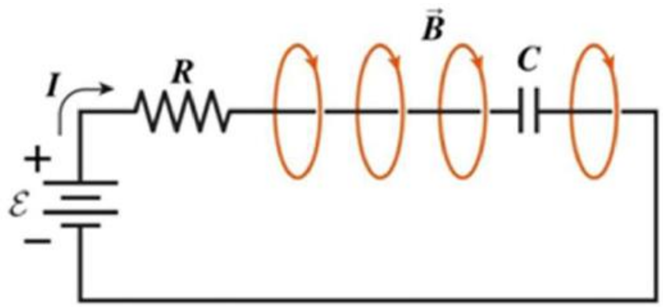
- The four laws of electromagnetism
- Plane electromagnetic wave
- Gauss’s laws
- Faraday’s law
- Ampere-Maxwell law
- Polarization
- The electromagnetic spectrum
- Producing electromagnetic waves
- Energy & momentum in electromagnetic waves
- Momentum & Radiation Pressure

The Four Laws of Electromagnetism

Law	Mathematical Statement	Physical Meaning
Gauss for **E**	$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_0}$	How *q* produces **E**; **E** lines begin & end on q's.
Gauss for **B**	$\oint \mathbf{B} \cdot d\mathbf{A} = 0$	No magnetic monopole; **B** lines form loops.
Faraday	$\oint \mathbf{E} \cdot d\mathbf{r} = -\frac{d\Phi_B}{dt}$	Changing Φ_B gives emf.
Ampere (Steady *I* only)	$\oint \mathbf{B} \cdot d\mathbf{r} = \mu_0 I$	Moving charges give **B**.

Note **E-B** asymmetry between the Faraday & Ampere laws.

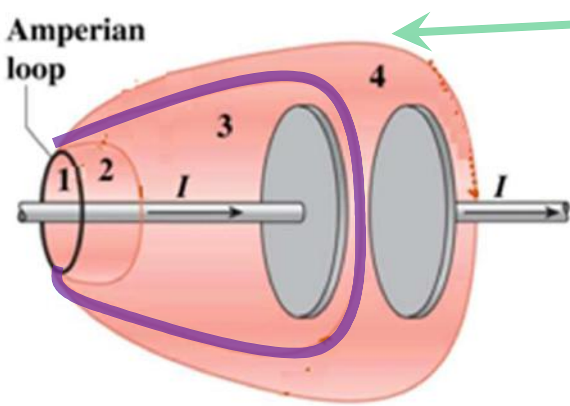
Ambiguity in Ampere's Law



B in a *RC* circuit.

Ampere's law: $\oint_C \mathbf{B} \cdot d\mathbf{r} = \mu_0 \, I$

I is current through any open surface *S* bounded by *C*.



Current flows through surfaces 1,2,& 4.
But not **3**.
$\rightarrow$ Ampere's law fails (for non-steady current).

Maxwell's modification:

$$\oint_C \mathbf{B} \cdot d\mathbf{r} = \mu_0 \, I + \mu_0 \, \varepsilon_0 \frac{d\Phi_E}{dt}$$

$$\varepsilon_0 \frac{d\Phi_E}{dt} = \text{Displacement current}$$

Changing Φ_E gives *I*, which in turn gives **B**.

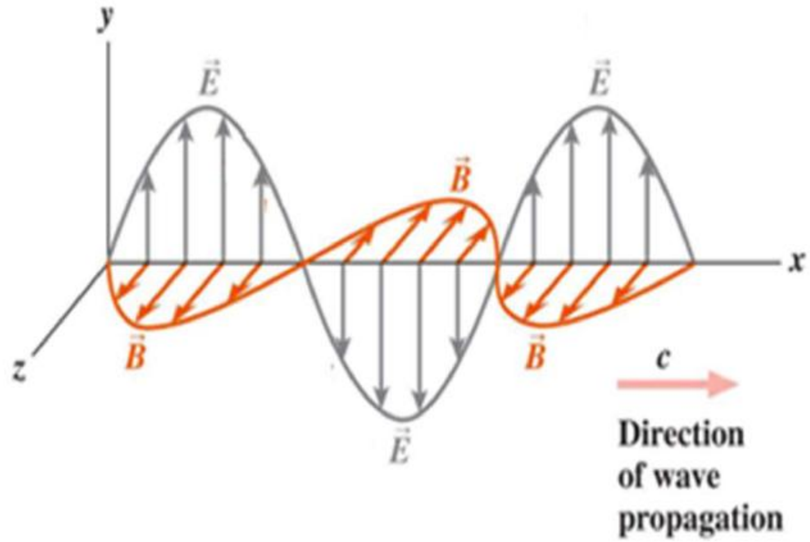
Maxwell's Equations

Law	Mathematical Statement	Physical Meaning
Gauss for **E**	$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_0}$	How *q* produces **E**; **E** lines begin & end on q's.
Gauss for **B**	$\oint \mathbf{B} \cdot d\mathbf{A} = 0$	No magnetic monopole; **B** lines form loops.
Faraday	$\oint \mathbf{E} \cdot d\mathbf{r} = -\frac{d\Phi_B}{dt}$	Changing Φ_B gives emf.
Ampere-Maxwell	$\oint \mathbf{B} \cdot d\mathbf{r} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$	Moving charges & changing Φ_E give **B**.

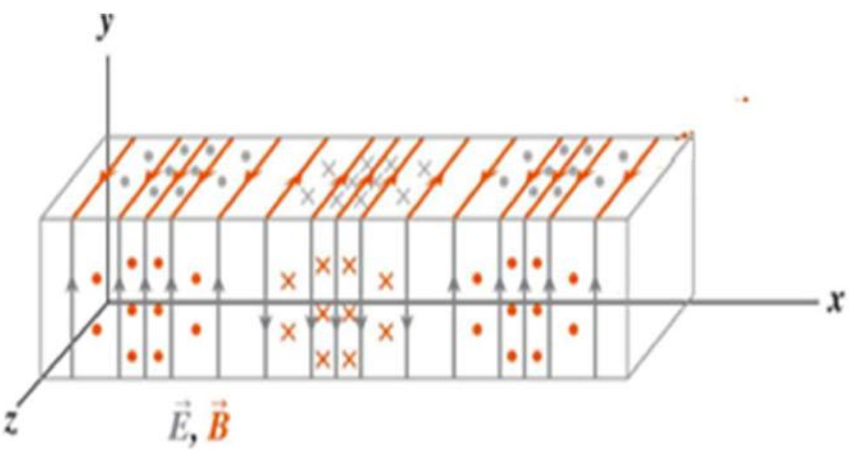
Ampere-Maxwel in vacuum $\oint \mathbf{B} \cdot d\mathbf{r} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$

Plane Electromagnetic Wave

- Faraday's law: Changing B gives E
- Ampere-Maxwell's law: Changing E gives B
- EM wave in vacuum is transverse: $\mathbf{E} \perp \mathbf{B} \perp \mathbf{k}$ (direction of propagation).



$\hat{\mathbf{k}} \parallel \mathbf{E}\times\mathbf{B}$ Right-hand rule



Sinusoidal plane waves going in *x*-direction:

$$\mathbf{E}(x,t) = E_y(x,t)\,\hat{\mathbf{j}} = E_p \sin(kx - \omega t)\,\hat{\mathbf{j}}$$

$$\mathbf{B}(x,t) = B_z(x,t)\,\hat{\mathbf{k}} = B_p \sin(kx - \omega t)\,\hat{\mathbf{k}}$$

Gauss's Laws

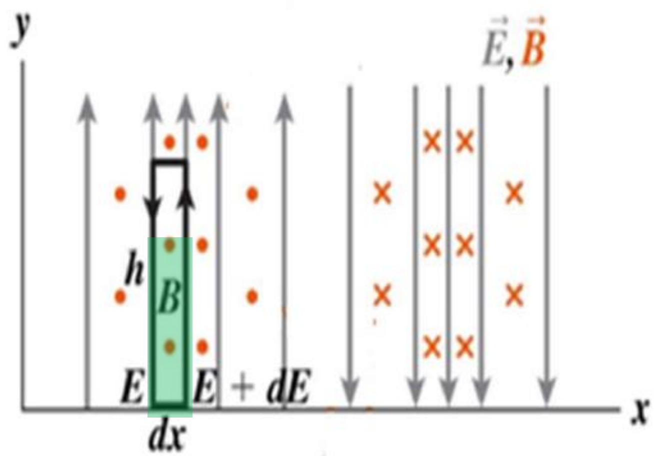
Plane wave :

$$\mathbf{E}(x,t) = E_y(x,t)\,\hat{\mathbf{j}} \quad = E_p \sin(kx - \omega t)\,\hat{\mathbf{j}}$$

$$\mathbf{B}(x,t) = B_z(x,t)\,\hat{\mathbf{k}} \quad = B_p \sin(kx - \omega t)\,\hat{\mathbf{k}}$$

Both **E** & **B** field lines are straight lines, so their flux over any closed surfaces vanish identically. Hence the Gauss's laws are satisfied.

Faraday's Law



$$\oint \mathbf{E} \cdot d\mathbf{r} = -\frac{d\,\Phi_B}{dt} = \int \nabla \times \mathbf{E} \cdot d\mathbf{A} = -\int \frac{\partial\,\mathbf{B}}{\partial\,t} \cdot d\mathbf{A}$$

For loop at *x* of height *h* & width *dx* :

$$\oint \mathbf{E} \cdot d\mathbf{r} = -E(x,t)\,h + E(x+dx,t)\,h \qquad \mathbf{E} = E\,\hat{\mathbf{y}}$$

$$\approx -E(x,t)\,h + \left[E(x,t) + \frac{\partial E}{\partial x}dx\right]h = \left(\frac{\partial E}{\partial x}dx\right)h$$

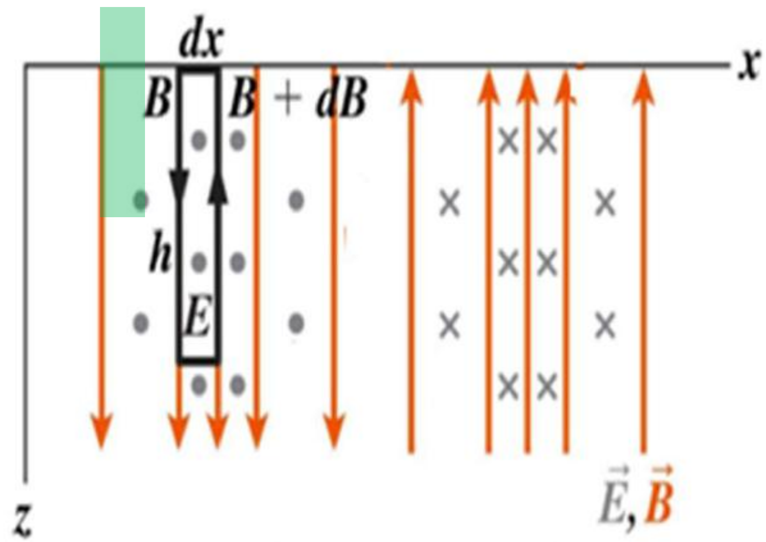
$$\nabla \times \mathbf{V} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial\,x} & \frac{\partial}{\partial\,y} & \frac{\partial}{\partial\,z} \\ V_x & V_y & V_z \end{vmatrix}$$

$$\Phi_B \approx B\;h\;dx \qquad \frac{d\Phi_B}{dt} \approx \frac{\partial B}{\partial t}\,h\;dx \qquad \mathbf{B} = B\;\hat{\mathbf{z}}$$

Faraday's Law : $\dfrac{\partial E}{\partial x} = -\dfrac{\partial B}{\partial t}$ $\qquad \dfrac{\partial E_y}{\partial x} = -\dfrac{\partial B_z}{\partial t}$

Faraday's law expressed as a differential eq : $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$

Ampere-Maxwell Law



$$\oint_C \mathbf{B} \cdot d\mathbf{r} = \mu_0 \, \varepsilon_0 \, \frac{d\Phi_E}{dt} \qquad I = 0$$

For loop at *x* of height *h* & width *dx* :

$$\oint_C \mathbf{B} \cdot d\mathbf{r} = B(x)h - B(x+dx)\,h \qquad \mathbf{B} = B\,\hat{\mathbf{z}}$$

$$\approx B(x,t)\,h - \left[B(x,t) + \frac{\partial B}{\partial x} dx \right] h \;= -\left(\frac{\partial B}{\partial x} dx \right) h$$

$$\Phi_E \approx E\; h\; dx \qquad \frac{d\Phi_E}{dt} \approx \frac{\partial E}{\partial t} h\; dx \qquad \mathbf{E} = E\;\hat{\mathbf{y}}$$

Ampere-Maxwell Law : $$-\frac{\partial B}{\partial x} = \mu_0 \, \varepsilon_0 \, \frac{\partial E}{\partial t} \qquad -\frac{\partial B_z}{\partial x} = \mu_0 \varepsilon_0 \frac{\partial E_y}{\partial t}$$

Ampere-Maxwell law expressed as a differential eq : $$\nabla \times \mathbf{B} = \mu_0 \, \varepsilon_0 \, \frac{\partial \mathbf{E}}{\partial t}$$ in vacuum

Conditions on Wave Fields

For **E** = $E(x,t)$ **j** & **B** = $B(x,t)$ **k**,

Faraday's Law : $$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$\nabla \times \mathbf{V} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ V_x & V_y & V_z \end{vmatrix}$$

Ampere-Maxwell Law : $$-\frac{\partial B}{\partial x} = \mu_0 \, \varepsilon_0 \, \frac{\partial E}{\partial t}$$

For a plane wave $$\mathbf{E}(x,t) = E_p \sin(kx - \omega t)\,\hat{\mathbf{j}}$$ $$\mathbf{B}(x,t) = B_p \sin(kx - \omega t)\,\hat{\mathbf{k}}$$

Faraday's Law : $$k\,E_p \cos(kx - \omega t) = \omega\,B_p \cos(kx - \omega t) \quad \rightarrow \quad \boxed{k\,E_p = \omega\,B_p}$$

Ampere-Maxwell Law : $$-k\,B_p \cos(kx - \omega t) = -\mu_0\,\varepsilon_0\,\omega\,E_p \cos(kx - \omega t)$$

$$\rightarrow \quad \boxed{k\,B_p = \mu_0\,\varepsilon_0\,\omega\,E_p}$$

Properties of Electromagnetic Waves

$$k\ E_p = \omega\ B_p \qquad k\ B_p = \mu_0\ \varepsilon_0\ \omega\ E_p$$

$$\rightarrow \qquad k^2 = \mu_0\ \varepsilon_0\ \omega^2$$

speed of wave = $\dfrac{\omega}{k} = \dfrac{1}{\sqrt{\mu_0\ \varepsilon_0}} = \dfrac{1}{\sqrt{\left(4\pi \times 10^{-7} N / A^2\right)\left(\dfrac{1}{4\pi \times 9 \times 10^9} C^2 / N \cdot m^2\right)}}$

$= 3 \times 10^8\ m/s$ = speed of light in vacuum = *c*

Maxwell: light is EM wave.

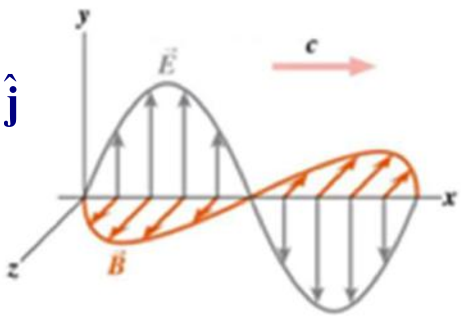
1983: meter is defined so that *c* is exactly 299,792,458 m/s.

Hence, $\varepsilon_0 = 1 / (4\ \pi\ c^2 \times 10^{-7})$ $C^2/N{\cdot}m^2$, where c = 299,792,458.

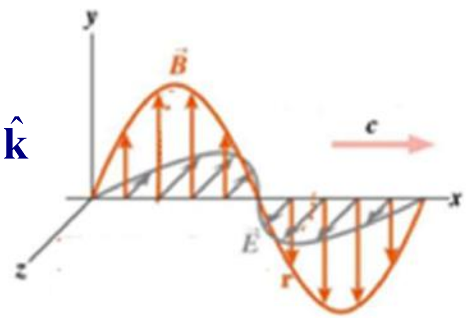
Polarization

Polarization ε // **E**.

$\hat{\boldsymbol{\varepsilon}} = \hat{\mathbf{j}}$



$\hat{\boldsymbol{\varepsilon}} = \hat{\mathbf{k}}$



Radiation from antennas are polarized.

E.g., radio, TV, ….

Light from hot sources are unpolarized.

E.g., sun, light bulb, …

Reflection from surfaces polarizes.
E.g., light reflecting off car hoods is partially polarized in horizontal direction.

Transmission through crystal / some plastics polarizes.

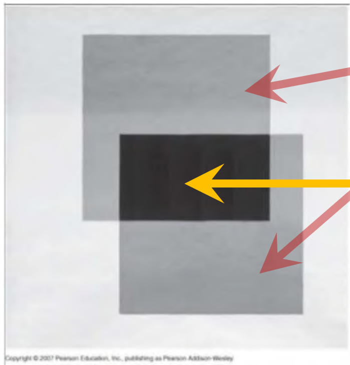
E.g., Polaroid sunglasses, …

Only component of **E** // preferred direction **e** is transmitted.

$$\mathbf{E}_{trans} = \left(\mathbf{E}_{inc} \cdot \hat{\boldsymbol{\varepsilon}}\right) \hat{\boldsymbol{\varepsilon}} = E_{inc} \cos\theta \;\; \hat{\boldsymbol{\varepsilon}}$$

θ = angle between $\mathbf{E}_{inc}$ & ε.

Law of Malus : $\left|\mathbf{E}_{trans}\right|^2 = \left|\mathbf{E}_{inc}\right|^2 \cos^2\theta$ or $S_{trans} = S_{inc} \cos^2\theta$



2 polarizers with mutually perpendicular transmission axes.

No light gets through where they overlap.

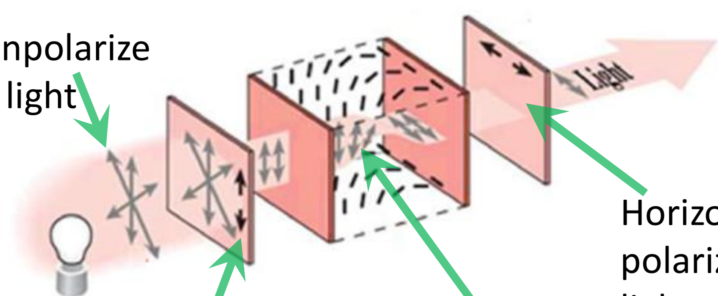
$$S = S_0 \cos^2 \theta$$

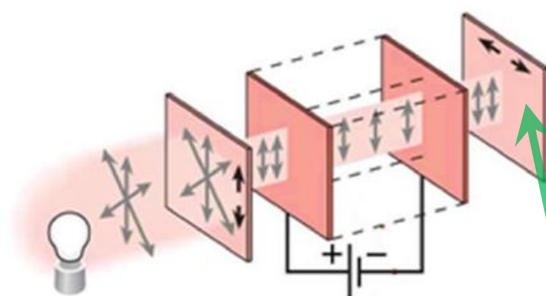
Polarization of EM wave gives info about its source & the medium it passes through.

Applications: astronomy, geological survey, material stress analysis, …

Liquid crystal display (LCD)

Unpolarized light





Horizontal polarizer passes light.

Horizontal polarizer blocks light.

Applied V aligns molecules; polarization not rotated.

Vertical polarizer passes only E_v .

LC molecules rotate polarization to horizontal direction.

Making the Connection

How does the intensity of light emerging from this polarizer "sandwich" compare with the intensity of the incident unpolarized light?

$$S_{trans} = S_{inc} \cos^2 \theta$$

Intensity of light emerging from 1st polarizer :

$$S_1 = S_{inc} \frac{1}{2\pi} \int_0^{2\pi} \cos^2 \theta \, d\theta = \frac{1}{2} S_{inc}$$

(polarized along axis of 1st polarizer)

Intensity of light emerging from middle polarizer :

$$S_2 = S_1 \cos^2 45° = \frac{1}{2} S_1 = \frac{1}{4} S_{inc}$$

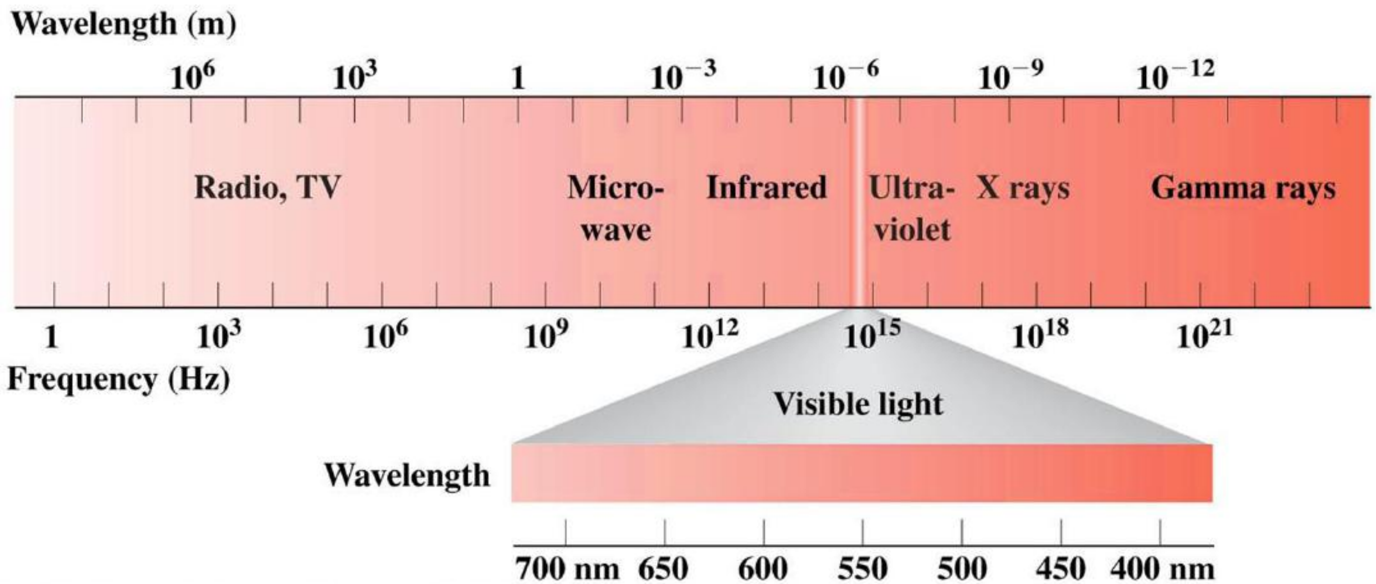
(polarized along axis of middle polarizer.)

Intensity of light emerging from ensemble :

$$S_3 = S_2 \cos^2 45° = \frac{1}{2} S_2 = \frac{1}{8} S_{inc}$$

(polarized along axis of 3rd polarizer.)

The Electromagnetic Spectrum



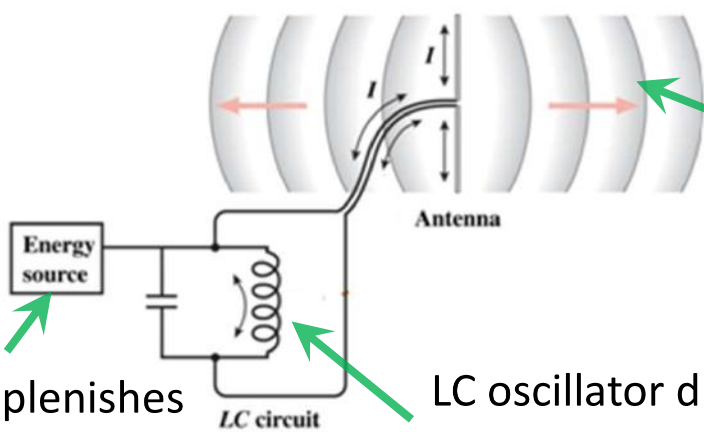
Earth's atmosphere:

Transparent to most radio, visible light. Opaque to most IR, upper UV, X-rays, γ rays. UV is absorbed by ozone layer, and IR by green house gases.

Producing Electromagnetic Waves

- Any changing **E** or **B** will create EM waves.
- Any accelerated charge produces radiation.
- Radio transmitter: e's oscillate in antenna driven by *LC* circuit.
- X-ray tube: accelerated e's slammed into target.
- MW magnetron tube: e's circle in **B**.

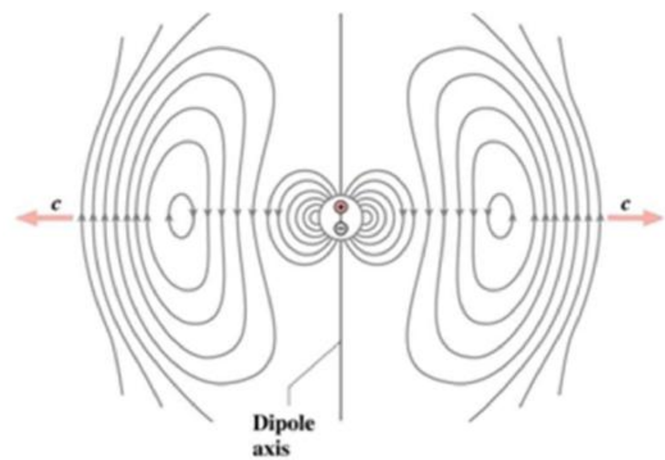
EM wave : $f = f$ of q motion. Most efficient: $\lambda \sim$ dimension of emitter / receiver



Outgoi ng EM waves

Source replenishes radiated energy

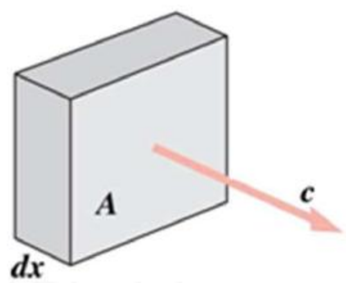
LC oscillator drives *I* in antenna



Waves emit / receive ⊥ axis of dipole.

Energy & Momentum in Electromagnetic Waves

Consider box of thickness *dx*,
& face *A* $\perp$ **k** of EM wave.



Energy densities: $u_E = \frac{1}{2}\varepsilon_0\,\mathbf{E}^2 \qquad u_B = \frac{1}{2\,\mu_0}\mathbf{B}^2$

Energy in box:

$$dU = \left(u_E + u_B\right) A\,dx \quad = \frac{1}{2}\left(\varepsilon_0\,\mathbf{E}^2 + \frac{1}{\mu_0}\mathbf{B}^2\right) A\,dx$$

Rate of energy moving through box: $\frac{dU}{dt} = \frac{d\,U}{dx/c} \quad = \frac{1}{2}\left(\varepsilon_0\,\mathbf{E}^2 + \frac{1}{\mu_0}\mathbf{B}^2\right) A\,c$

Intensity S = rate of energy flow per unit area $\quad S = \frac{1}{2}\left(\varepsilon_0\,\mathbf{E}^2 + \frac{1}{\mu_0}\mathbf{B}^2\right) c$

Plane waves:

$$B = \frac{E}{c} \qquad \to \qquad S = \frac{1}{2}\left(c\,\varepsilon_0 + \frac{1}{\mu_0\,c}\right) E\,B\,c \quad = \frac{1}{2\mu_0}\left(c^2\,\varepsilon_0\mu_0 + 1\right) E\;B \quad = \frac{1}{\mu_0}E\;B$$

Plane waves: $S = \frac{1}{\mu_0} E \ B$

In general: $\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$ Poynting vector

Average intensity for plane waves :

$$\overline{S} = \frac{1}{\mu_0} \overline{E \ B} = \frac{1}{\mu_0} \frac{E_{pk} \ B_{pk}}{2}$$

E, **B** in phase

$$= \frac{1}{\mu_0} \frac{E_{pk}^2}{2 \ c} = \frac{1}{\mu_0} c \frac{B_{pk}^2}{2}$$

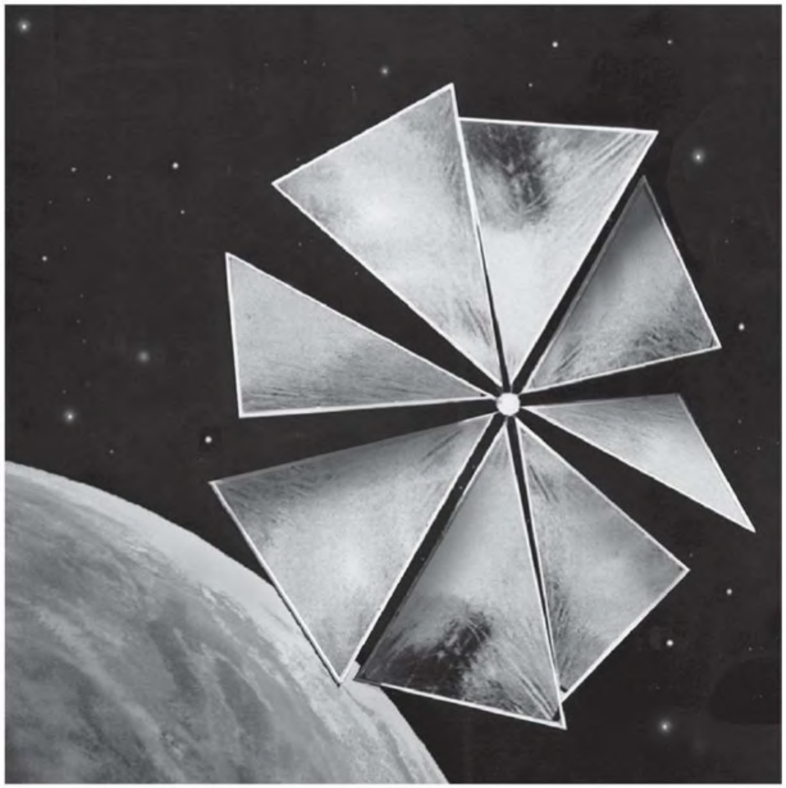
Waves from Localized Sources

Afar from localized source, wave is spherical : $S = \frac{P}{4\pi \ r^2}$

$S \propto E^2 , B^2 \quad \rightarrow \quad E , B \ \propto \frac{1}{r}$ Intensity = power / area

$\therefore$ wave fields dominates static fields away from the sources.

Momentum & Radiation Pressure



Cosmos 1, a solar light-sailing spacecraft, failed at launch in 2005.

Maxwell :

$$\mathbf{p}_{rad} = \frac{1}{c} U \, \hat{\mathbf{S}}$$

radiation momentum

$$\mathbf{P}_{rad} = \frac{1}{c} \mathbf{S}$$

radiation pressure on absorbing surface

$$\mathbf{P}_{rad} = 2 \frac{1}{c} \mathbf{S}$$

radiation pressure on reflecting surface

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Waves & Mechanical Wave

Waves & Mechanical Wave

- About Wave
- Mechanical Wave
- Wave Characteristics
- Harmonic Wave
- Reflection
- Refraction
- Interference
- Diffraction
- Standing Wave
- Resonance

About Waves

- Definition
  - rhythmic disturbances that carry energy through matter or space

- Medium
  - material through which a wave transfers energy
  - solid, liquid, gas, or combination
  - electromagnetic waves don't need a medium (e.g. visible light)

- Interaction
  - When a wave meets an object or another wave.
  - When a wave passes into another medium
  - Examples: reflection, diffraction, refraction, interference, resonance

Types of Waves

- A *mechanical wave* is just a disturbance that propagate through a medium. The *medium* could be air, water, a spring, the Earth, or even people. A medium is any material through which a wave travels. Mechanical wave examples: sound, water waves, a pulse traveling on a spring, earthquakes, a "people wave" in a football stadium.
- An *electromagnetic wave* is simply light of a visible or invisible wavelength. Oscillating intertwined electric and magnetic fields comprise light. Light can travel without medium—super, duper fast.
- A *matter wave* is a term used to describe particles like electrons that display wavelike properties. It is an important concept in quantum mechanics.
- A *gravity wave* is a ripple in the "fabric of space time" itself. They are predicted by Einstein's theory of relativity, but they're very difficult to detect.

Mechanical Waves

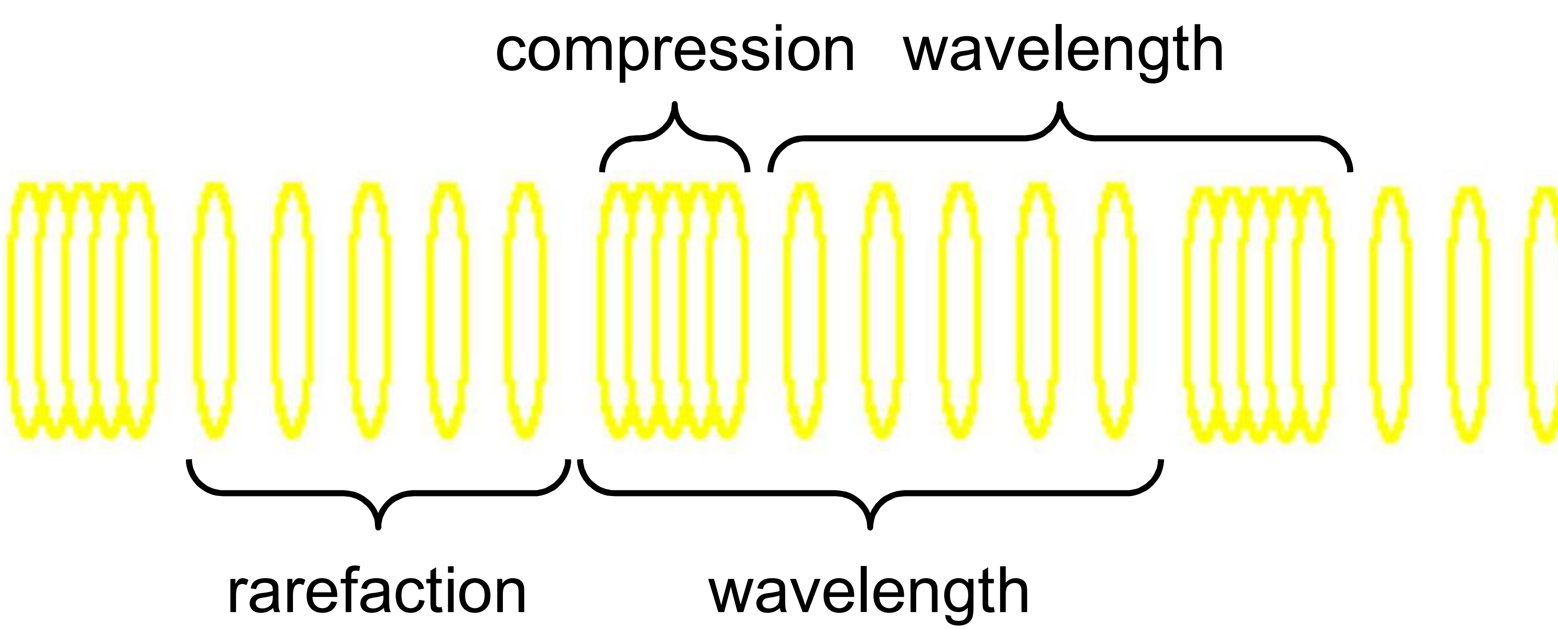
Mechanical waves require a physical medium. The particles in the medium can move in two different ways: either perpendicular or parallel to direction of the wave itself.

Longitudinal	$\leftrightarrow$	Parallel
Transverse	$\leftrightarrow$	Perpendicular
Surface	$\leftrightarrow$	Combo

- In a *longitudinal* wave, the particles in the medium move parallel to the direction of the wave.
- In a *transverse* wave, the particles in the medium move perpendicular to the direction of the wave.
- A *surface* wave is often a combination of the two. Particles typically move in circular or elliptical paths at the surface of a medium.

Longitudinal Waves

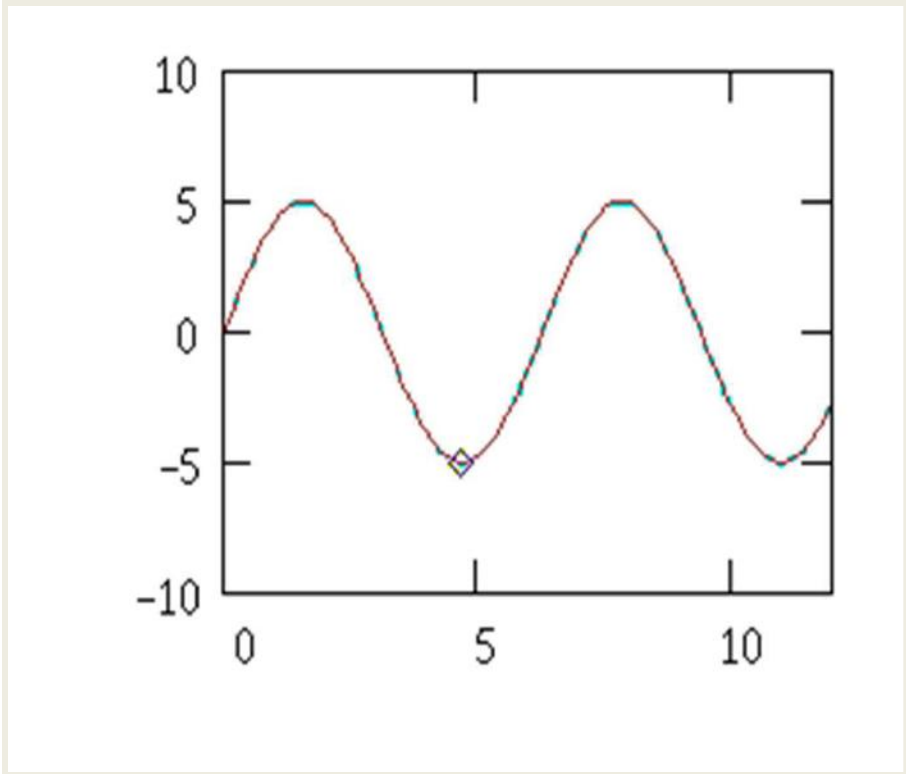
- **Longitudinal Waves** (a.k.a. compressional waves) medium moves in the same direction as the wave's motion. Examples: sound waves, springs, slinky



Amount of compression corresponds to amount of energy ≈ AMPLITUDE

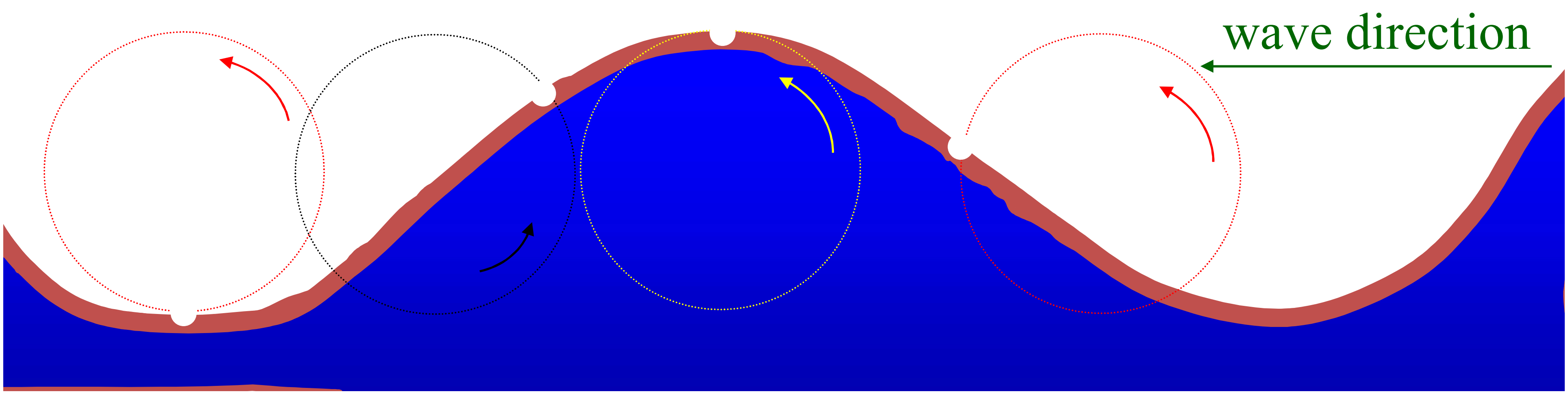
Transverse Waves

- **Transverse Waves**
  - medium vibrates perpendicular to the direction of wave motion
  - Examples: water waves, electromagnetic waves



Surface Waves

Below the surface fluids can typically only transmit longitudinal waves, since the attraction between neighboring molecules is not as strong as in a fluid. At the surface of a lake, water molecules (white dots) move in circular paths, which are partly longitudinal and partly transverse. The molecules are offset, though: when one is at the top of the circle, the one in front of it is near the top. As in any wave, the particles of the medium do not move along with the wave. The water molecules complete a circle each time a crest passes by.



Wave Characteristics

Amplitude (A) – Maximum displacement of particle of the medium from its equilibrium point. The bigger the amplitude, the more energy the wave carries.

Wavelength (λ) – Distance from crest (max positive displacement) to crest; same as distance from trough (max negative displacement) to trough.

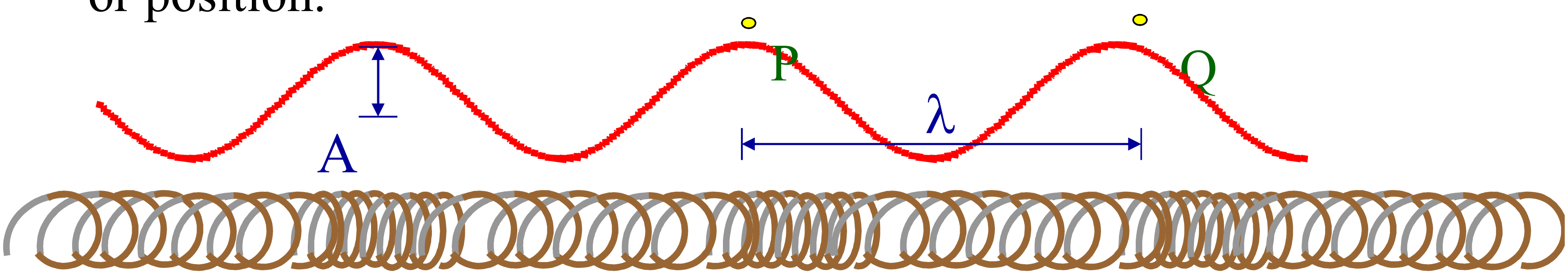
Period (T) – Time it takes consecutive crests (or troughs) to pass a given point, i.e., the time required for one full cycle of the wave to pass by. Period is the reciprocal of frequency: $T = 1 / f$.

Frequency (f) – The number of cycles passing by in a given time. The SI unit for frequency is the Hertz (Hz), which is one cycle per second.

Wave speed (v) – How fast the wave is moving (the disturbance itself, not how fast the individual particles are moving, which constantly varies). Speed depends on the medium. We'll prove that $v = \lambda f$.

Amplitude & Wavelength

The red transverse wave has the same wavelength as the longitudinal wave in the spring. (P to Q is one full cycle.) Note that where the spring is most compressed, the red wave is at a crest, and where the spring is most stretched (rarified), the red wave is at a trough. The amplitude in the red wave is easy to see. In the longitudinal wave, the amplitude refers to how far a particle on the spring moves to the left or right of its equilibrium point. Often a graph like the red wave is used to represent a longitudinal wave. For sound, the y-axis might be pressure deviation from normal air pressure, and the x-axis might be time or position.



Wave Frequency, Period, Speed

Period (T)= seconds per cycle.

Frequency (f) = cycles per second.

They're reciprocals no matter what unit we use for time.

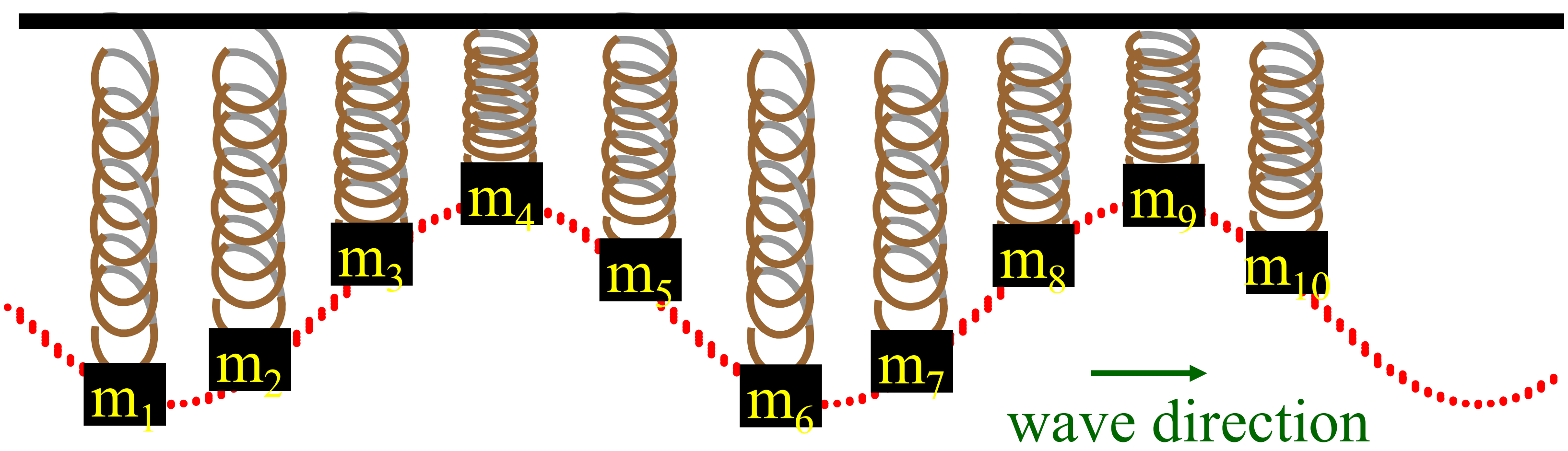
A sound wave that has a frequency of 1,000 Hz has a period of 1 / 1,000 of a second. This means that 1,000 high pressure fronts are moving through the air and hitting your eardrum each second.

Wave Speed $v = \lambda f$ where $f = 1 / T$

λ = Wavelength

Harmonic Waves

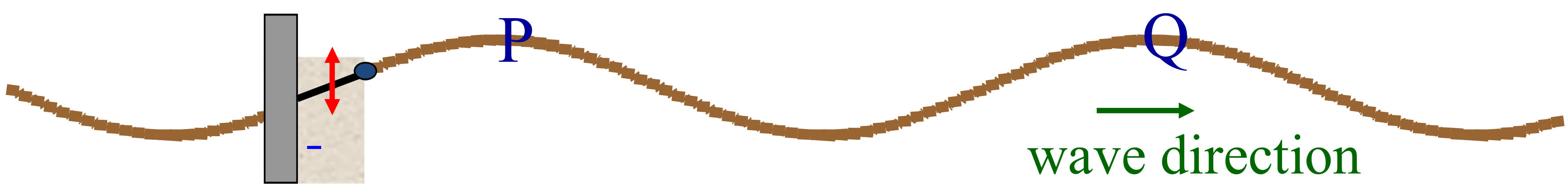
If the masses are set to bobbing at staggered time intervals, a snapshot of the masses forms a transverse wave. Each mass undergoes simple harmonic motion, and the period of each is the same. If the release of the masses is timed so that the masses form a sinusoid at each point in time, the wave is called harmonic. Right now, m_4 is peaking. A little later m_4 will be lower and m_3 will be peaking. The masses (the particles of the medium) bob up and down but do not move horizontally, but the wave does move horizontally.



Making a Harmonic Wave

A generator attached to a rope moves up and down in simple harmonic motion. This generates a harmonic wave in the rope. Each little piece of rope moves vertically just like the masses on the last slide. Only the wave itself moves horizontally. The time it takes the wave to move from P to Q is the period of the wave, T. The distance from P to Q is the wavelength, λ. So, the wave speed is given by: $v = \lambda / T = \lambda f$ (since frequency and period are reciprocals).

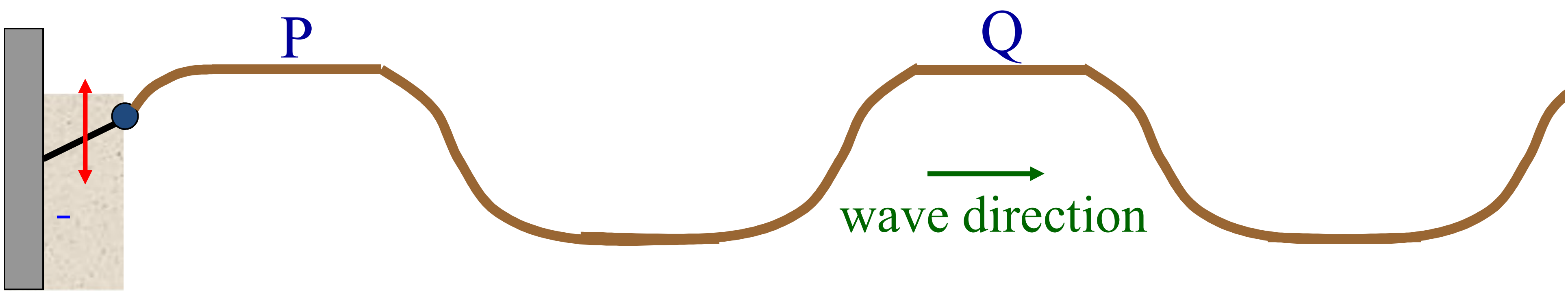
Since the generator moves vertically in SHM, the vertical position of the black doo-jobber is given by $y(t) = A \cos \omega t$. The period is given by $T = 2\pi / \omega$. This is also the period of the wave.



Making a Non-harmonic Wave

If it does not move in SHM, the wave it generates will not be harmonic. As long as the generator has some sort of periodic motion, the wave generated will have a well defined period and wavelength. Here the generator pauses at the high and low points, causing the wave to flatten.

If the wave had moved at a constant speed and changed direction instantly, a saw-tooth wave would have been the result. Sound is not a transverse wave, but a graph of pressure vs. time as a sound waves pass by would look like a very few simple sinusoid in the case of a pure tone. It would be a very complicated wave if the sound is a musical instrument of someone's voice.



Transmission

Let's look at 4 different scenarios of a waves traveling along a rope. The link below has an animation of each.

1. Hard boundary (fixed end): Reflected wave is inverted.
2. Soft boundary (free end): Reflected wave is upright.
3. Light rope to heavy rope: Reflected wave is faster and wider than transmitted wave. Transmitted wave is upright, but reflected wave is inverted (since to the thin rope, the thick rope is like a hard boundary).
4. Heavy rope to light rope: Transmitted wave is faster, wider, and has a greater amplitude than reflected wave. Both waves are upright. (The transmitted wave is upright this time since, to the thick rope, the thin rope is like a soft boundary).

Wave Speed on a Rope

If a pulse is traveling along a rope to the right at a speed v, from its point of view it's still and the rope is moving to the left at a speed v. As the red segment of rope of length s rounds the turn in the pulse, a centripetal force must act on it. The tension in the rope is F, and the downward components of the tension vectors add to make the centripetal force.

$F_C = m v^2 / r$

$F \sin(\theta / 2) = m v^2 / r$

(since the sine of an angle ≈ the angle itself in radians)

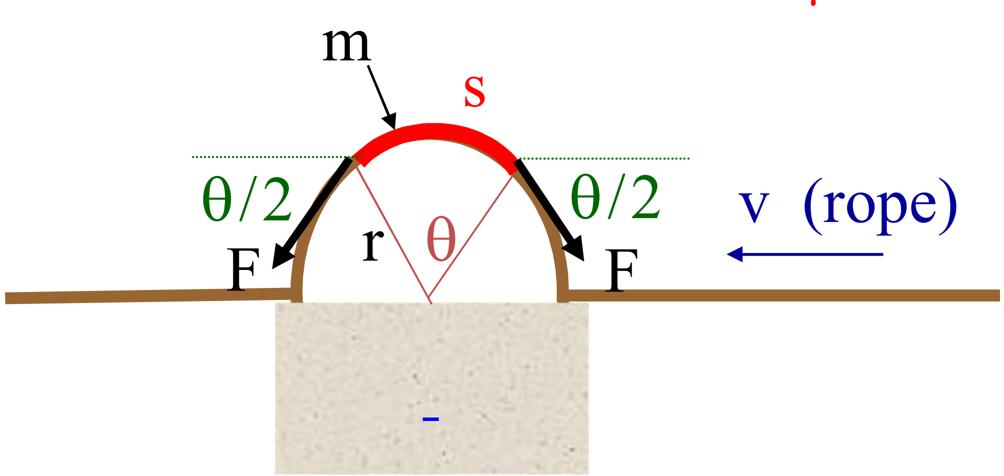
$F \theta = m v^2 / r$

$F r \theta / m = v^2$ *($s = r\theta$)*

$F s / m = v^2$

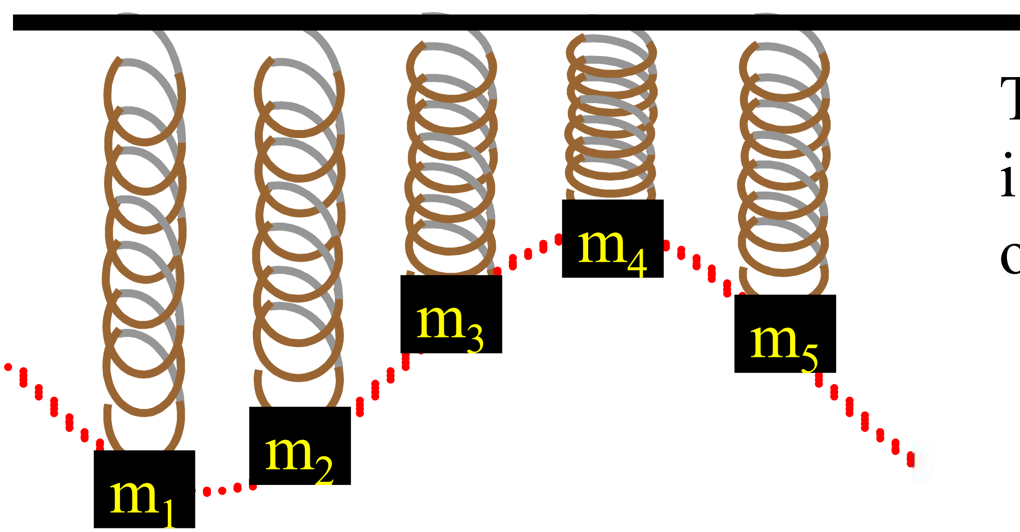
$v^2 = F s/m = F / \mu$

$$v = \sqrt{\frac{F}{\mu}}$$



Amplitude & Energy

The amount of potential energy stored in a spring is given by $U = \frac{1}{2} k x^2$, where k is the spring constant and x is the distance from equilibrium. For m_1 or m_4, $U = \frac{1}{2} k A^2$. The other masses have kinetic energy but less potential. Since energy is conserved, the total energy any mass has is $\frac{1}{2} k A^2$. This shows that energy varies as the square of the amplitude. The constant of proportionality depends on the medium.



The energy carried by a wave is proportional to the square of its amplitude:

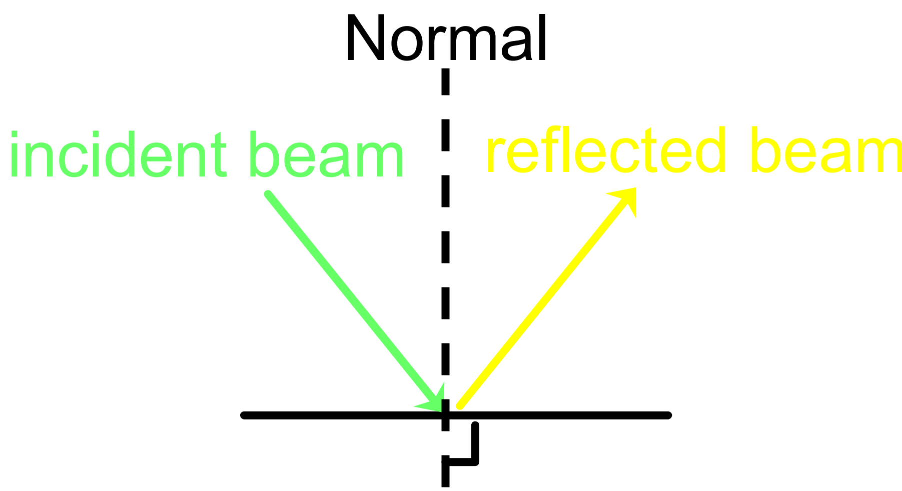
$$E \propto A^2$$

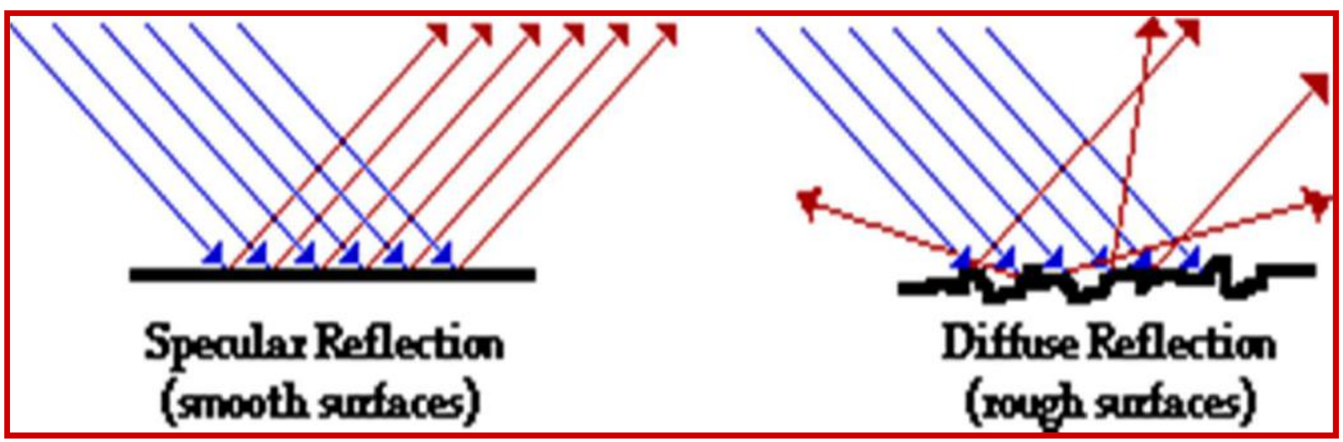
Reflection

Whenever a wave encounters different medium, some of the wave may be reflected back, and some of the wave penetrate and be absorbed or transmitted through the new medium. Light waves reflects off of objects. If it didn't, we would only be able to see objects that emitted their own light. We see the moon because it's reflecting sunlight. Sound waves also reflect off of objects, creating echoes. Water waves, seismic waves, and waves traveling on a rope all can reflect.

Types of Reflection

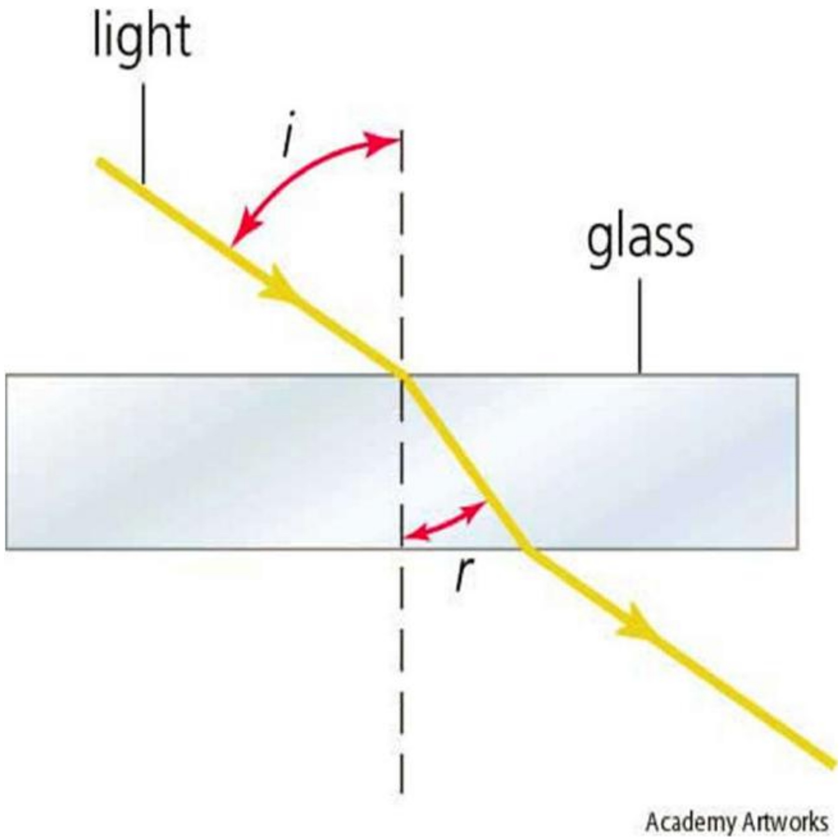
- when a wave strikes an object and bounces off
- When a wave bounces off a surface that is cannot pass through





Refraction

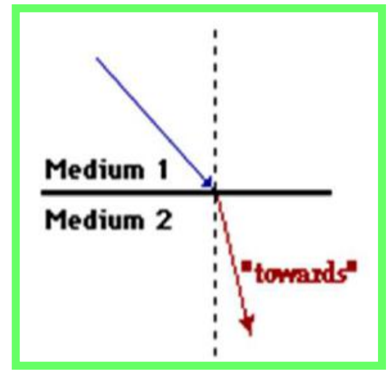
We've seen that when a wave reaches an interface (a change from one medium to another), part of the wave can be transmitted, and part can be reflected back. A rope is a 1-dimensional medium; in a 2-dimensional medium a transmitted wave can change direction. This is refraction—the bending of a wave as it passes from one medium to another.



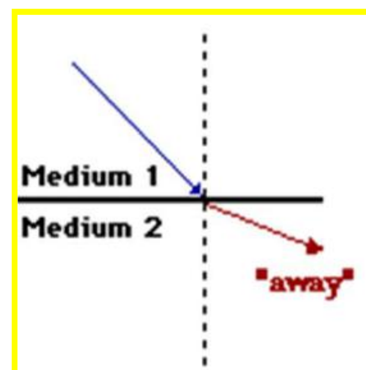
Refraction Bending

- Bending of waves when passing from one medium to another. The bending of a wave as it enters a new medium at an angle.
- caused by a change in speed
  - slower (more dense) $\Rightarrow$ light bends toward the normal
  - faster (less dense) $\Rightarrow$ light bends away from the normal

SLOWER



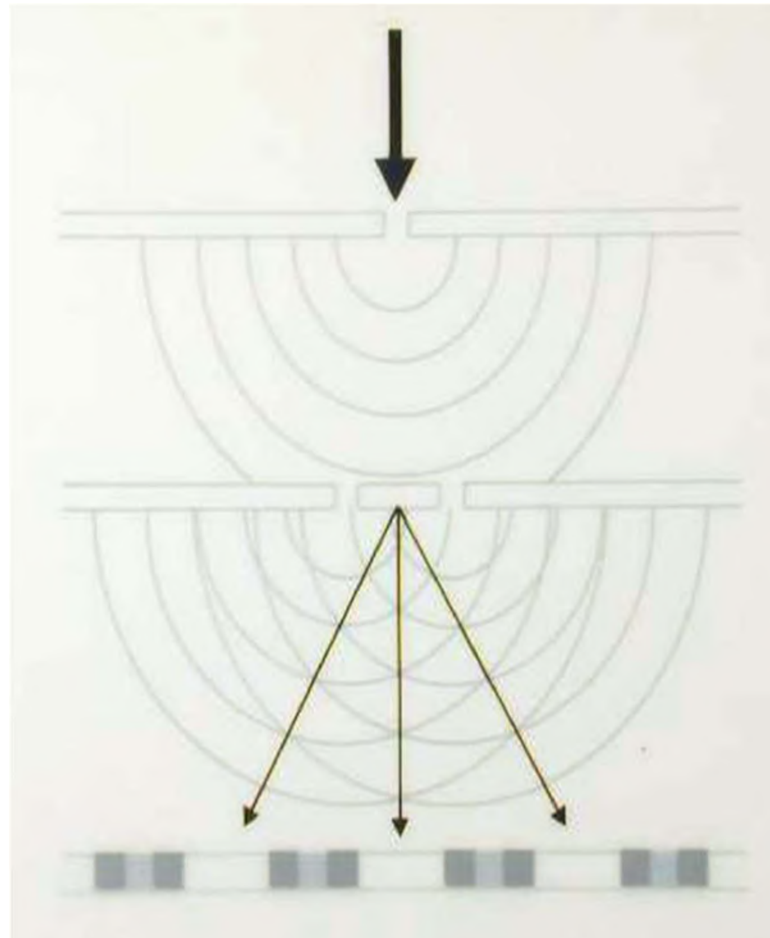
FASTER



Diffraction

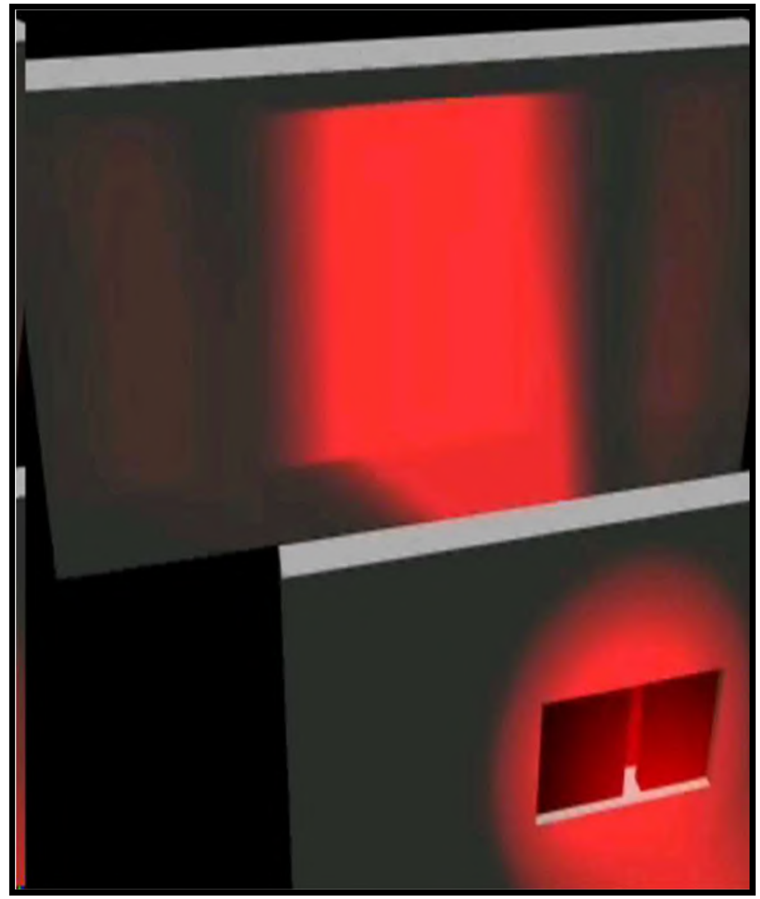
When waves change direction as they pass around a barrier or through a small opening, this is diffraction. Refraction involves a change in wave speed and wavelength; diffraction doesn't.

When waves pass a barrier they curve around it slightly. When they pass through a small opening, they spread out almost as if they had come from a point source. These effects happen for any type of wave: water; sound; light; seismic waves, etc.



Diffraction Bending

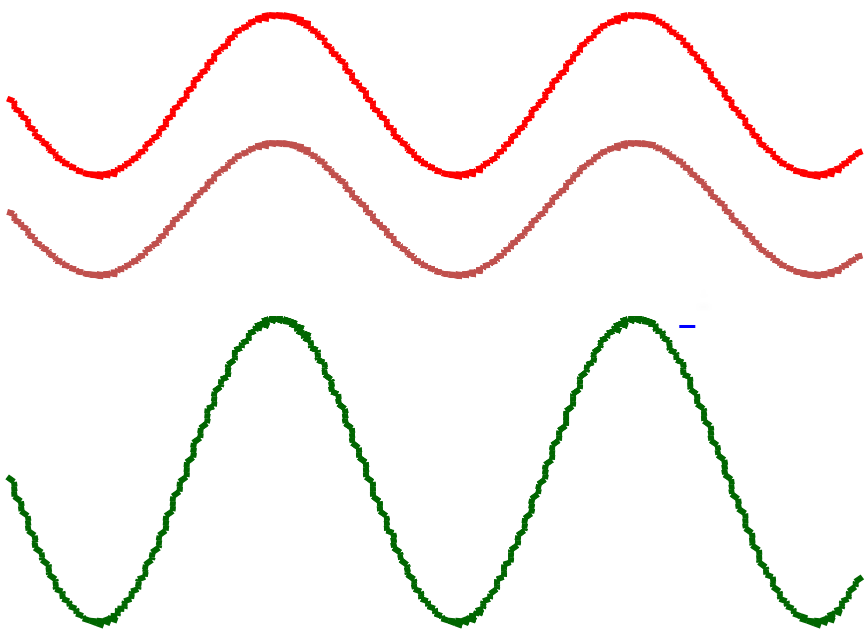
- The bending of a wave as it moves around an obstacle or passes through a narrow opening.
  - bending of waves around a barrier
  - longer wavelengths (red) bend more - opposite of refraction



Interference

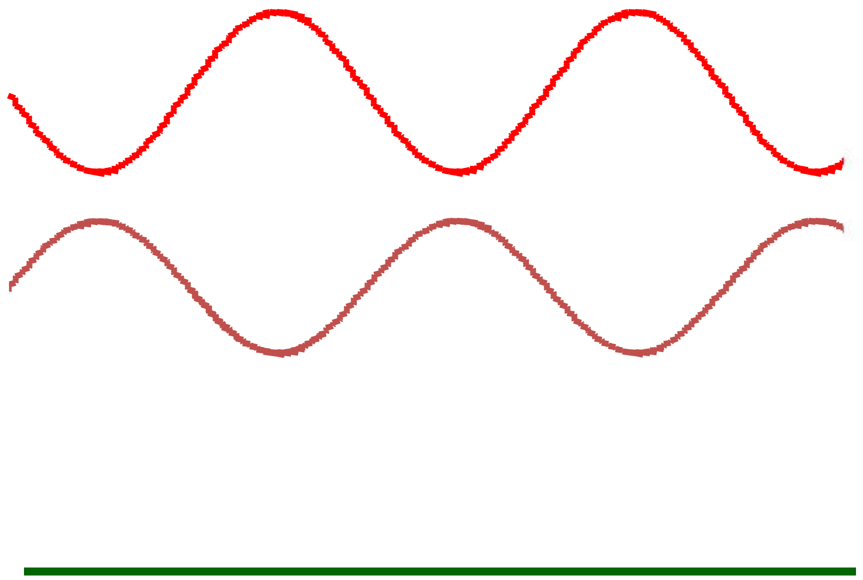
- The interaction of two or more waves (superposition) that combine in a region of overlap.
- Superposition can involve both constructive and destructive interference at the same time (but at different points in the medium). Both are caused by two or more waves interacting, but **Constructive interference** combines the energies of the two waves into a greater amplitude, **Destructive interference** reduces the energies of the two waves into a smaller amplitude.

Constructive & Destructive Interference



Constructive Interference

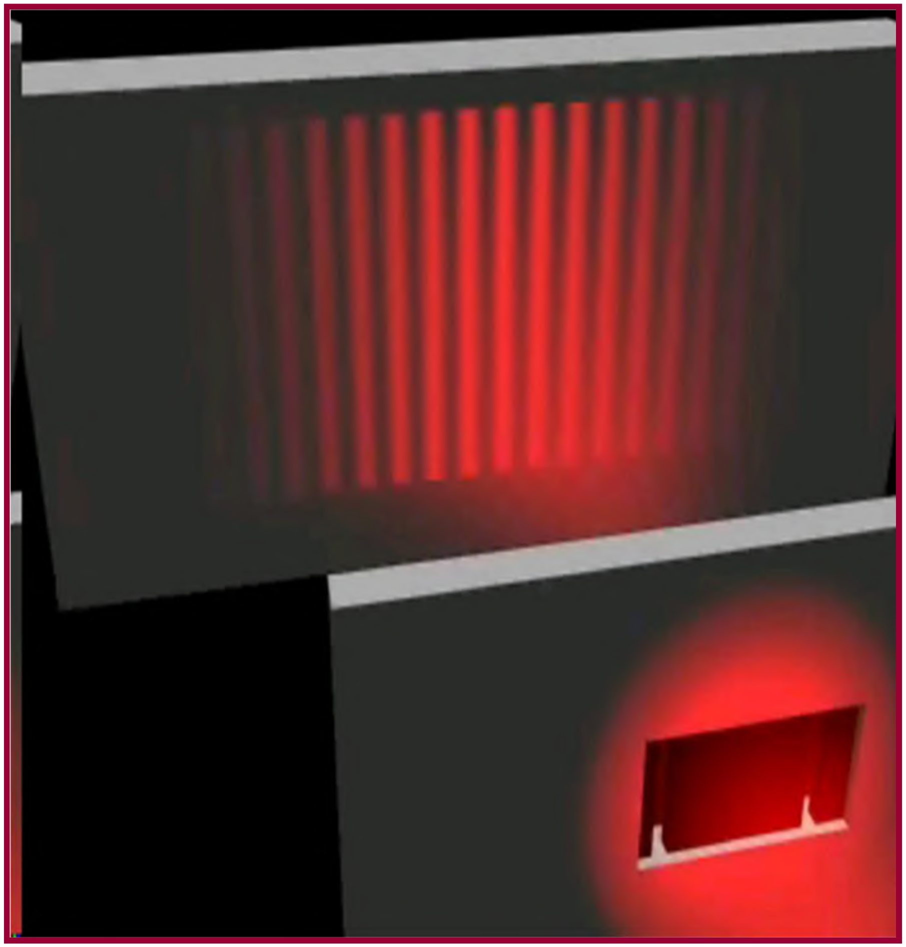
Occurs at a point when two waves have displacements in the same direction. The amplitude of the combo wave is larger either individual wave.



Destructive Interference

Destructive interference occurs at a point when two waves have displacements in opposite directions. The amplitude of the combo wave is smaller than that of the wave biggest wave.

Interference Bending



constructive $\Rightarrow$ brighter light
destructive $\Rightarrow$ dimmer light

Standing Waves

- When waves on a rope hits a fixed end, it reflects and is inverted. This reflected waves then combine with oncoming incident waves. At certain frequencies the resulting superposition yields a standing wave, in which some points on the rope called nodes never move at all, and other points called antinodes have an amplitude twice as big as the original wave.
- A rope of given length can support standing waves of many different frequencies, called harmonics, which are named based on the number of antinodes.

- It is important to understand that a standing is the result of the a wave interfering constructively and destructively with its reflection. Only certain wavelengths will interfere with themselves and produce a standing wave. The wavelengths that work depend on the length of the rope, and we'll learn how to calculate them in the sound unit. (Standing waves are very important in music.)

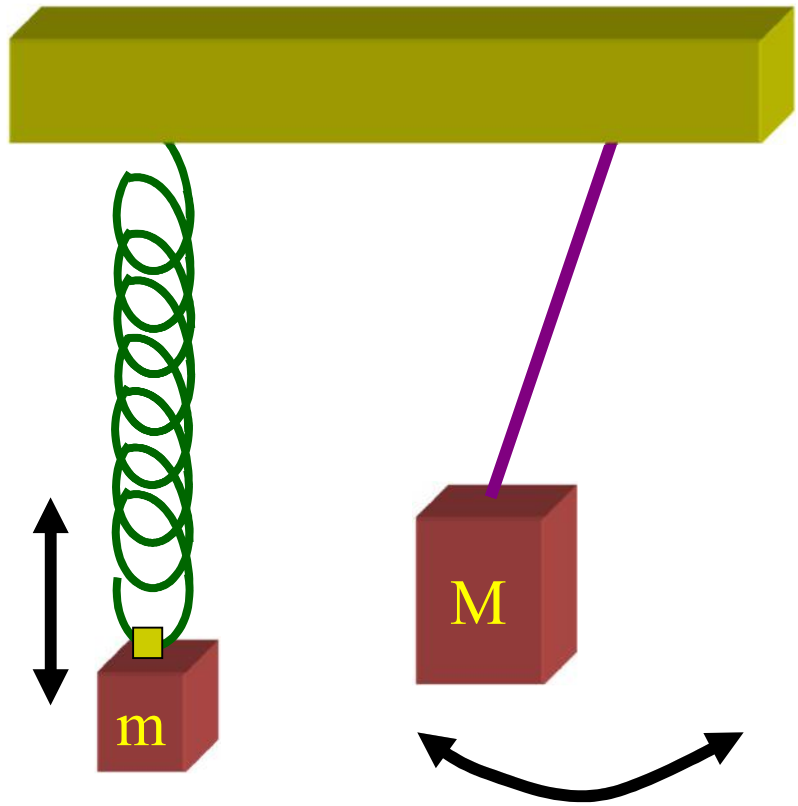
- Wavelengths that don't work result in irregular patterns. A standing wave could be simulated with a series of masses on springs, as long as their amplitudes varied sinusoidal.

Resonance

- Objects that oscillate or vibrate tend to do so at a particular frequency called the natural frequency.
- Resonance involves timing and matching the natural frequency of an oscillator. When it happens, the oscillator's amplitude increases.
- The example is given on the next slide
- Do you know about Tacoma Bridge ?

Resonance Example

A pendulum will swing back and forth at a certain frequency that only depends on its length, and a mass on a spring will bob up in down at a frequency that depends on the mass and the spring constant. If left alone, friction will rob the masses of their energy, and their amplitudes will decay. If a periodic force, like an occasional push, matches the period of one of the masses, this is called resonance, and the mass's amplitude will grow.

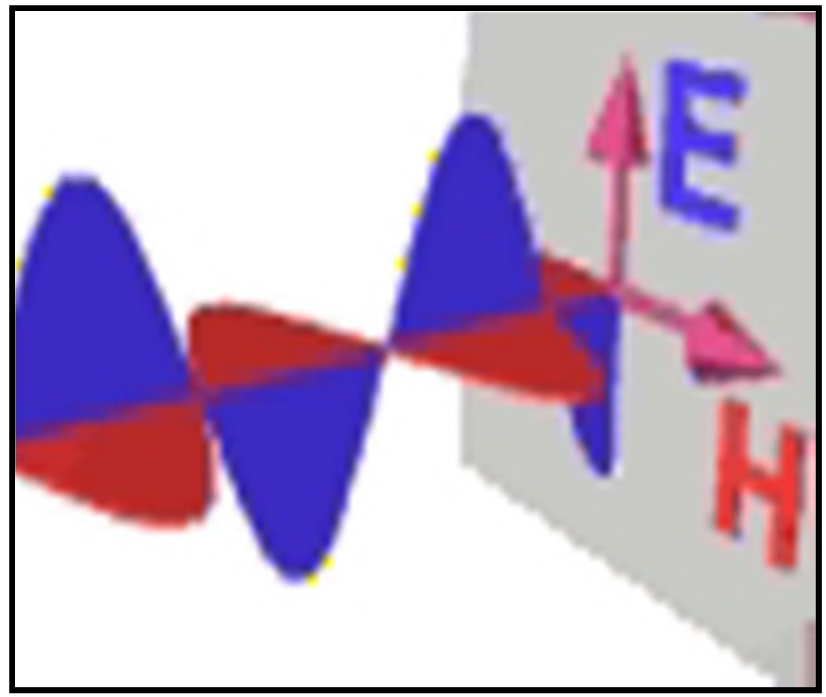


Tacoma Narrows Bridge

Even bridges have resonant (natural) frequencies. The Tacoma Narrows bridge in Washington state collapsed due to the complicated effects of wind. One day in 1940 the wind blew at just the right speed. The wind was like Jane pushing Tarzan, and the bridge was like Tarzan. The bridge twisted and shook violently for about an hour. Eventually, the vibrations caused the by wind grew in amplitude until the bridge was destroyed.

Electromagnetic Wave

- Transverse waves produced by the motion of electrically charged particles, and it does not require a mediu
- Speed in a vacuum = 300,000 km/s
- Electric and magnetic components are perpendicular

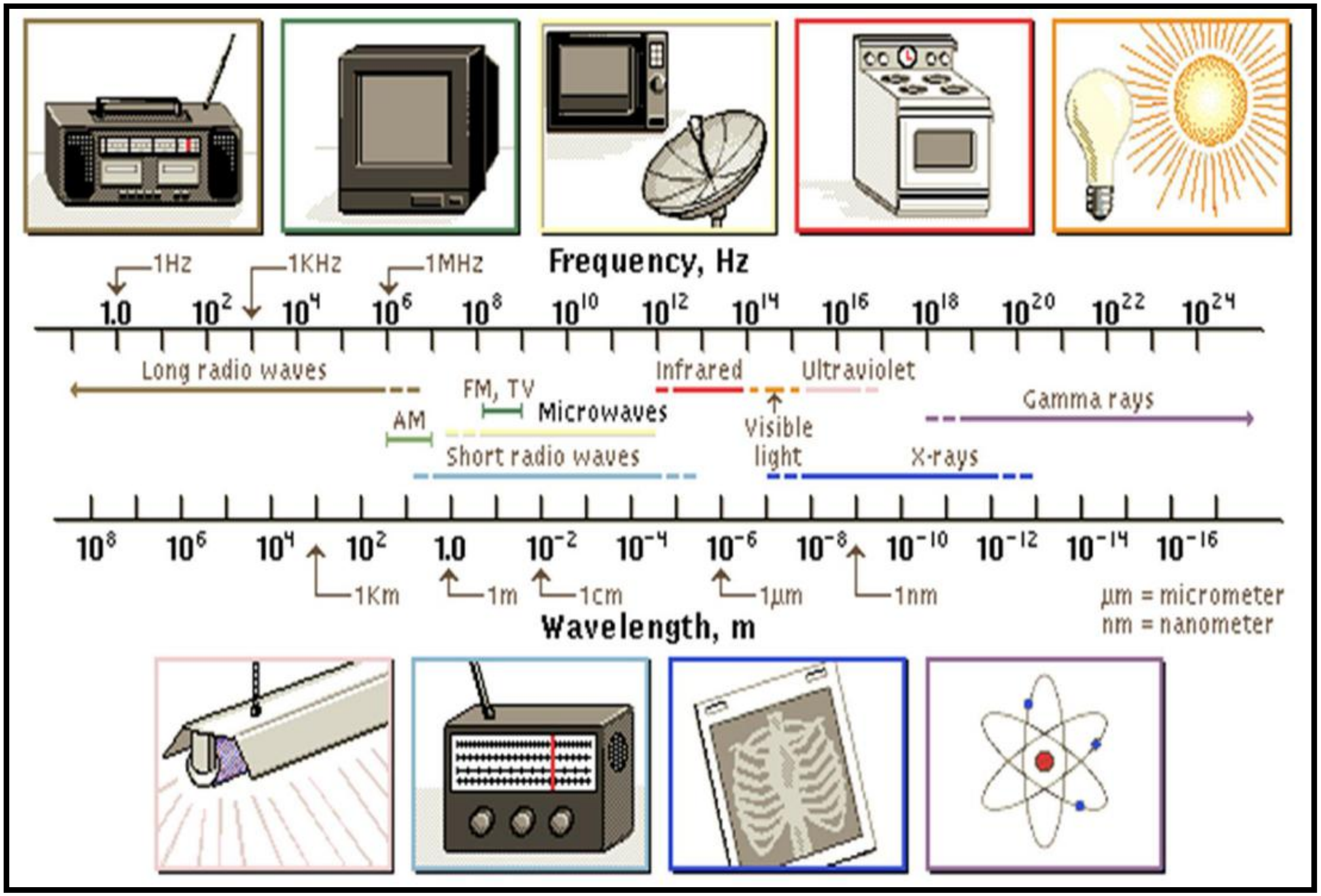


Electromagnetic Spectrum

long
λ

low *f*

low
energ
y



short
λ

high *f*

high
energ
y

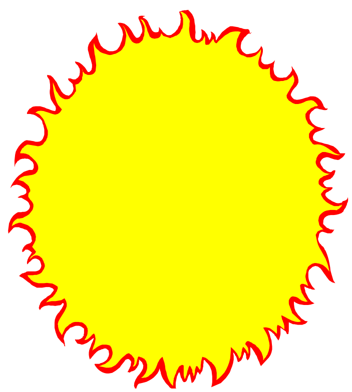
Comparison for MW and EW

Mechanical Waves

- Must travel through a medium
- Cannot travel through a vacuum
- Examples: sound, ocean waves

Electromagnetic Waves

- Does not require a medium
- Can be transferred through a vacuum
- Examples: light, UV rays, Visible light



Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

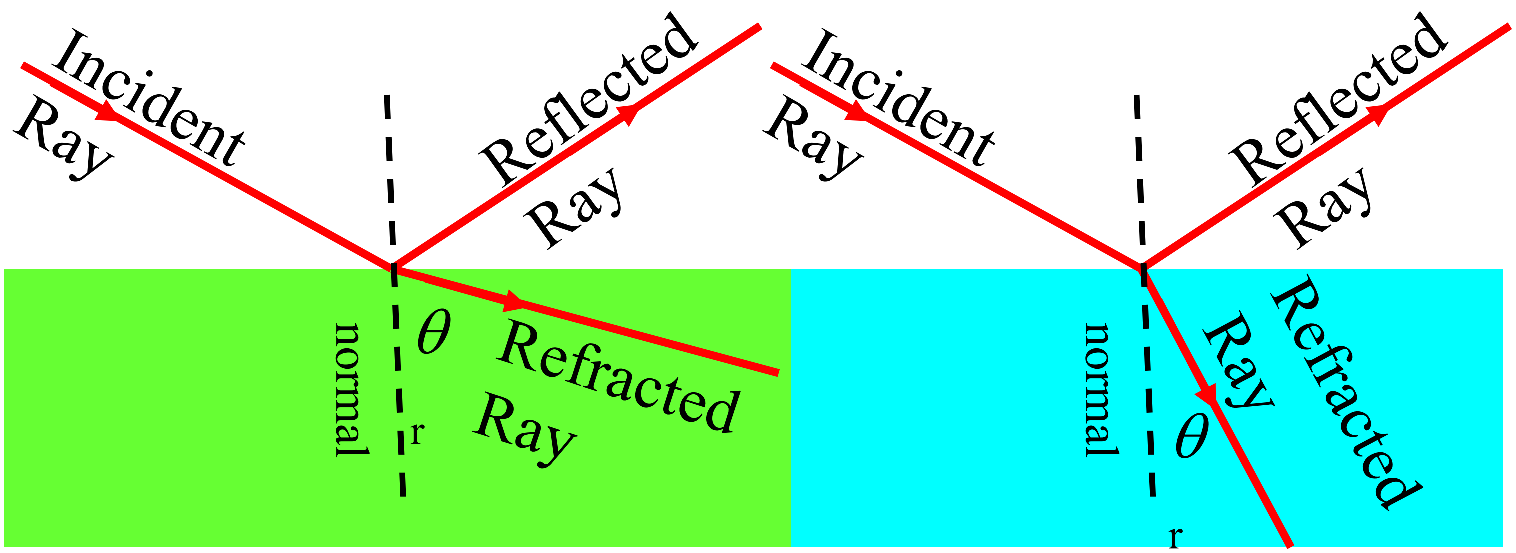
Optics

Optics

- Reflection & Refraction
- Snell’s law
- Brewster angle
- Critical angle
- Total internal reflection
- Fiber optics
- Mirages
- Dispersion
- Atmospheric optics
- Plane mirrors
- Concave and convex mirrors
- Spherical aberration
- Mirror / lens equation
- Convex and concave lenses
- Chromatic aberration
- Human eye
- Telescopes

Reflection & Refraction

At an interface between two media, both reflection and refraction can occur. The angles of incidence, reflection, and refraction are all measured with respect to the normal. The angles of incidence and reflection are always the same. If light speeds up upon entering a new medium, the angle of refraction, θ_r, will be greater than the angle of incidence, as depicted on the left. If the light slows down in the new medium, θ_r will be less than the angle of incidence, as shown on the right.



Index of Refraction, *n*

The index of refraction of a substance is the ratio of the speed in light in a vacuum to the speed of light in that substance:

$$n = \frac{c}{v}$$

n = Index of Refraction
c = Speed of light in vacuum
v = Speed of light in medium

Note that a large index of refraction corresponds to a relatively slow light speed in that medium.

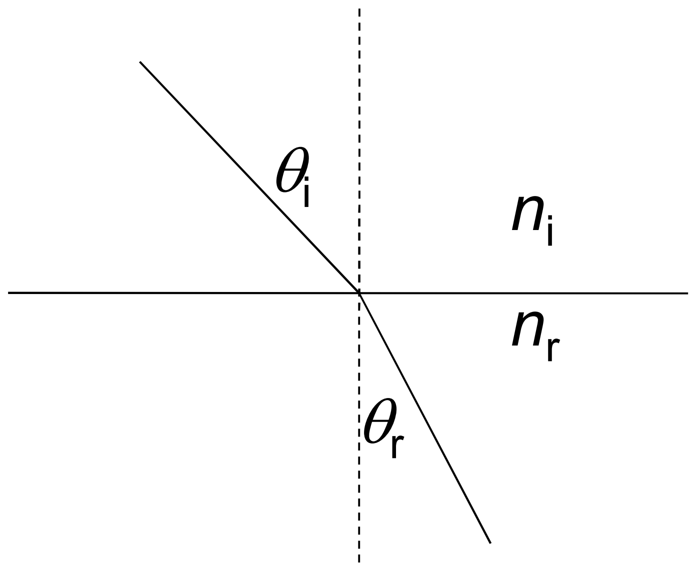
Medium	*n*
Vacuum	1
Air (STP)	1.00029
Water (20º C)	1.33
Ethanol	1.36
Glass	~1.5
Diamond	2.42

Snell's Law

- Snell's law states that a ray of light bends in such a way that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant.

- Here n_i is the index of refraction in the original medium and n_r is the index in the medium the light enters. θ_i and θ_r are the angles of incidence and refraction, respectively.

$$n_i \sin\theta_i = n_r \sin\theta_r$$



Brewster Angle

The Brewster angle is the angle of incidence the produces reflected and refracted rays that are perpendicular.

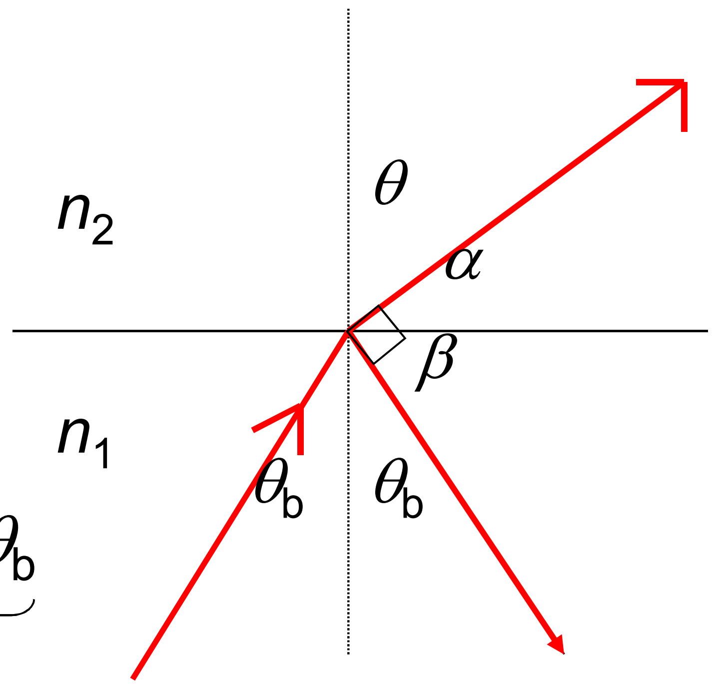
From Snell, $n_1 \sin\theta_b = n_2 \sin\theta$.

$\alpha = \theta_b$ since $\alpha + \beta = 90^\circ$,
and $\theta_b + \beta = 90^\circ$.

$\beta = \theta$ since $\alpha + \beta = 90^\circ$,
and $\theta + \alpha = 90^\circ$. Thus,

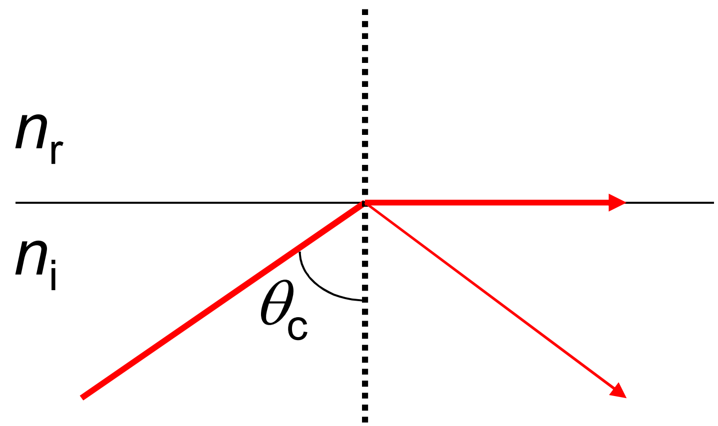
$$\underbrace{n_1 \sin\theta_b = n_2 \sin\theta = n_2 \sin\beta = n_2 \cos\theta_b}$$

$$\tan\theta_b = n_2 / n_1$$



Critical Angle

The incident angle that causes the refracted ray to skim right along the boundary of a substance is known as the critical angle, θ_c. The critical angle is the angle of incidence that produces an angle of refraction of 90º. If the angle of incidence exceeds the critical angle, the ray is completely reflected and does not enter the new medium. A critical angle only exists when light is attempting to penetrate a medium of higher optical density than it is currently traveling in.



From Snell,

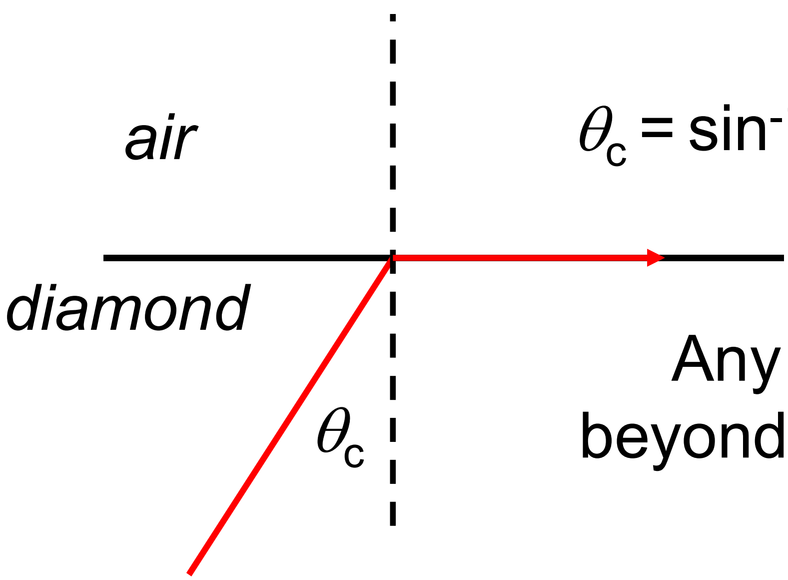
$n_1 \sin\theta_c = n_2 \sin 90°$

Since $\sin 90° = 1$, we have $n_1 \sin\theta_c = n_2$ and the critical angle is

$$\theta_c = \sin^{-1} \frac{n_r}{n_i}$$

Diamond Critical Angle

Calculate the critical angle for the diamond-air boundary ! Please refer to the Index of Refraction chart for the information.

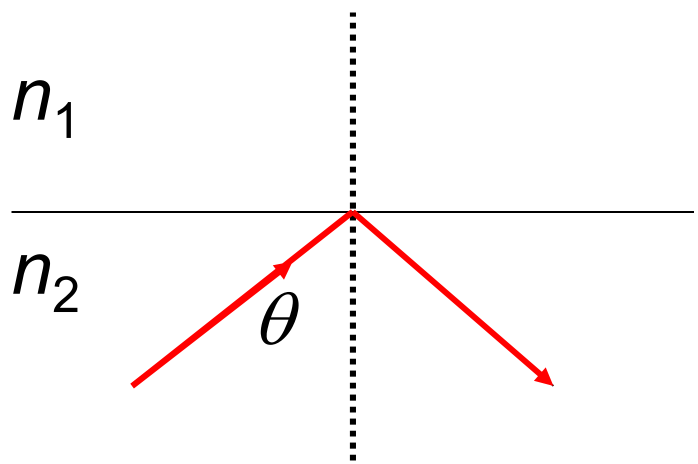


$\theta_c = \sin^{-1} (n_r / n_i) = \sin^{-1} (1 / 2.42) = 24.4°$

Any light shone on this boundary beyond this angle will be reflected back into the diamond.

Total Internal Reflection

Total internal reflection occurs when light attempts to pass from a more optically dense medium to a less optically dense medium at an angle greater than the critical angle. When this occurs there is no refraction, only reflection.



$n_2 > n_1$

$\theta > \theta_c$

Total internal reflection can be used for practical applications like fiber optics.

Fiber Optics

A fiber optic wire

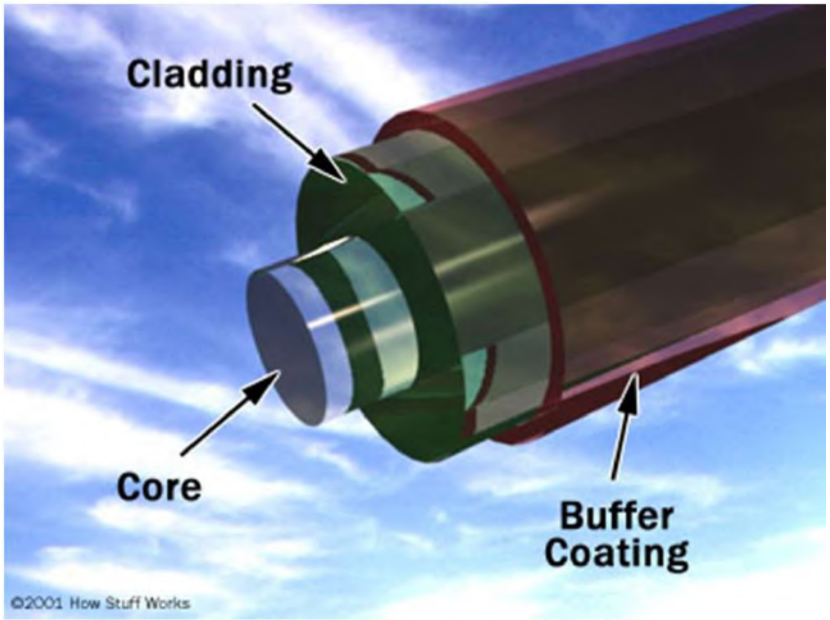
Fiber optic lines are strands of glass or transparent fibers that allows the transmission of light and digital information over long distances. They are used for the telephone system, the cable TV system, the internet, medical imaging, and mechanical engineering inspection.

Optical fibers have many advantages over copper wires. They are less expensive, thinner, lightweight, and more flexible. They aren't flammable since they use light signals instead of electric signals. Light signals from one fiber do not interfere with signals in nearby fibers, which means clearer TV reception or phone conversations.

spool of optical fiber

Fiber Optics Characteristic

Fiber optics are often long strands of very pure glass. They are very thin, about the size of a human hair. Hundreds to thousands of them are arranged in bundles (optical cables) that can transmit light great distances. There are three main parts to an optical fiber:



- **Core**- the thin glass center where light travels.
- **Cladding**- optical material (with a lower index of refraction than the core) that surrounds the core that reflects light back into the core.
- **Buffer Coating**- plastic coating on the outside of an optical fiber to protect it from damage.

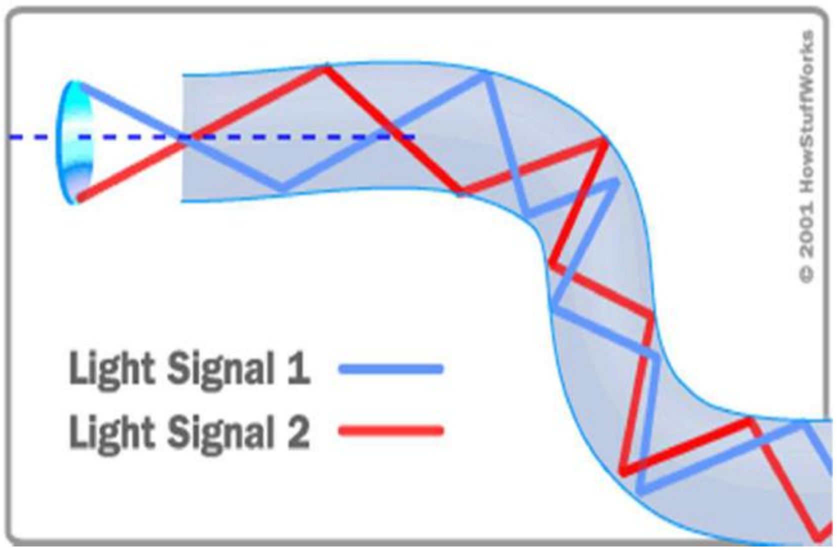
Types of Fiber Optics

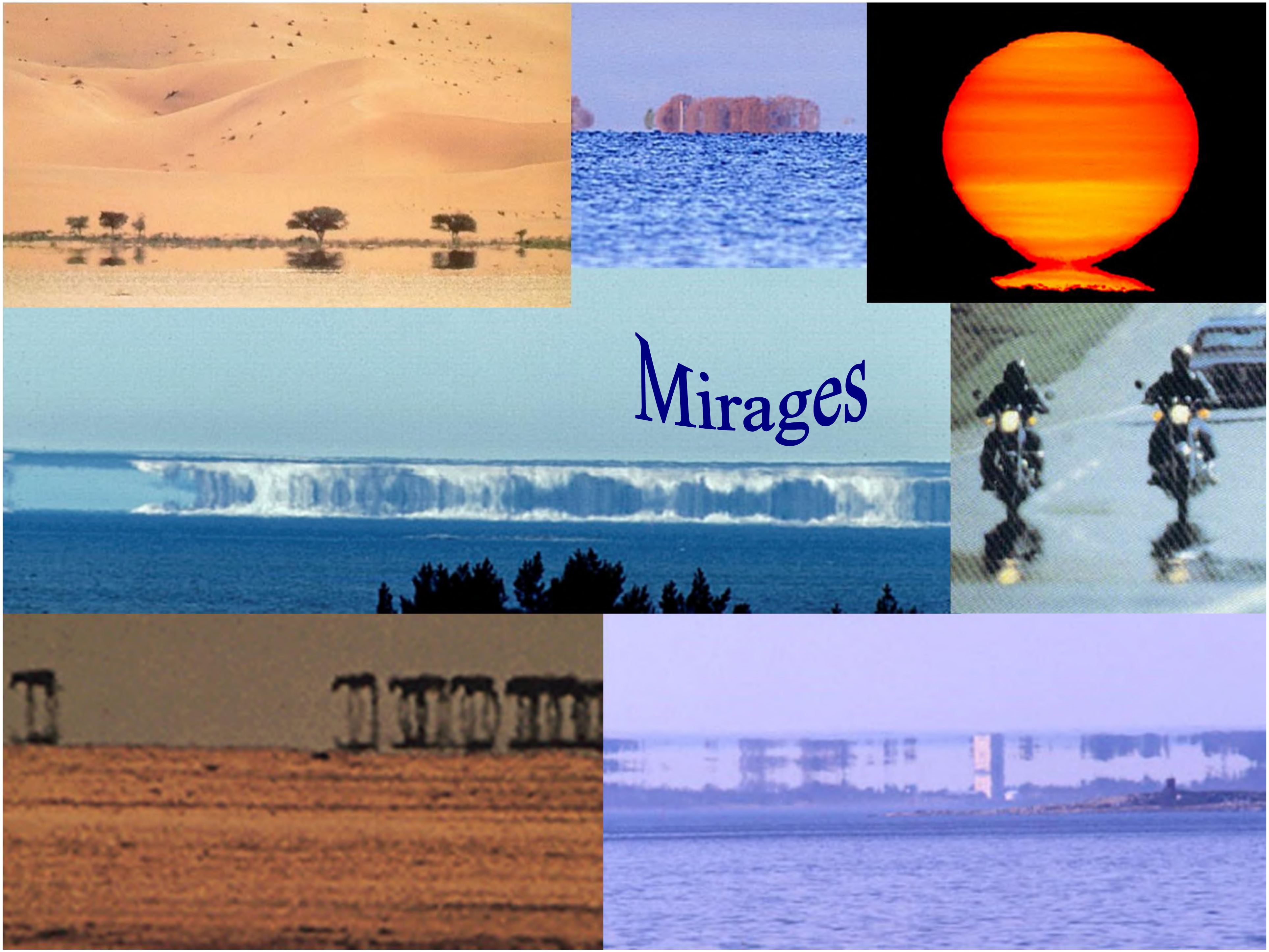
There are two types of optical fibers:

• **Single-mode fibers**- transmit one signal per fiber (used in cable TV and telephones).

• **Multi-mode fibers**- transmit multiple signals per fiber (used in computer networks).

Light travels through the core of a fiber optic by continually reflecting off of the cladding. Due to total internal reflection, the cladding does not absorb any of the light, allowing the light to travel over great distances. Some of the light signal will degrade over time due to impurities in the glass.



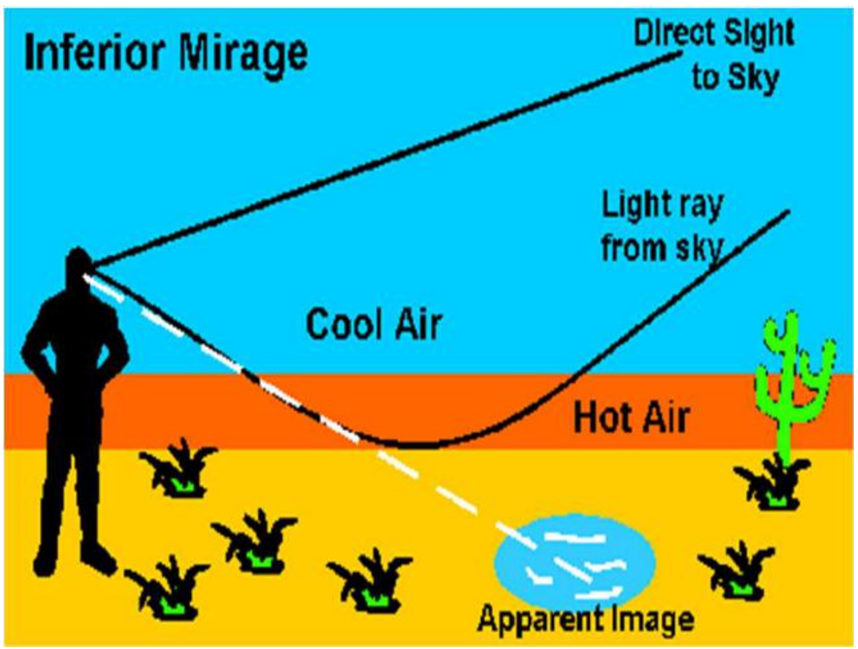

Mirages

Mirages

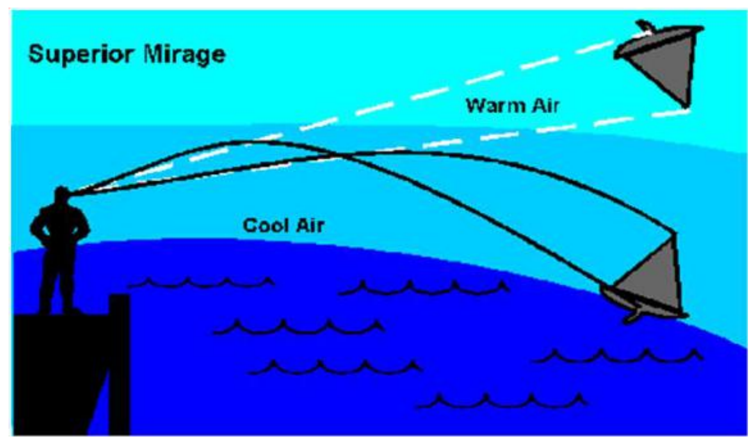
- Mirages are caused by the refracting properties of a non-uniform atmosphere.
- Several examples of mirages include seeing “puddles” ahead on a hot highway or in a desert and the lingering daylight after the sun is below the horizon.

Types of Mirages

Inferior Mirage

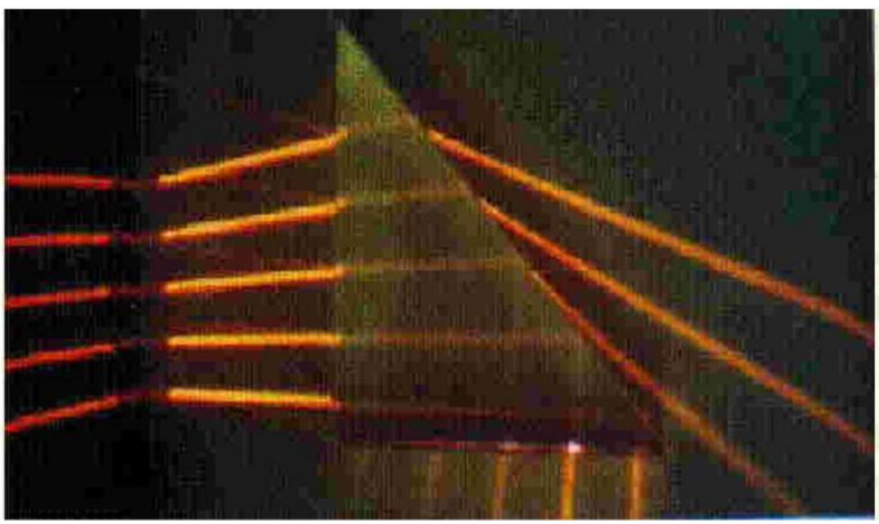


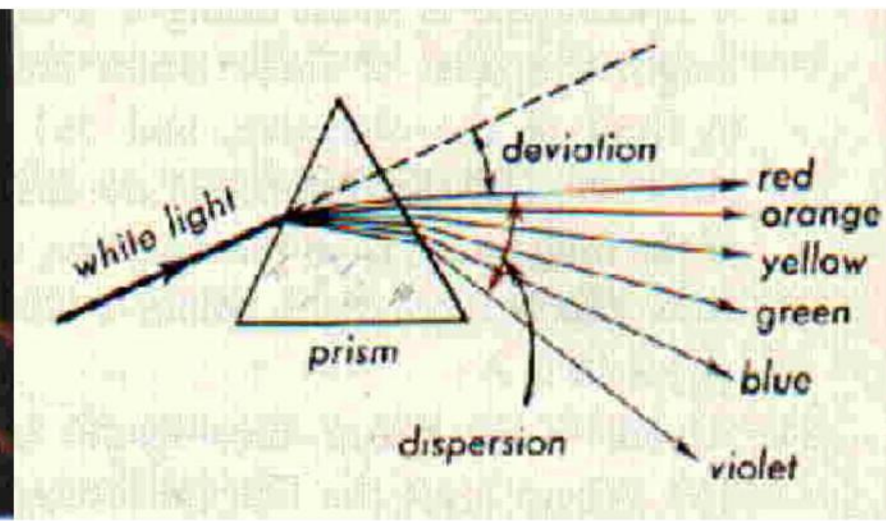
Superior Mirage



Dispersion

Dispersion is the separation of light into a spectrum by refraction. The index of refraction is actually a function of wavelength. For longer wavelengths the index is slightly small. Thus, red light refracts less than violet. This effect causes white light to split into it spectrum of colors. Red light travels the fastest in glass, has a smaller index of refraction, and bends the least. Violet is slowed down the most, has the largest index, and bends the most. In other words: the higher the frequency, the greater the bending.



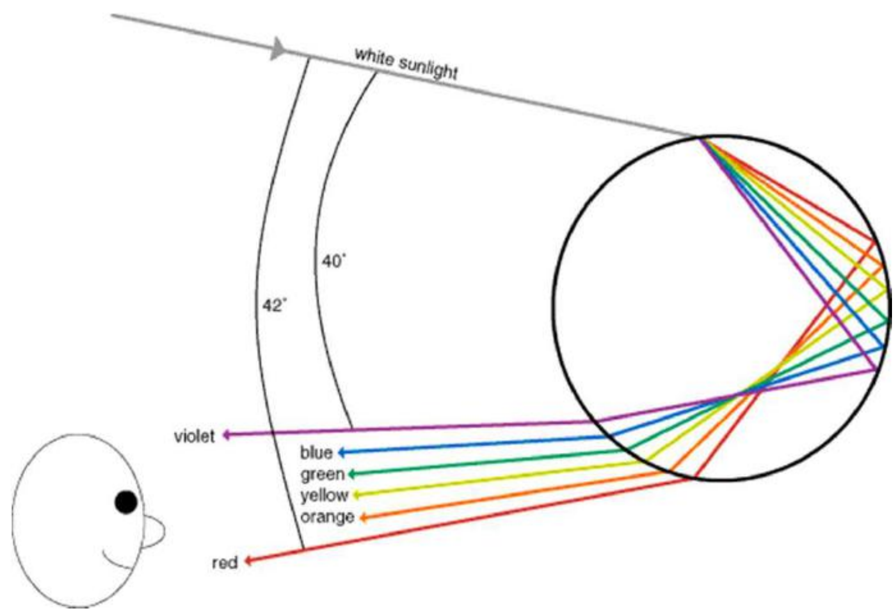


Atmospheric Optics

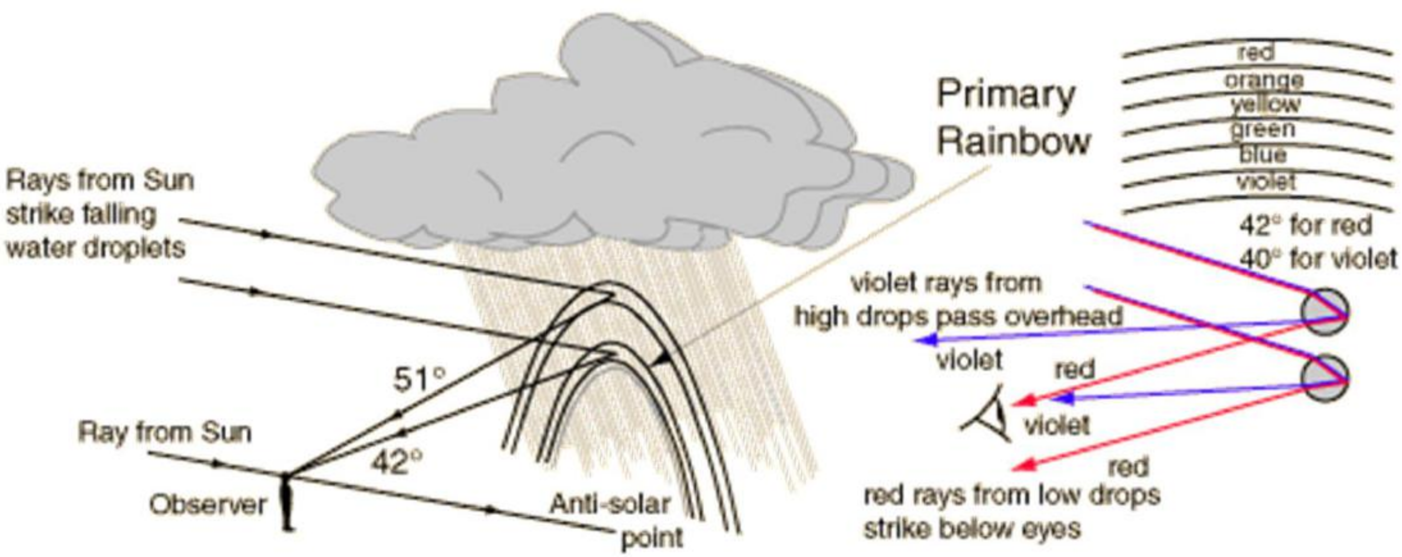
Rainbows

- A rainbow is a spectrum formed when sunlight is dispersed by water droplets in the atmosphere. Sunlight incident on a water droplet is refracted. Because of dispersion, each color is refracted at a slightly different angle. At the back surface of the droplet, the light undergoes total internal reflection. On the way out of the droplet, the light is once more refracted and dispersed. Although each droplet produces a complete spectrum, an observer will only see a certain wavelength of light from each droplet (the wavelength depends on the relative positions of the sun, droplet, and observer).

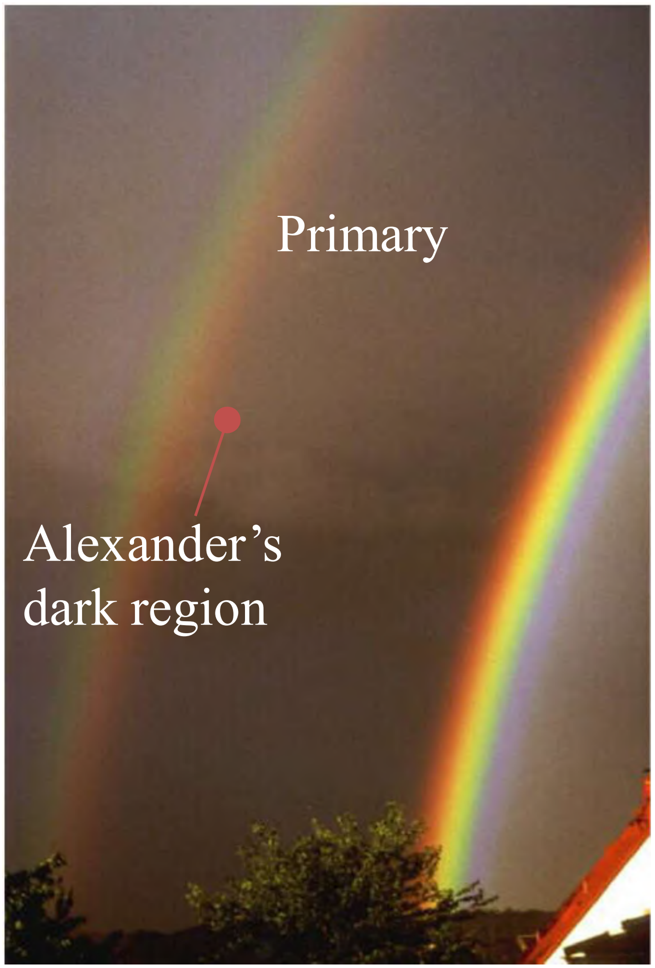
- Two kinds of rainbow:
  - Primary rainbow
  - Secondary rainbow



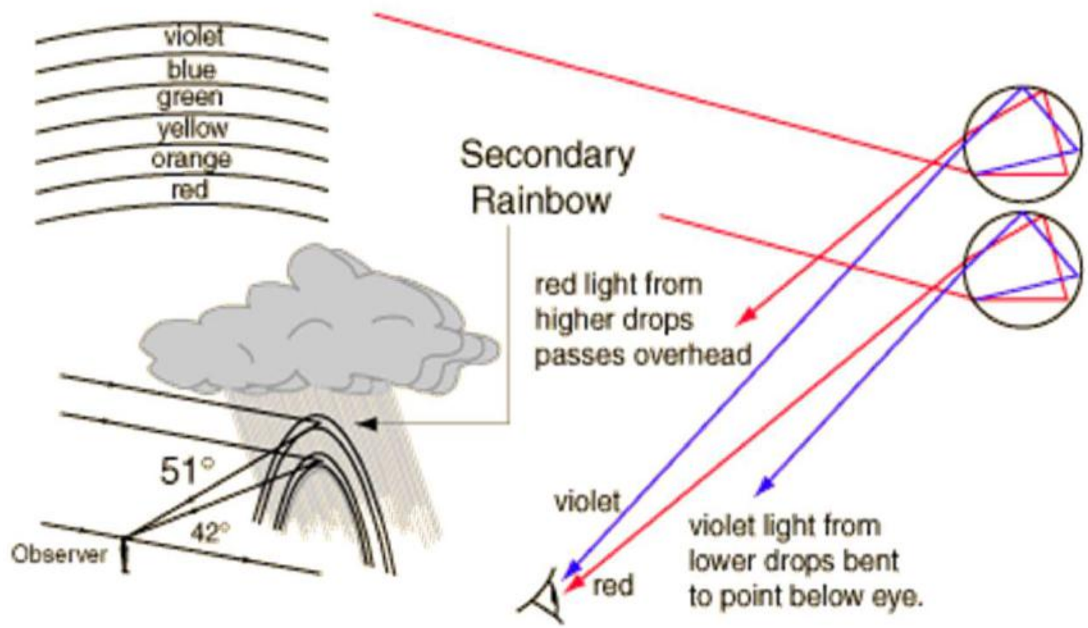
Primary Rainbow



Secondary Rainbow



The secondary rainbow is a rainbow of radius 51°, occasionally visible outside the primary rainbow. It is produced when the light entering a cloud droplet is reflected twice internally and then exits the droplet. The color spectrum is reversed in respect to the primary rainbow, with red appearing on its inner edge.



Supernumerary Arcs

Supernumerary arcs are faint arcs of color just inside the primary rainbow. They occur when the drops are of uniform size. If two light rays in a raindrop are scattered in the same direction but have take different paths within the drop, then they could interfere with each other constructively or destructively. The type of interference that occurs depends on the difference in distance traveled by the rays. If that difference is nearly zero or a multiple of the wavelength, it is constructive, and that color is reinforced. If the difference is close to half a wavelength, there is destructive interference.

Real & Virtual Images

Real images are formed by mirrors or lenses when light rays actually converge and pass through the image. Real images will be located in front of the mirror forming them. A real image can be projected onto a piece of paper or a screen. If photographic film were placed here, a photo could be created.

Virtual images occur where light rays only appear to have originated. For example, sometimes rays appear to be coming from a point behind the mirror. Virtual images can't be projected on paper, screens, or film since the light rays do not really converge there.

Lens / Mirror Sign Convention

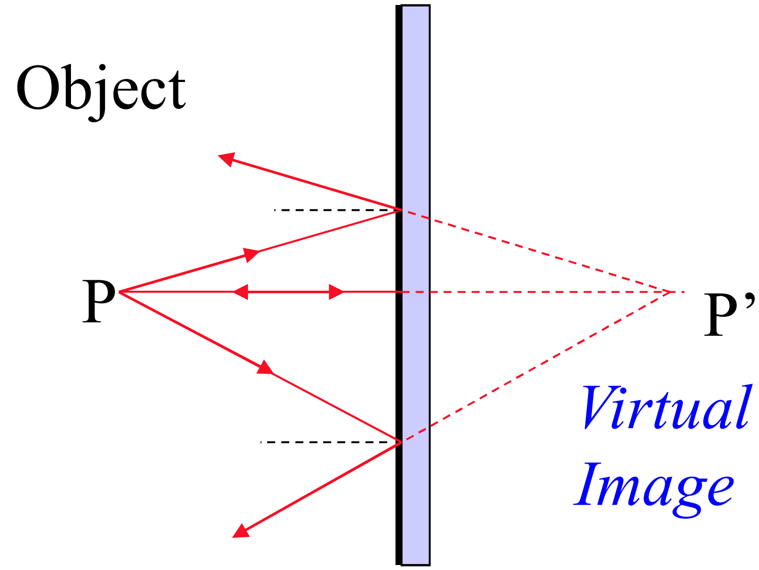
The general rule for lenses and mirrors is this:

$$d_i \begin{cases} + \text{ for real image} \\ - \text{ for virtual image} \end{cases}$$

and if the lens or mirror has the *ability* to converge light, f is positive. Otherwise, f must be treated as negative for the mirror/lens equation to work correctly.

Plane Mirror

- Rays emanating from an object at point P strike the mirror and are reflected with equal angles of incidence and reflection. After reflection, the rays continue to spread. If we extend the rays backward behind the mirror, they will intersect at point P’, which is the image of point P. To an observer, the rays appear to come from point P’, but no source is there and no rays actually converging there . For that reason, this image at P’ is a virtual image.
- The image, I, formed by a plane mirror of an object, O, appears to be a distance d_i , behind the mirror, equal to the object distance d_o.



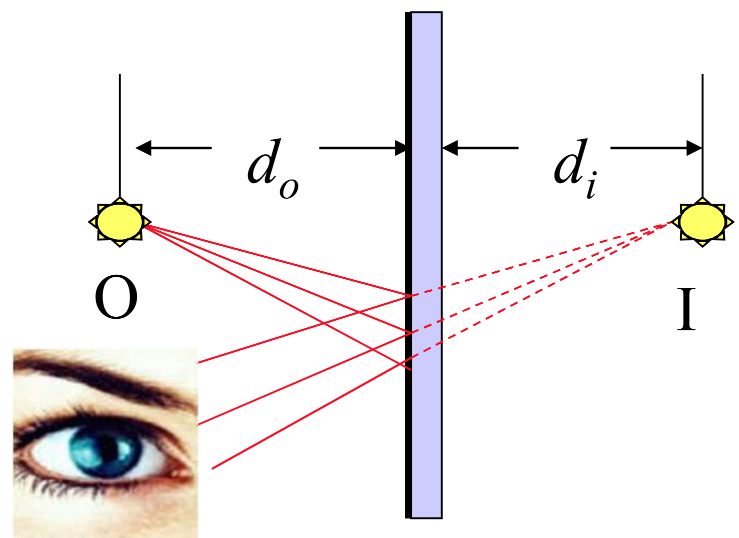
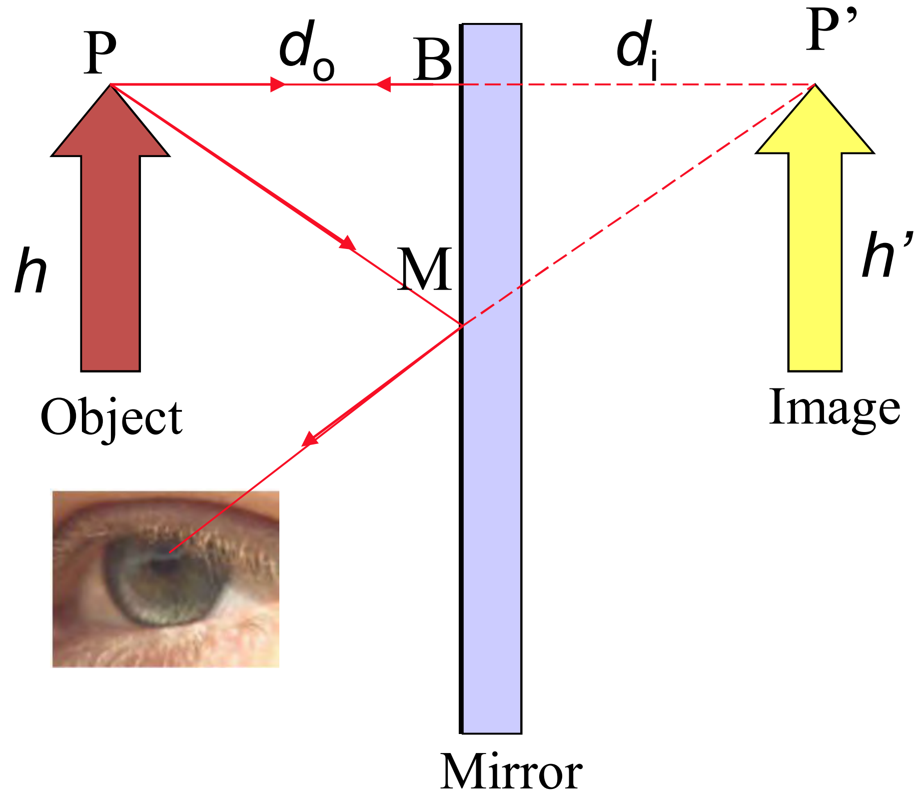


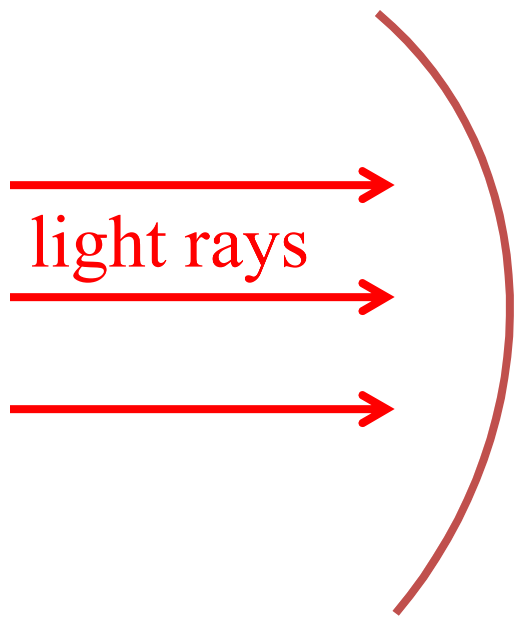
Image Characteristic

Two rays from object P strike the mirror at points B and M. Each ray is reflected such that $i = r$. Triangles BPM and BP'M are congruent by ASA (show this), which implies that $d_o = d_i$ and $h = h'$. Thus, the image is the same distance behind the mirror as the object is in front of it, and the image is the same size as the object.

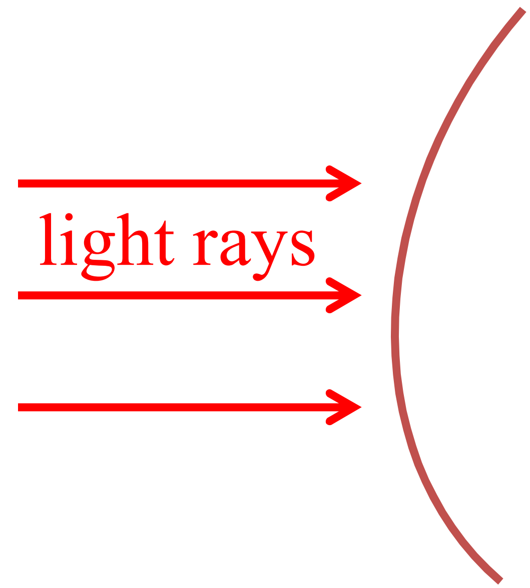


Concave and Convex Mirrors

Concave and convex mirrors are curved mirrors similar to portions of a sphere.



Concave mirrors reflect light from their inner surface, like the inside of a spoon.



Convex mirrors reflect light from their outer surface, like the outside of a spoon.

Concave Mirrors

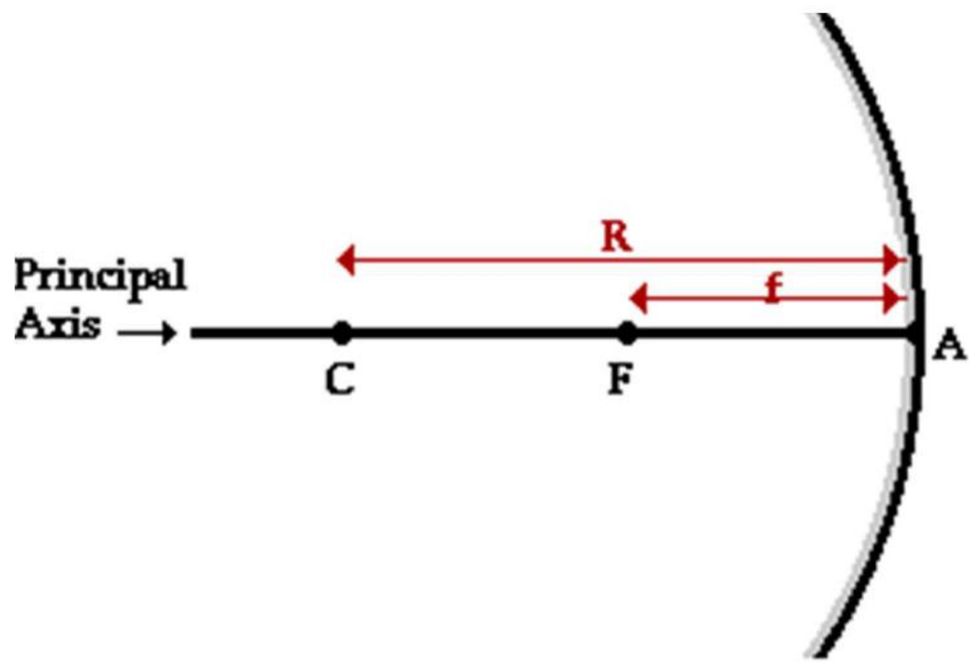
• Concave mirrors are approximately spherical and have a principal axis that goes through the center, C, of the imagined sphere and ends at the point at the center of the mirror, A. The principal axis is perpendicular to the surface of the mirror at A.

• CA is the radius of the sphere,or the radius of curvature of the mirror, *R* .

• Halfway between C and A is the focal point of the mirror, F. This is the point where rays parallel to the principal axis will converge when reflected off the mirror.

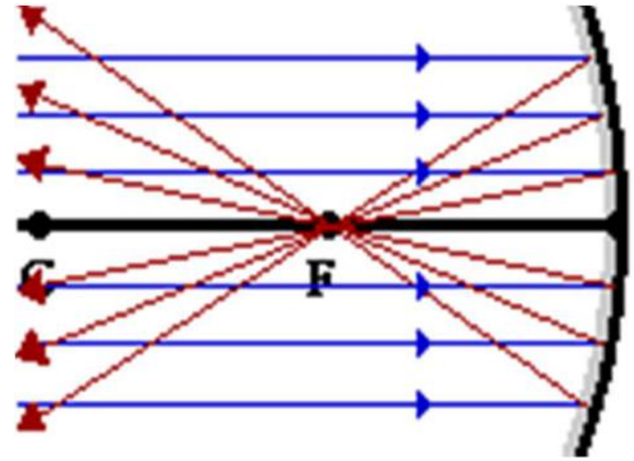
• The length of FA is the focal length, *f*.

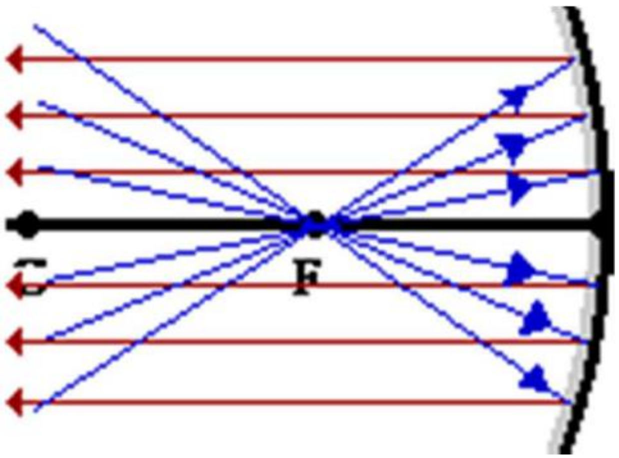
• The focal length is half of the radius of the sphere (proven on next slide).



Focusing Light with Concave Mirrors

Light rays parallel to the principal axis will be reflected through the focus (disregarding spherical aberration, explained on next slide.)



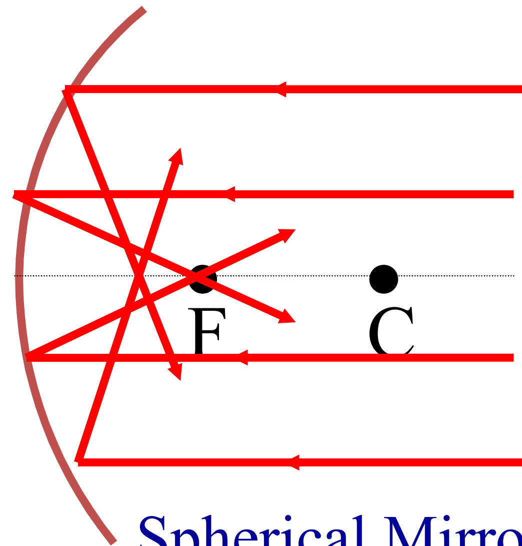


In reverse, light rays passing through the focus will be reflected parallel to the principal axis, as in a flood light.

Concave mirrors can form both real and virtual images, depending on where the object is located, as will be shown in upcoming slides.

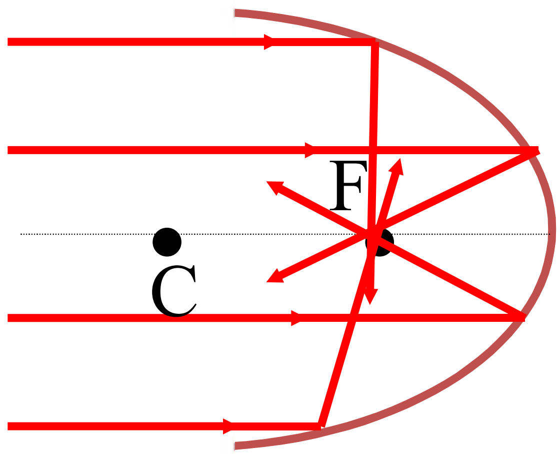
Spherical Aberration

- Only parallel rays close to the principal axis of a spherical mirror will converge at the focal point. Rays farther away will converge at a point closer to the mirror. The image formed by a large spherical mirror will be a disk, not a point. This is known as spherical aberration.



Spherical Mirror

- Parabolic mirrors don’t have spherical aberration. They are used to focus rays from stars in a telescope. They can also be used in flashlights and headlights since a light source placed at their focal point will reflect light in parallel beams. However, perfectly parabolic mirrors are hard to make and slight errors could lead to spherical aberration.

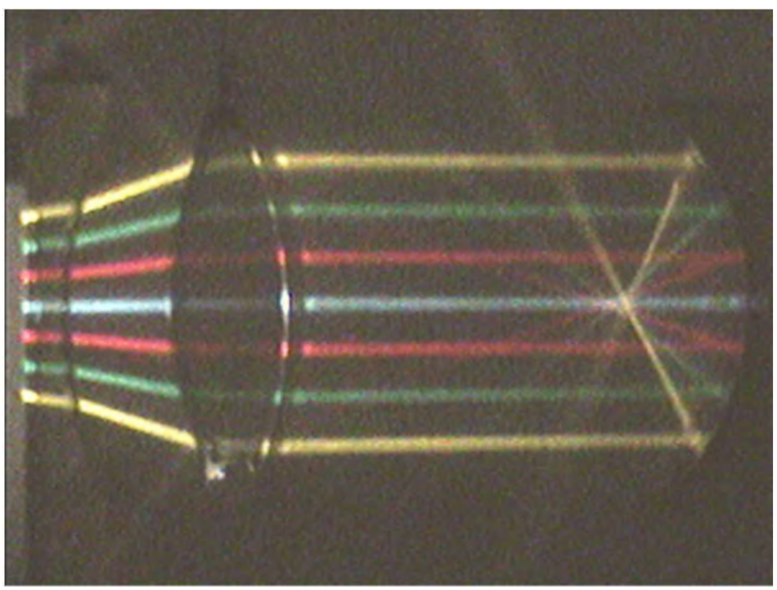


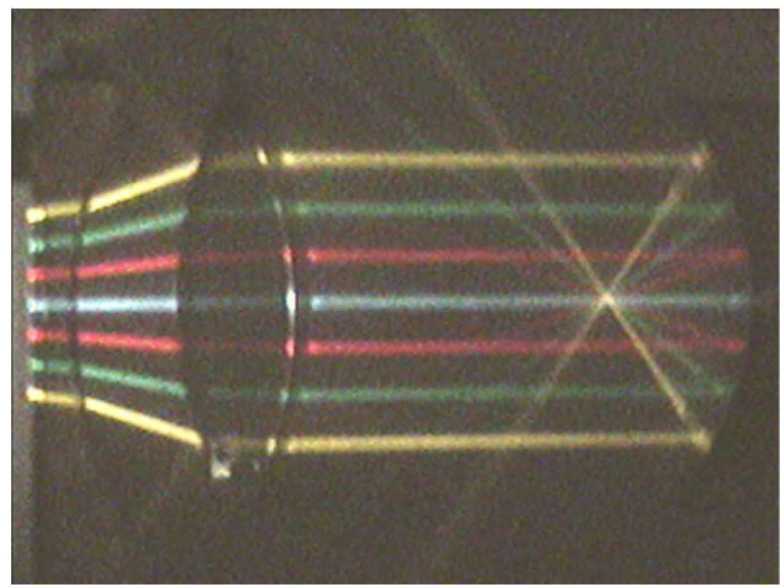
Parabolic Mirror

Spherical vs Parabolic Mirrors

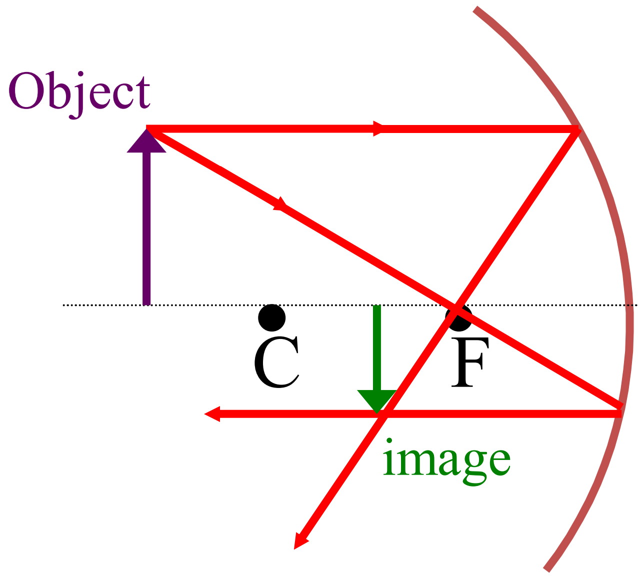
Parallel rays converge at the focal point of a spherical mirror only if they are close to the principal axis. The image formed in a large spherical mirror is a disk, not a point (spherical aberration).

Parabolic mirrors have no spherical aberration. The mirror focuses all parallel rays at the focal point. That is why they are used in telescopes and light beams like flashlights and car headlights.



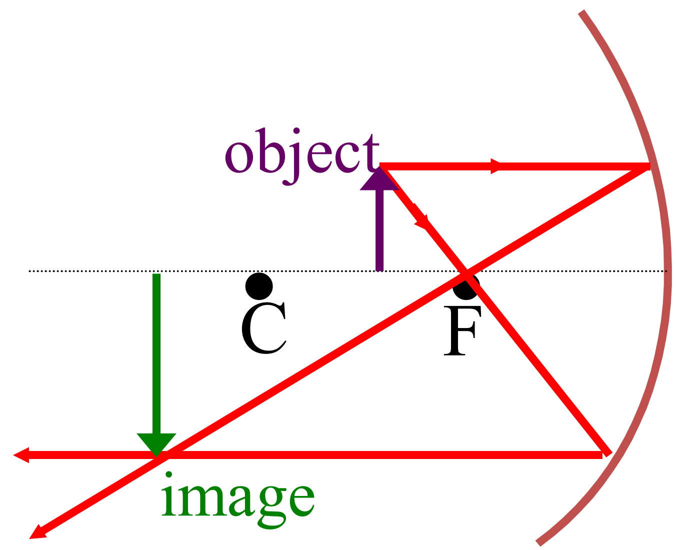


Concave Mirror Diagram

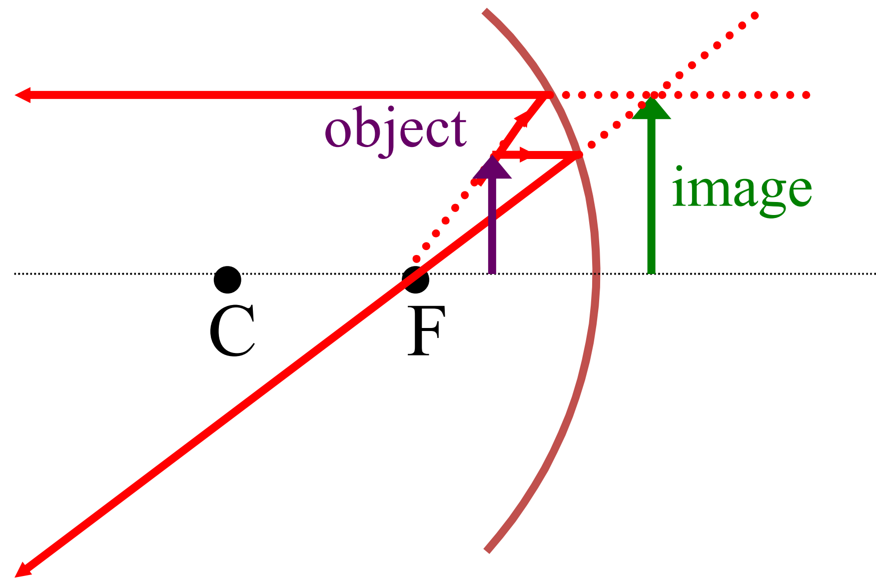


Object placed at beyond C. The image formed when an object is placed beyond C is located between C and F. It is a real, inverted image that is smaller in size than the object.

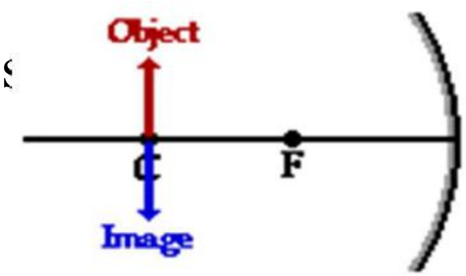
Object placed at between C and F. The image formed when an object is placed between C and F is located beyond C. It is a real, inverted image that is larger in size than the object.



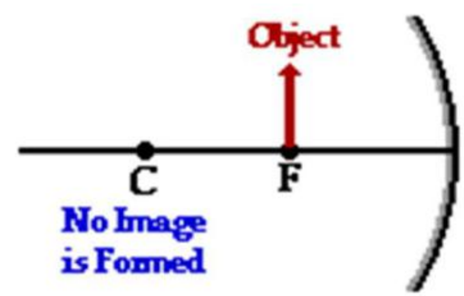
Object in front of F. The image formed when an object is placed in front of F is located behind the mirror. It is a virtual, upright image that is larger in size than the object. It is virtual since it is formed only where light rays *seem* to be diverging from.



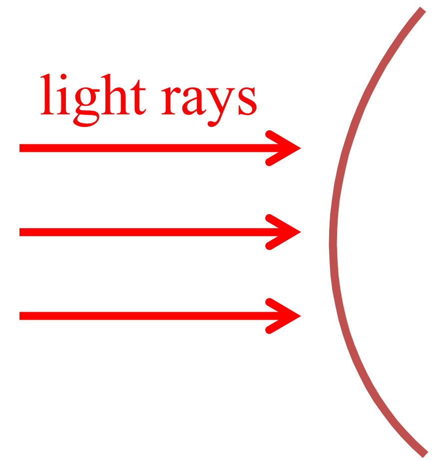
Object is placed at C. The image will be formed at C als
but it will be inverted. It will be real and the same size
the object.



Object placed at F. No image will be formed. All rays will reflect parallel to the principal axis and will never converge. The image is "at infinity."



Convex Mirrors



• A convex mirror has the same basic properties as a concave mirror but its focus and center are located behind the mirror.

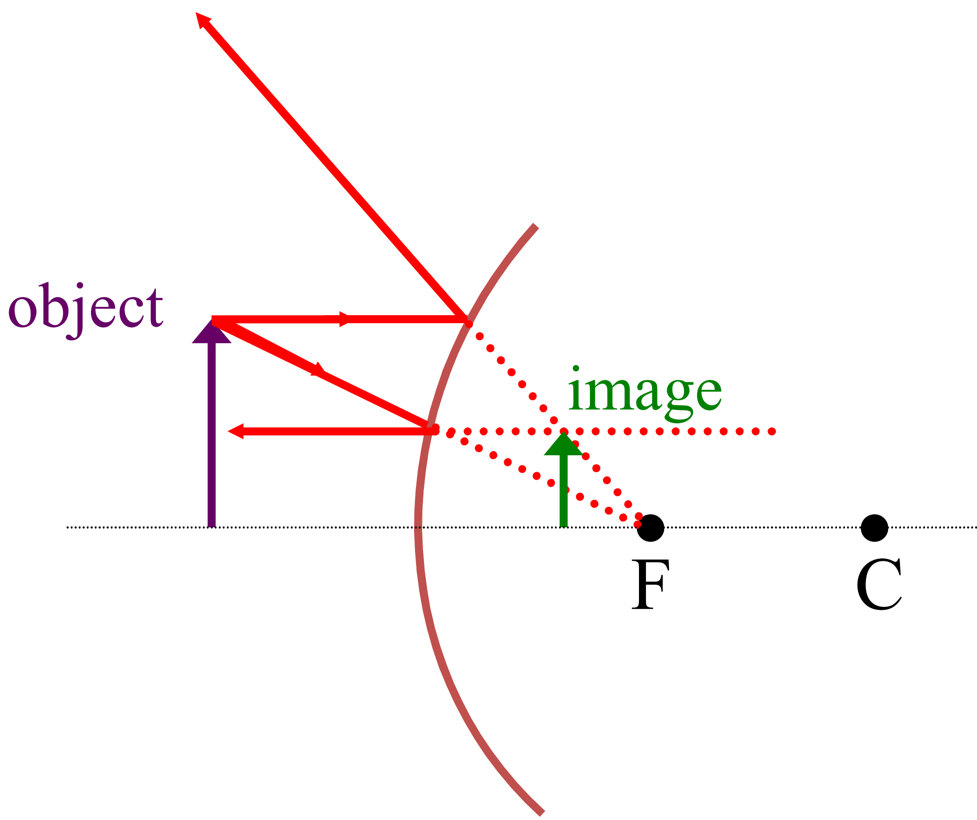
• This means a convex mirror has a negative focal length (used later in the mirror equation).

• Light rays reflected from convex mirrors always diverge, so only virtual images will be formed.

• Rays parallel to the principal axis will reflect as if coming from the focus behind the mirror.

• Rays approaching the mirror on a path toward F will reflect parallel to the principal axis.

Convex Mirror Diagram



The image formed by a convex mirror no matter where the object is placed will be virtual, upright, and smaller than the object. As the object is moved closer to the mirror, the image will approach the size of the object.

Image Distance

$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$$

f = focal length
d_i = image distance
d_o = object distance

d_i { + for real image; - for virtual image }

The equation applies to convex and concave mirrors, as well as to lenses

f { + for concave mirrors; - for convex mirrors }

Image Magnification

$$m = \frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

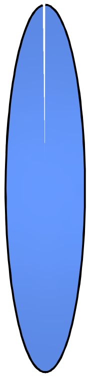
m = magnification
h_i = image height (negative means inverted)
h_o = object height
d_i = image distance
d_o = object distance

Magnification is simply the ratio of image height to object height. A positive magnification means an upright image. The equation applies to convex and concave mirrors, as well as to lenses

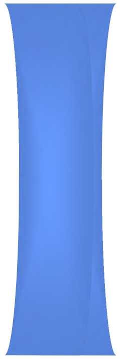
Lenses

Lenses are made of transparent materials, like glass or plastic, that typically have an index of refraction greater than that of air. Each of a lens' two faces is part of a sphere and can be convex or concave (or one face may be flat). If a lens is thicker at the center than the edges, it is a convex, or converging, lens since parallel rays will be converged to meet at the focus. A lens which is thinner in the center than the edges is a concave, or diverging, lens since rays going through it will be spread out.

Convex (Converging) Lens

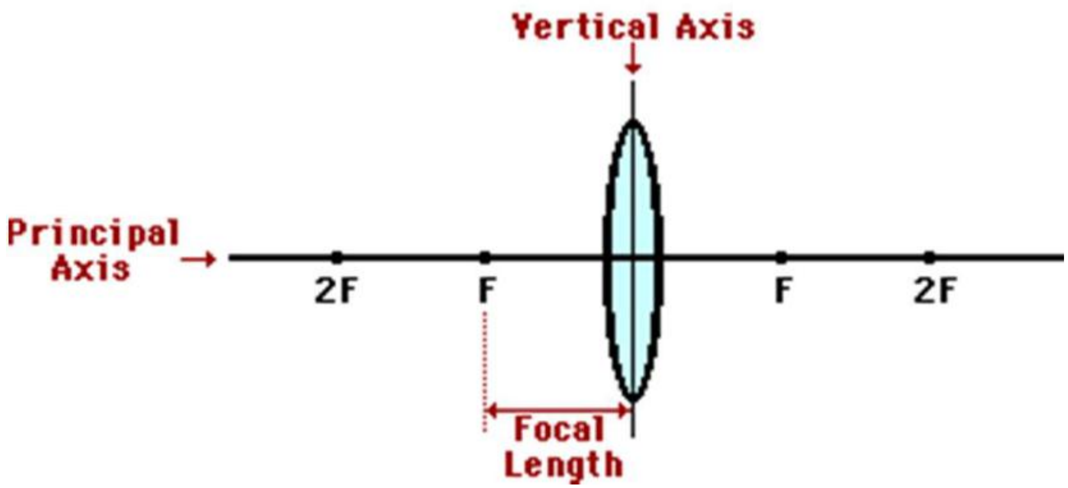


Concave (Diverging) Lens



Focal Length of Lenses

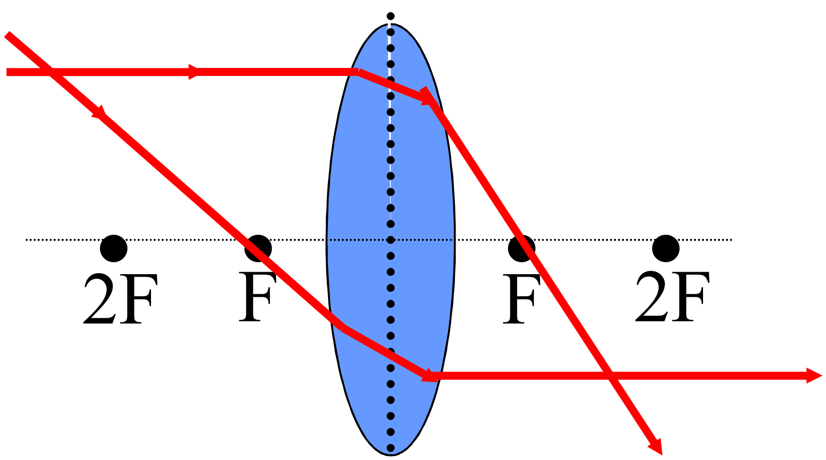
• Like mirrors, lenses have a principal axis perpendicular to their surface and passing through their midpoint.
• Lenses also have a vertical axis, or principal plane, through their middle.



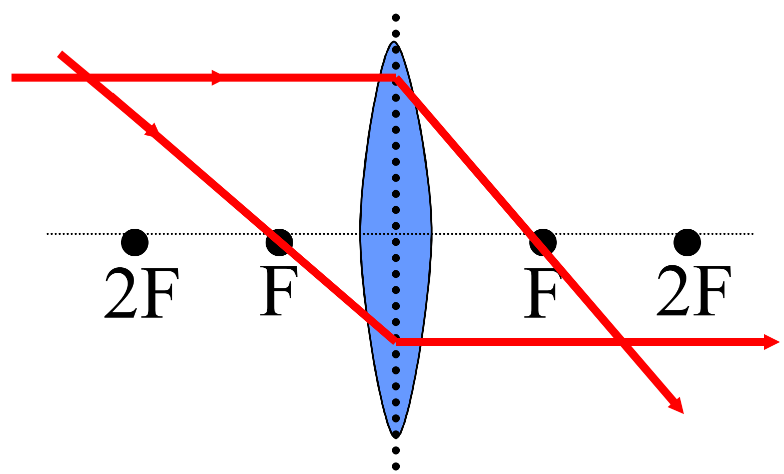
• They have a focal point, F, and the focal length is the distance from the vertical axis to F.
• There is no real center of curvature, so 2F is used to denote twice the focal length.

Ray Diagrams For Lenses

When light rays travel through a lens, they refract at both surfaces of the lens, upon entering and upon leaving the lens. At each interface the bends toward the normal (Imagine the wheels and axle). To simplify ray diagrams, we often pretend that all refraction occurs at the vertical axis. This simplification works well for thin lenses and provides the same results as refracting the light rays twice.



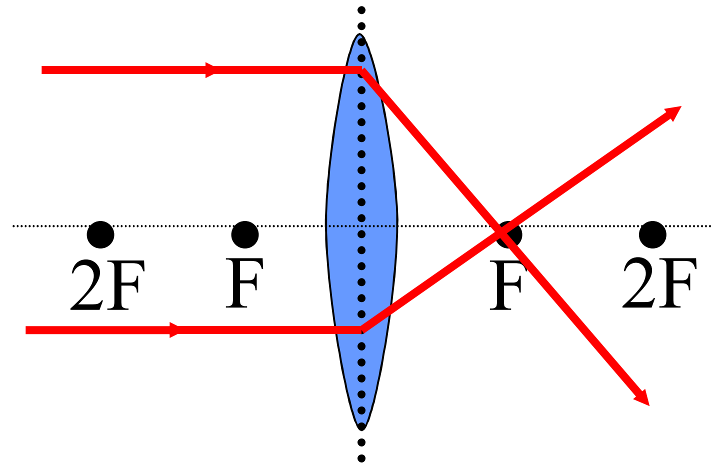
Reality

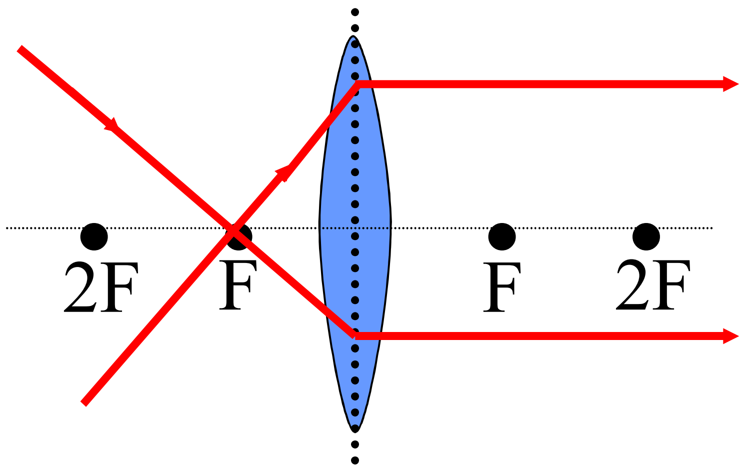


Approximation

Convex Lenses

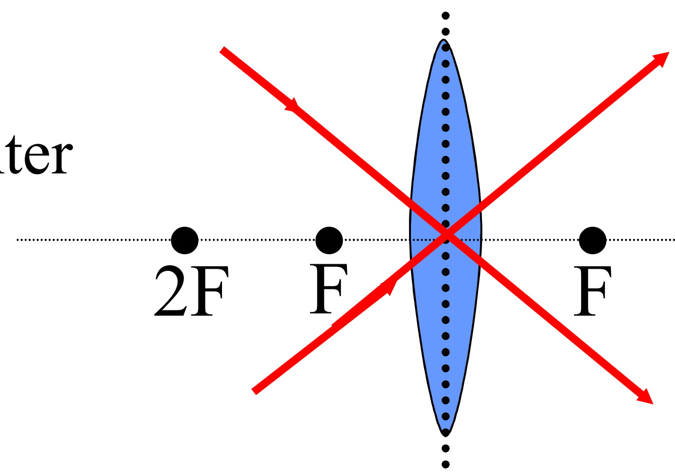
Rays traveling parallel to the principal axis of a convex lens will refract toward the focus.



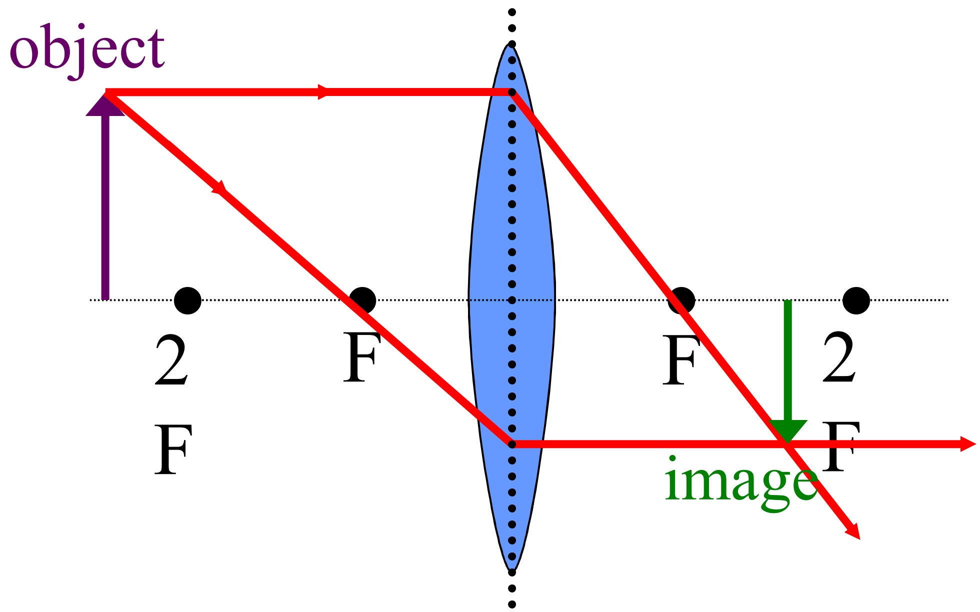


Rays traveling from the focus will refract parallel to the principal axis.

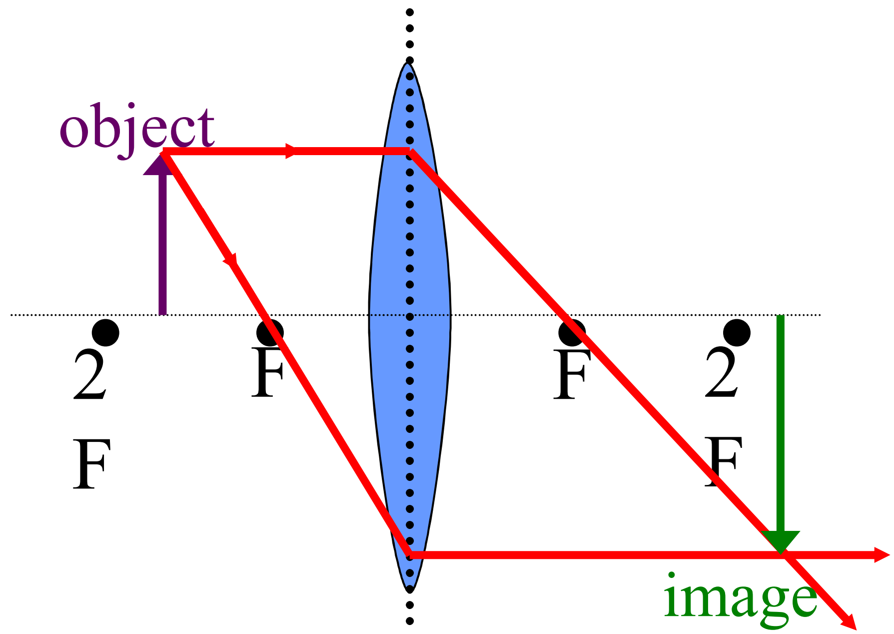
Rays traveling directly through the center of a convex lens will leave the lens traveling in the exact same direction.



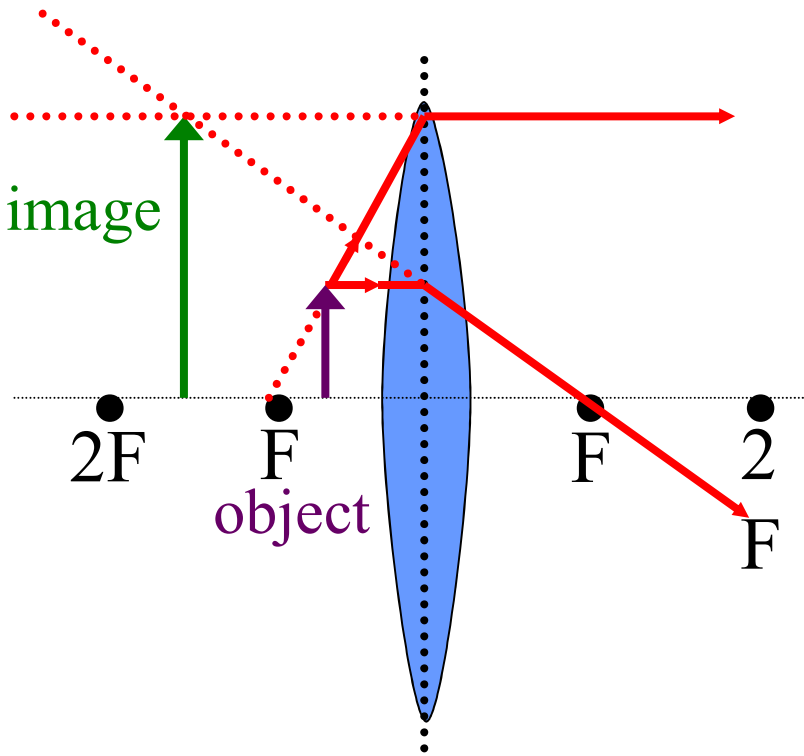
Convex Lens Image Diagram



The image formed when an object is placed beyond 2F is located behind the lens between F and 2F. It is a real, inverted image which is smaller than the object itself.



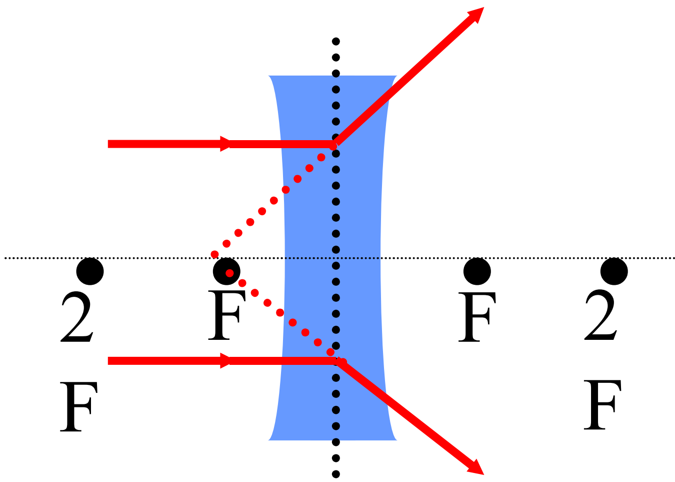
The image formed when an object is placed between 2F and F is located beyond 2F behind the lens. It is a real, inverted image, larger than the object.



The image formed when an object is placed in front of F is located somewhere beyond F on the same side of the lens as the object. It is a virtual, upright image which is larger than the object. This is how a magnifying glass works. When the object is brought close to the lens, it will be magnified greatly.

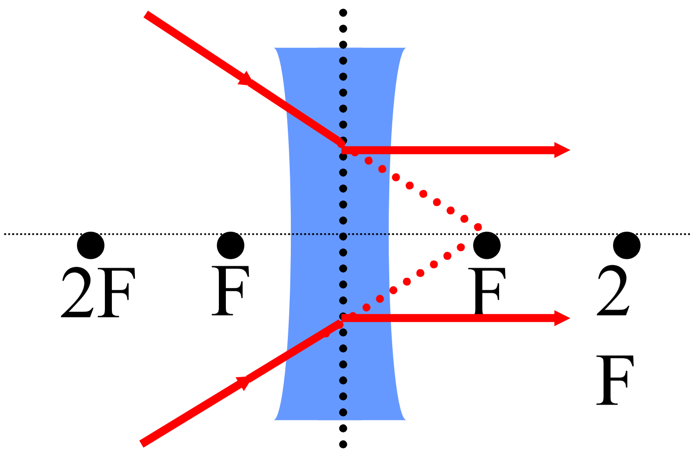
convex lens used as a magnifier

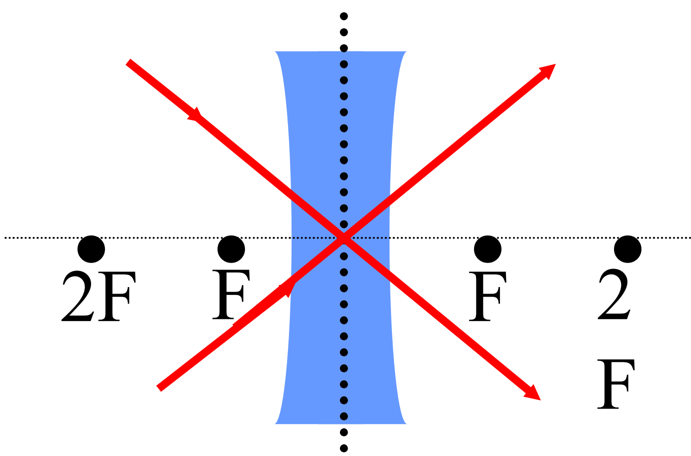
Concave Lenses



Rays traveling parallel to the principal axis of a concave lens will refract as if coming from the focus.

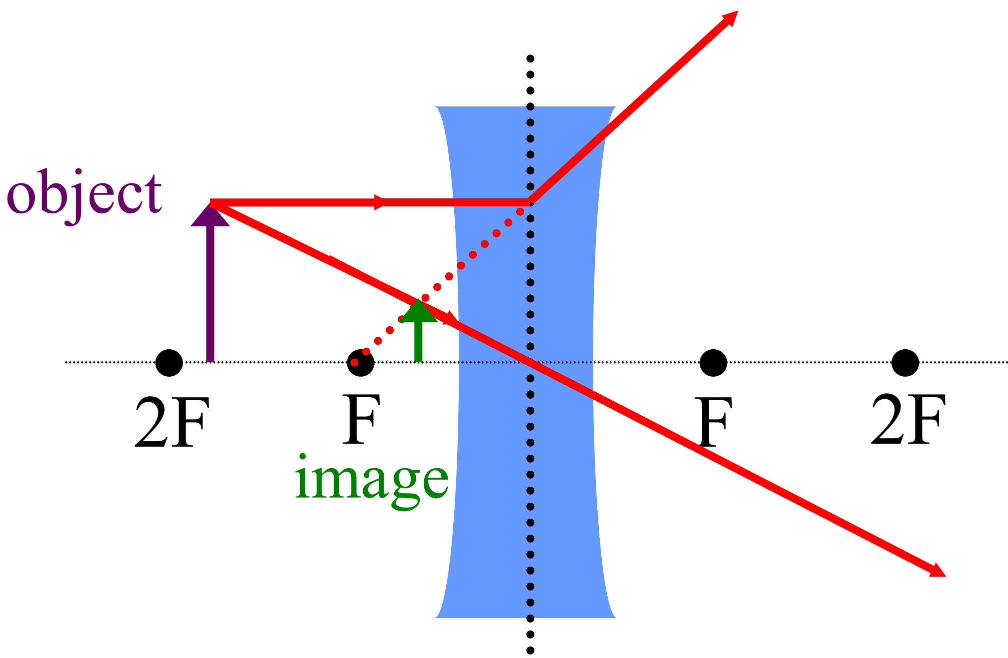
Rays traveling toward the focus will refract parallel to the principal axis.





Rays traveling directly through the center of a concave lens will leave the lens traveling in the exact same direction, just as with a convex lens.

Concave Lens Image Diagram



No matter where the object is placed, the image will be on the same side as the object. The image is virtual, upright, and smaller than the object with a concave lens.

Image Distance

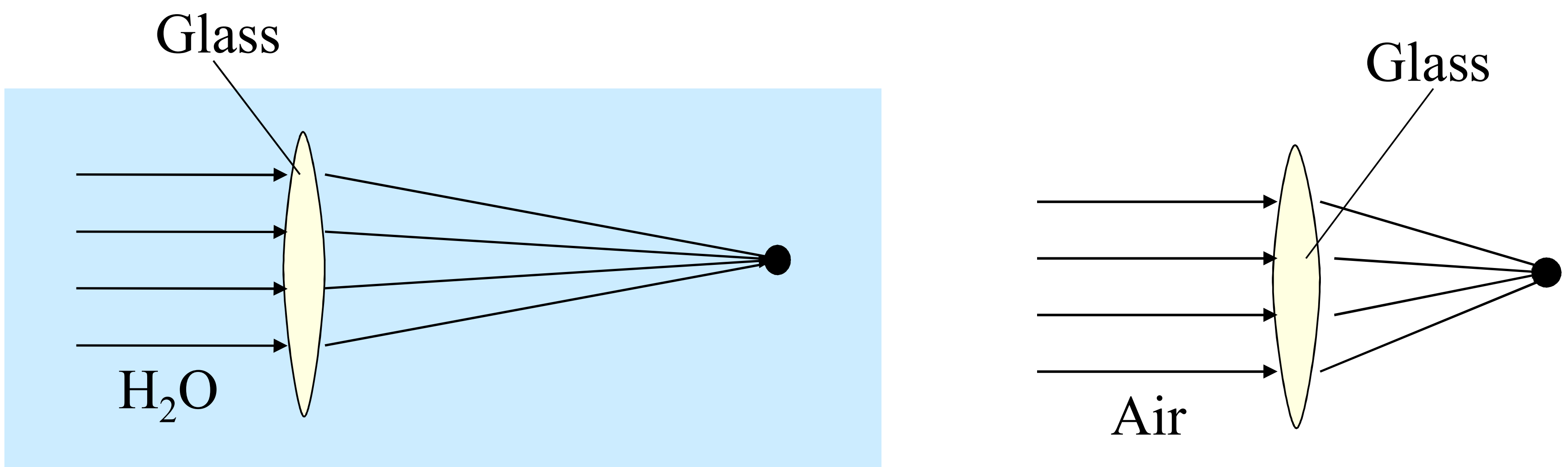
$$\frac{1}{f} = \frac{1}{d_i} + \frac{1}{d_o}$$

f = focal length
d_i = image distance
d_o = object distance

d_i { + for real image; - for virtual image

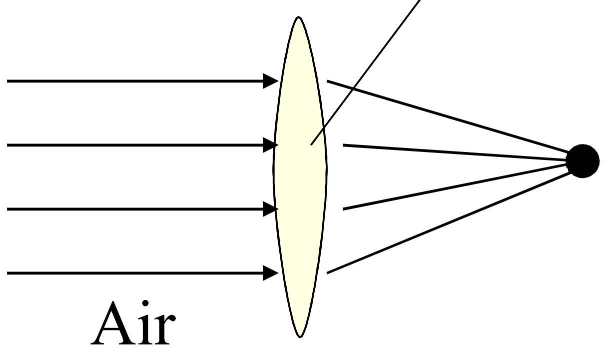
f { + for convex lenses; - for concave lenses

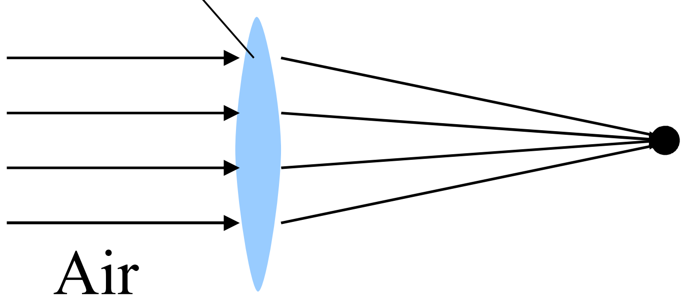
Convex Lens in Water



Because glass has a higher index of refraction that water the convex lens at the left will still converge light, but it will converge at a greater distance from the lens that it normally would in air. This is due to the fact that the difference in index of refraction between water and glass is small compared to that of air and glass. A large difference in index of refraction means a greater change in speed of light at the interface and, hence, a more dramatic change of direction.

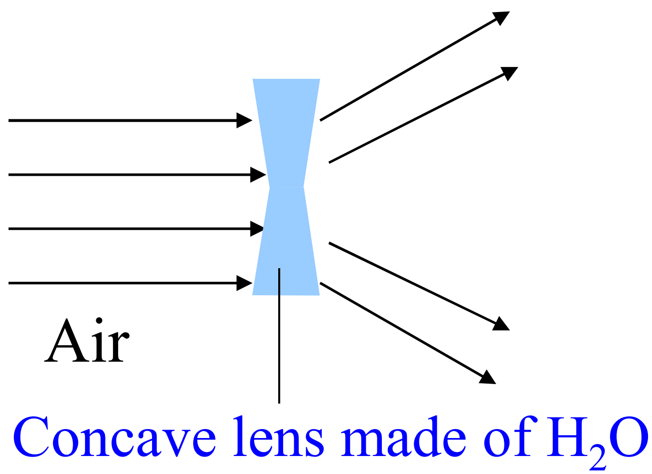
Convex Lens Made of Water





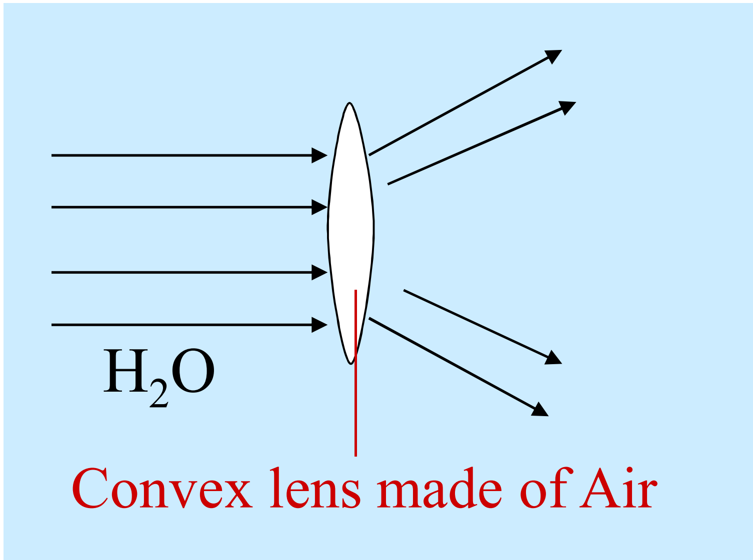
Since water has a higher index of refraction than air, a convex lens made of water will converge light just as a glass lens of the same shape. However, the glass lens will have a smaller focal length than the water lens (provided the lenses are of same shape) because glass has an index of refraction greater than that of water. Since there is a bigger difference in refractive index at the air-glass interface than at the air-water interface, the glass lens will bend light more than the water lens.

Air & Water Lenses



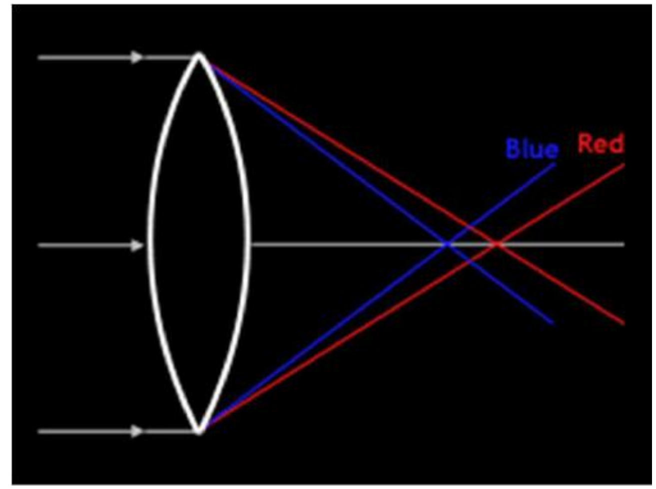
On the left is depicted a concave lens filled with water, and light rays entering it from an air-filled environment. Water has a higher index than air, so the rays diverge just like they do with a glass lens.

To the right is an air-filled convex lens submerged in water. Instead of converging the light, the rays diverge because air has a lower index than water.

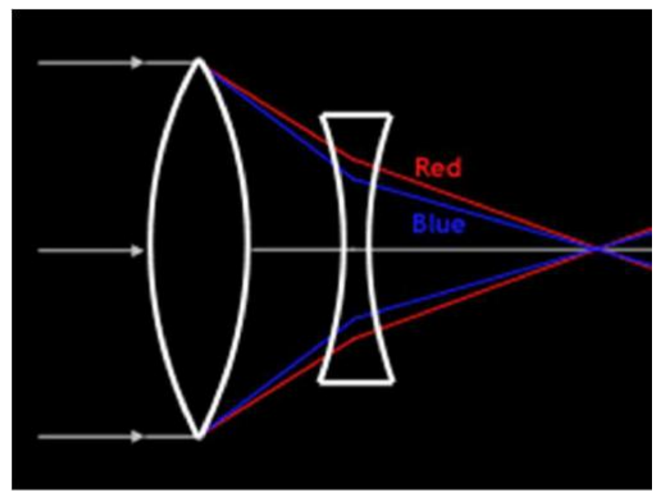


Chromatic Aberration

As in a raindrop or a prism, different wave-lengths of light are refracted at different angles (higher frequency ↔ greater bending). The light passing through a lens is slightly dispersed, so objects viewed through lenses will be ringed with color. This is known as chromatic aberration and it will always be present when a single lens is used. Chromatic aberration can be greatly reduced when a convex lens is combined with a concave lens with a different index of refraction. The dispersion caused by the convex lens will be almost canceled by the dispersion caused by the concave lens. Lenses such as this are called achromatic lenses and are used in all precision optical instruments.



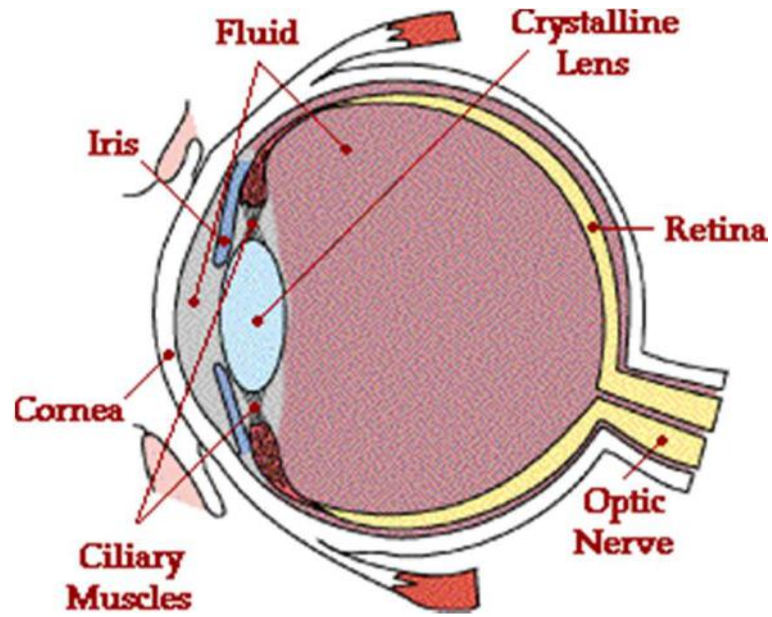
Chromatic Aberration



Achromatic Lens

Human eye

The human eye is a fluid-filled object that focuses images of objects on the retina. The cornea, with an index of refraction of about 1.38, is where most of the refraction occurs. Some of this light will then passes through the pupil opening into the lens, with an index of refraction of about 1.44. The lens is flexible and the ciliary muscles contract or relax to change its shape and focal length.



When the muscles relax, the lens flattens and the focal length becomes longer so that distant objects can be focused on the retina. When the muscles contract, the lens is pushed into a more convex shape and the focal length is shortened so that close objects can be focused on the retina. The retina contains rods and cones to detect the intensity and frequency of the light and send impulses to the brain along the optic nerve.

Hyperopia

Formation of image behind the retina in a hyperopic eye.

Convex lens correction for hyperopic eye.

- The first eye shown suffers from farsightedness, which is also known as **hyperopia**. This is due to a focal length that is too long, causing the image to be focused behind the retina, making it difficult for the person to see close up things.
- The second eye is being helped with a convex lens. The convex lens helps the eye refract the light and decrease the image distance so it is once again focused on the retina.
- Hyperopia usually occurs among adults due to weakened ciliary muscles or decreased lens flexibility.

Farsighted means "can see far" and the rays focus too far from the lens.

Myopia

Formation of image in front of the retina in a myopic eye.

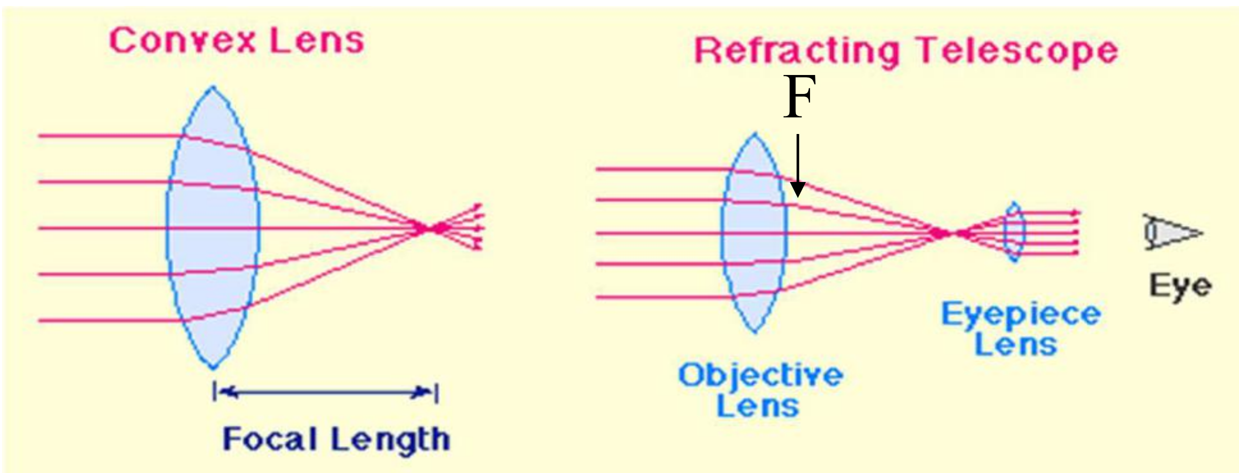
Concave lens correction for myopic eye.

- The first eye suffers from nearsightedness, or **myopia**. This is a result of a focal length that is too short, causing the images of distant objects to be focused in front of the retina.
- The second eye's vision is being corrected with a concave lens. The concave lens diverges the light rays, increasing the image distance so that it is focused on the retina.
- Nearsightedness is common among young people, sometimes the result of a bulging cornea (which will refract light more than normal) or an elongated eyeball.

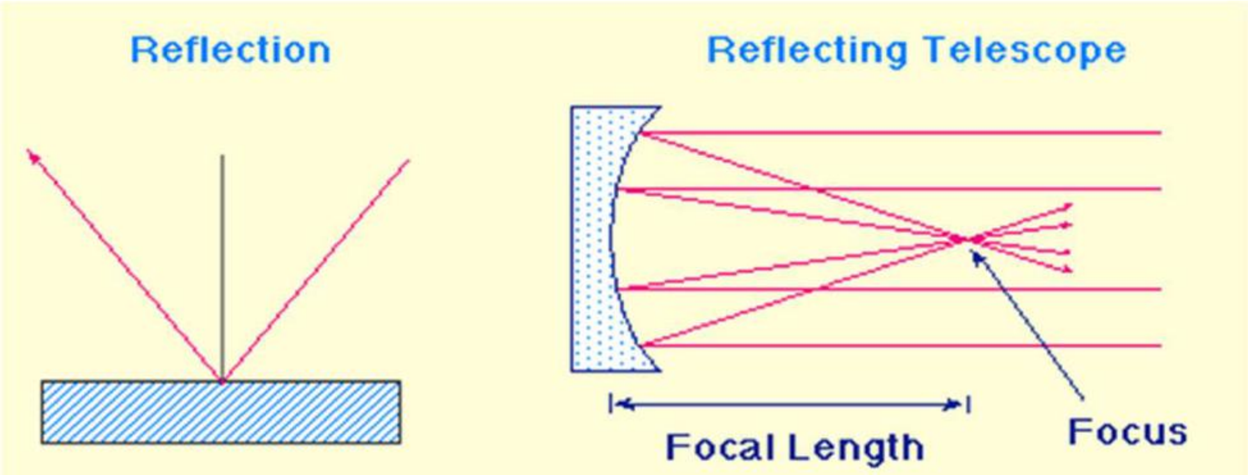
Nearsighted means "can see near" and the rays focus too near the lens.

Telescopes

- Refracting telescopes are comprised of two convex lenses. The objective lens collects light from a distant source, converging it to a focus and forming a real, inverted image inside the telescope. The objective lens needs to be fairly large in order to have enough light-gathering power so that the final image is bright enough to see. An eyepiece lens is situated beyond this focal point by a distance equal to its own focal length. Thus, each lens has a focal point at F. The rays exiting the eyepiece are nearly parallel, resulting in a magnified, inverted, virtual image. Besides magnification, a good telescope also needs resolving power, which is its ability to distinguish objects with very small angular separations.



- Galileo was the first to use a refracting telescope for astronomy. It is difficult to make large refracting telescopes, though, because the objective lens becomes so heavy that it is distorted by its own weight. In 1668 Newton invented a reflecting telescope. Instead of an objective lens, it uses a concave objective mirror, which focuses incoming parallel rays. A small plane mirror is placed at this focal point to shoot the light up to an eyepiece lens (perpendicular to incoming rays) on the side of the telescope. The mirror serves to gather as much light as possible, while the eyepiece lens, as in the refracting scope, is responsible for the magnification.



Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

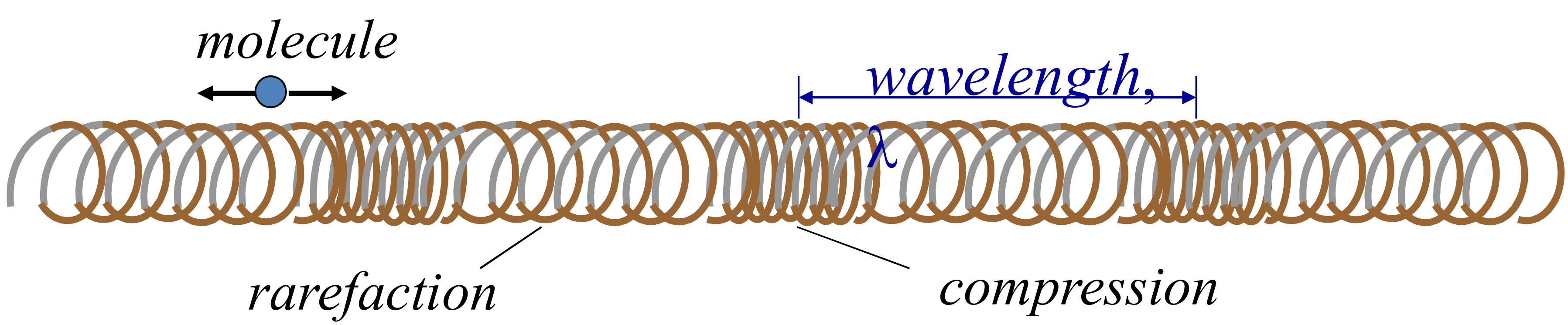
Sound, Doppler, Acoustic

Sound, Doppler, Acoustic

- **Longitudinal Waves**
- **Pressure Graphs**
- **Sound**
- **Wave fronts**
- **Frequency & Pitch**
- **Human Ear**
- **Sonar & Echolocation**
- **Doppler Effect**
- **Interference**
- **Standing Waves in a String**
- **Standing Waves in a Tube**
- **Acoustic**
- **Musical Instruments**
- **Beats**
- **Intensity**
- **Sound Level (decibels)**

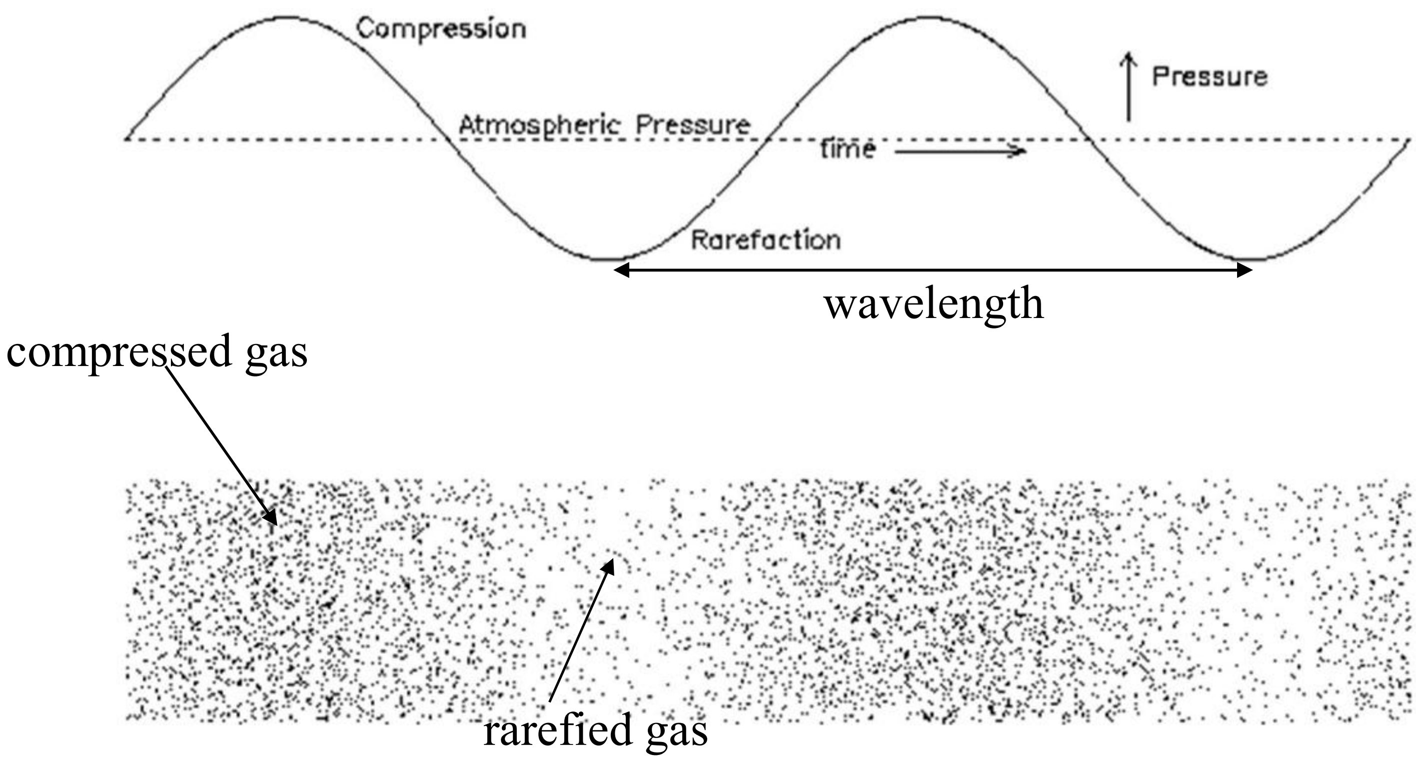
Longitudinal Waves

A longitudinal wave the particles in a medium travel back & forth parallel to the wave itself. Sound waves are longitudinal and they can travel through most any medium, so molecules of air (or water, etc.) move back & forth in the direction of the wave creating high pressure zones (compressions) and low pressure zones (rarefactions). The molecules act just like the individual coils in the spring. The faster the molecules move back & forth, the greater the frequency of the wave, and the greater distance they move, the greater the wave's amplitude.



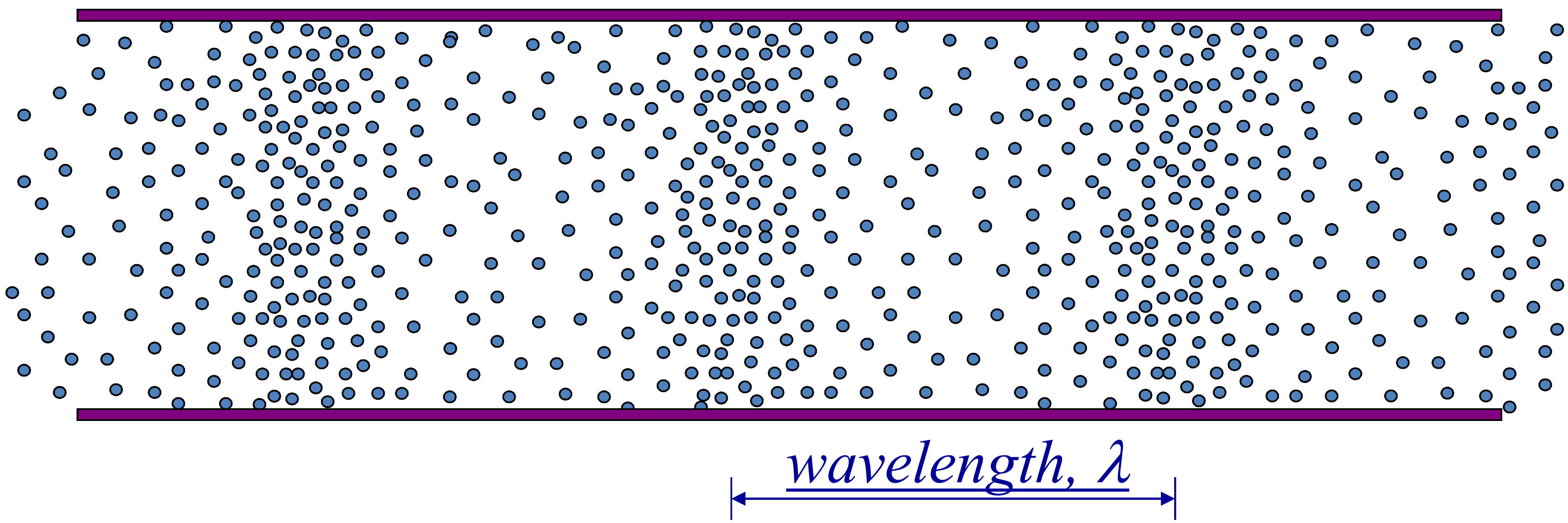
Sound

- Sound is really tiny fluctuations of air pressure
  - units of pressure: N/m^2 or psi (lbs/square-inch)
- Carried through air at 345 m/s (770 m.p.h) as *compressions* and *rarefactions* in air pressure



Sound Waves: Molecular Point of View

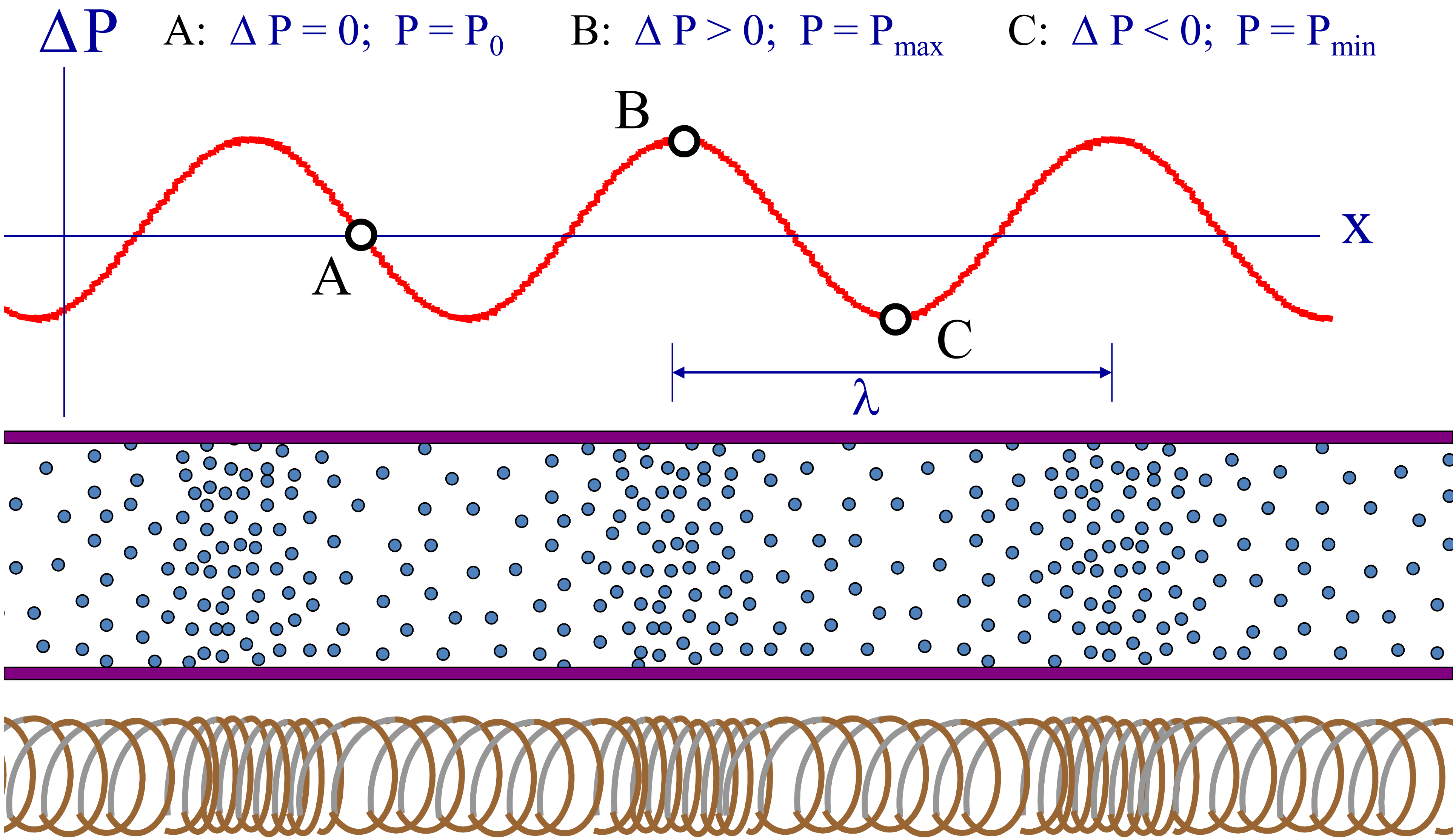
When sound travels through a medium, there are alternating regions of high and low pressure. Compressions are high pressure regions where the molecules are crowded together. Rarefactions are low pressure regions where the molecules are more spread out. An individual molecule moves side to side with each compression. The speed at which a compression propagates through the medium is the wave speed, but this is different than the speed of the molecules themselves.



Pressure vs Position

The pressure at a given point in a medium fluctuates slightly as sound waves pass by. The wavelength is determined by the distance between consecutive compressions or consecutive rarefactions. At each compression the pressure is a tad bit higher than its normal pressure. At each rarefaction the pressure is a tad bit lower than normal. Let's call the equilibrium (normal) pressure P_0 and the difference in pressure from equilibrium ΔP. ΔP varies and is at a max at a compression or rarefaction. In a fluid like air or water, ΔP_{max} is typically very small compared to P_0 but our ears are very sensitive to slight deviations in pressure. The bigger ΔP is, the greater the amplitude of the sound wave, and the louder the sound.

Pressure vs Position Graph



Pressure vs Time

The pressure at a given point does not stay constant. If we only observed one position we would find the pressure there varies sinusoidally with time, ranging from:

P_0 to $P_0 + \Delta P_{max}$ back to P_0 then to $P_0 - \Delta P_{max}$ and back to P_0

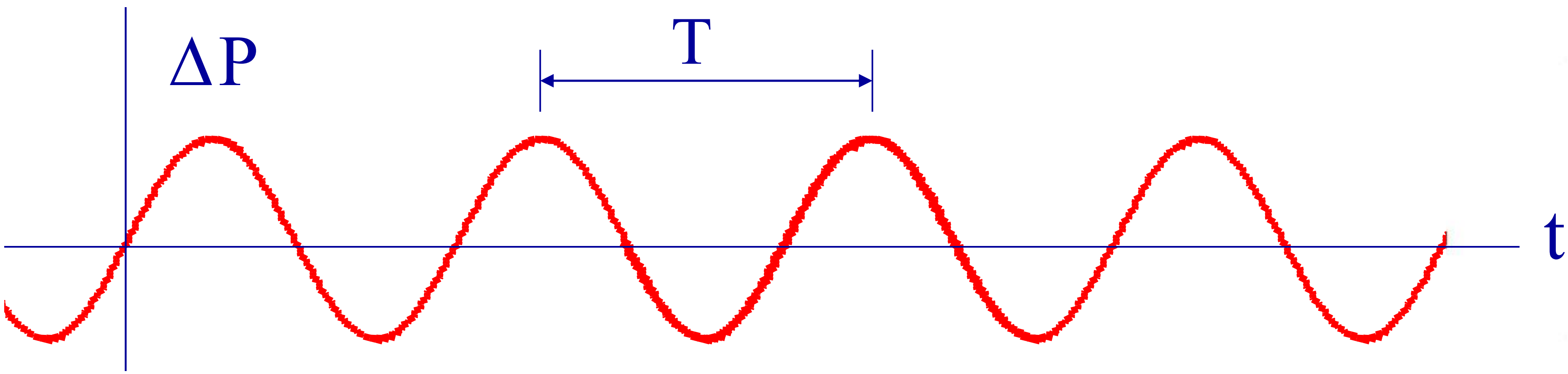
The cycle can also be described as:

equilibrium → compression → equilibrium → rarefaction → equilibrium

The time it takes to go through this cycle is the period of the wave. The number of times this cycle happens per second is the frequency of the wave in Hertz.

Therefore, the pressure in the medium is a function of both position and time!

Pressure vs Time Graph



Rather than looking at a region of space at an instant in time, here we're looking at just one point in space over an interval of time. At time zero, when the pressure readings began, the molecules were at their normal pressure. The pressure at this point in space fluctuates sinusoidally as the waves pass by: normal → high → normal → low → normal. The time needed for one cycle is the period. The higher the frequency, the shorter the period. The amplitude of the graph represents the maximum deviation from normal pressure (as it did on the pressure vs. position graph), and this corresponds to loudness.

Comparison of Pressure Graphs

- Pressure vs Position: The graph is for a snapshot in time and displays pressure variation for over an interval of space. The distance between peaks on the graph is the wavelength of the wave.
- Pressure vs Time: The graph displays pressure variation over an interval of time for only one point in space. The distance between peaks on the graph is the period of the wave. The reciprocal of the period is the frequency.
- Both Graphs: Sound waves are longitudinal even though these graphs look like transverse waves. Nothing in a sound wave is actually waving in the shape of these graphs! The amplitude of either graph corresponds to the loudness of the sound. The absolute pressure matters not. For loudness, all that matters is how much the pressure deviates from its norm, which doesn't have to be much. In real life the amplitude would diminish as the sound waves spread out.

Speed of Sound

As with all waves, the speed of sound depends on the medium through which it is traveling. In the wave unit we learned that the speed of a wave traveling on a rope is given by:

Rope: $v = \sqrt{\dfrac{F}{\mu}}$

F = tension in rope
μ = mass per unit length of rope

In a rope, waves travel faster when the rope is under more tension and slower if the rope is denser. The speed of a sound wave is given by:

Sound: $v = \sqrt{\dfrac{B}{\rho}}$

B = bulk modulus of medium
ρ = mass per unit volume (density)

The bulk modulus, B, of a medium basically tells you how hard it is to compress it, just as the tension in a rope tells you how hard it is stretch it or displace a piece of it.

Rope: $v = \sqrt{\frac{F}{\mu}}$

Notice that each equation is in the form

Sound: $v = \sqrt{\frac{B}{\rho}}$

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

The bulk modulus for air is tiny compared to that of water, since air is easily compressed and water nearly incompressible. So, even though water is much denser than air, water is so much harder to compress that sound travels over 4 times faster in water.

Steel is almost 8 times denser than water, but it's over 70 times harder to compress. Consequently, sound waves propagate through steel about 3 times faster than in water, since $(70 / 8)^{0.5} \approx 3$.

Temperature & Speed of Sound

$$v = \sqrt{\frac{B}{\rho}}$$

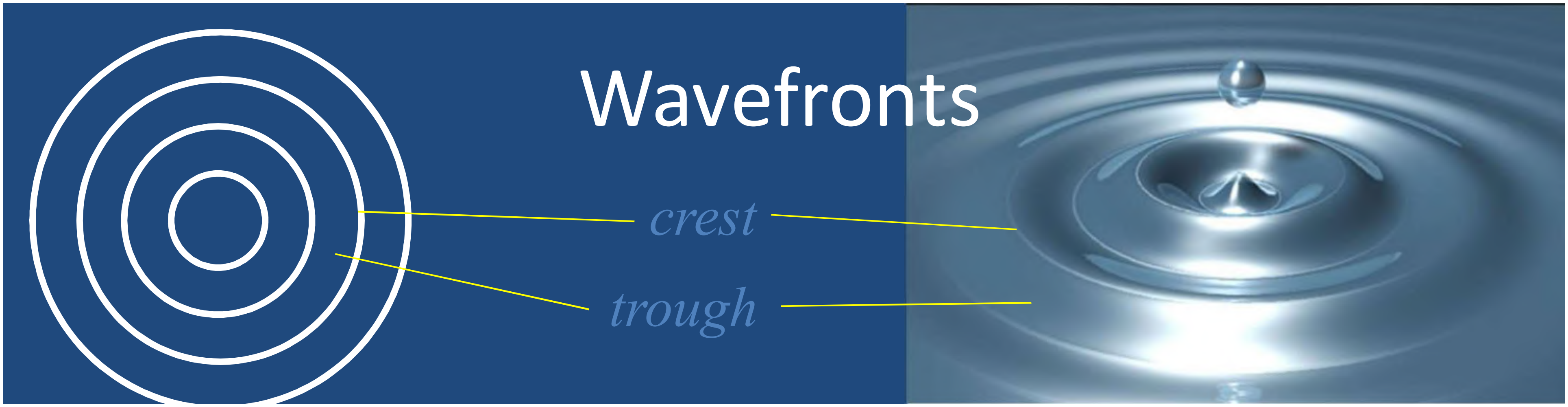
The speed of sound in dry air is given by:
$v \approx 331.4 + 0.60\, T$, where T is air temp in ° C.

Because the speed of sound is inversely proportional to the medium's density, the less dense the medium, the faster sound travels. The hotter a substance is, the faster its molecules/atoms vibrate and the more room they take up. This lowers the substance's density, which is significant in a gas. So, in the summer, sound travels slightly faster outside than it does in the winter. To visualize this keep in mind that molecules must bump into each other in order to transmit a longitudinal wave. When molecules move quickly, they need less time to bump into their neighbors.

Sound Speeds

Medium	sound speed (m/s)
air (0°C) air (20°C)	331 343
water	1497
gold diamond	3240 12000
brick	3650
wood	3800–4600
glass Pyrex	5100 5640
steel iron	5790 5130
aluminum	6420

Wavefronts



Some waves are one dimensional, like vibrations in a guitar string or sound waves traveling along a metal rod. Some waves are two dimensional, such as surface water waves or seismic waves traveling along the surface of the Earth. Some waves are 3-D, such as sound traveling in all directions from a bell, or light doing the same from a flashlight. To visualize 2-D and 3-D waves, we often draw wavefronts. The red wavefronts below could represent the crest of water waves on a pond moving outward after a rock was dropped in the middle. They could also be used to represent high pressure zonesin sound waves. The wavefronts for 3-D sound waves would be spherical, but concentric circles are often used to simplify the picture. If the wavefronts are evenly spaced, then λ is a constant.

Frequency & Pitch

Just as the amplitude of a sound wave relates to its loudness, the frequency of the wave relates to its pitch. The higher the pitch, the higher the frequency. The frequency you hear is just the number of wavefronts that hit your eardrums in a unit of time. Wavelength doesn't necessarily correspond to pitch because, even if wavefronts are very close together, if the wave is slow moving, not many wavefronts will hit you each second. Even in a fast moving wave with a small wavelength, the receiver or source could be moving, which would change the frequency, hence the pitch.

Frequency $\leftrightarrow$ Pitch

Amplitude $\leftrightarrow$ Loudness

Human Ear

The exterior part of the ear (the auricle, or pinna) is made of cartilage and helps funnel sound waves into the auditory canal, which has wax fibers to protect the ear from dirt. At the end of the auditory canal lies the eardrum (tympanic membrane), which vibrates with the incoming sound waves and transmits these vibrations along three tiny bones (ossicles) called the hammer, anvil, and stirrup (malleus, incus, and stapes). The little stapes bone is attached to the oval window, a membrane of the cochlea.

The cochlea is a coil that converts the vibrations it receives into electrical impulses and sends them to the brain via the auditory nerve. Delicate hairs (stereocilia) in the cochlea are responsible for this signal conversion. These hairs are easily damaged by loud noises, a major cause of hearing loss!

The semicircular canals help maintain balance, but do not aid hearing.

Range of Human Hearing

The maximum range of frequencies for most people is from about 20 to 20 thousand hertz. This means if the number of high pressure fronts (wavefronts) hitting our eardrums each second is from 20 to 20 000, then the sound may be detectable. If you listen to loud music often, you'll probably find that your range (bandwidth) will be diminished.

Some animals, like dogs and some fish, can hear frequencies that are higher than what humans can hear (ultrasound). Bats and dolphins use ultrasound to locate prey (echolocation). Doctors make use of ultrasound for imaging fetuses and breaking up kidney stones. Elephants and some whales can communicate over vast distances with sound waves too low in pitch for us to hear (infrasound).

Echoes & Reverberation

An echo is simply a reflected sound wave. Echoes are more noticeable if you are out in the open except for a distant, large object. If went out to the dessert and yelled, you might hear a distant canyon yell back at you. The time between your yell and hearing your echo depends on the speed of sound and on the distance to the to the canyon. In fact, if you know the speed of sound, you can easily calculate the distance just by timing the delay of your echo.

Reverberation is the repeated reflection of sound at close quarters. If you were to yell while inside a narrow tunnel, your reflected sound waves would bounce back to your ears so quickly that your brain wouldn't be able to distinguish between the original yell and its reflection. It would sound like a single yell of slightly longer duration.

Sonar

SOund NAvigation and Ranging. In addition to locating prey, bats and dolphins use sound waves for navigational purposes. Submarines do this too. The principle is to send out sound waves and listen for echoes. The longer it takes an echo to return, the farther away the object that reflected those waves. Sonar is used in commercial fishing boats to find schools of fish. Scientists use it to map the ocean floor. Special glasses that make use of sonar can help blind people by producing sounds of different pitches depending on how close an obstacle is.

If radio (low frequency light) waves are used instead of sound in an instrument, we call it radar (radio detection and ranging).

Doppler Effect

A tone is not always heard at the same frequency at which it is emitted. When a train sounds its horn as it passes by, the pitch of the horn changes from high to low. Any time there is relative motion between the source of a sound and the receiver of it, there is a difference between the actual frequency and the observed frequency. This is called the Doppler effect.

The Doppler effect applied to electromagnetic waves helps meteorologists to predict weather, allows astronomers to estimate distances to remote galaxies, and aids police officers catch you speeding. The Doppler effect applied to ultrasound is used by doctors to measure the speed of blood in blood vessels, just like a cop's radar gun. The faster the blood cell are moving toward the doc, the greater the reflected frequency.

Doppler Equation

This equation takes into account the speed of the source of the sound, as well as the listener's speed, relative to the air (or whatever the medium happens to be). The only tricky part is the signs. First decide whether the motion will make the observed frequency higher or lower. (If the source is moving toward the listener, this will increase f_L, but if the listener is moving away from the source, this will decrease f_L.) Then choose the plus or minus as appropriate. A plus sign in the numerator will make f_L bigger, but a plus in the denominator will make f_L smaller. Examples are on the next slide.

$$f_L = f_S\left(\frac{v \pm v_L}{v \pm v_S}\right)$$

f_L = frequency as heard by a listener

f_S = frequency produced by the source

v = speed of sound in the medium

v_L = speed of the listener

v_S = speed of the source

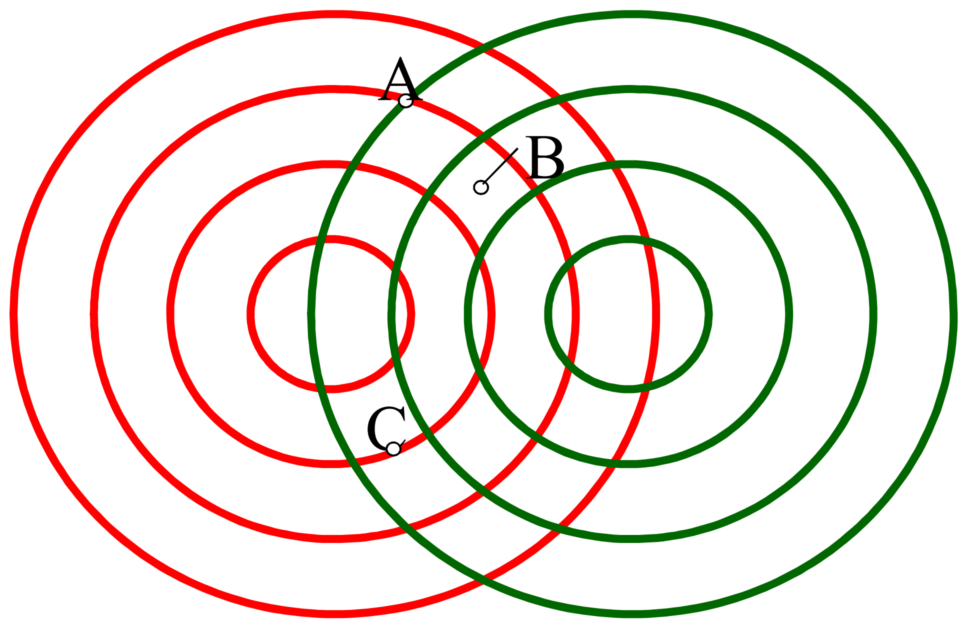
Interference

As we saw in the wave presentation, waves can passes through each other and combine via superposition. Sound is no exception. The pic shows two sets of wavefronts, each from a point source of sound. (The frequencies are the same here, but this is <u>not</u> required for interference.) Wherever constructive interference happens, a listener will here a louder sound. Loudness is diminished where destructive interference occurs.

A: 2 crests meet;
constructive interference

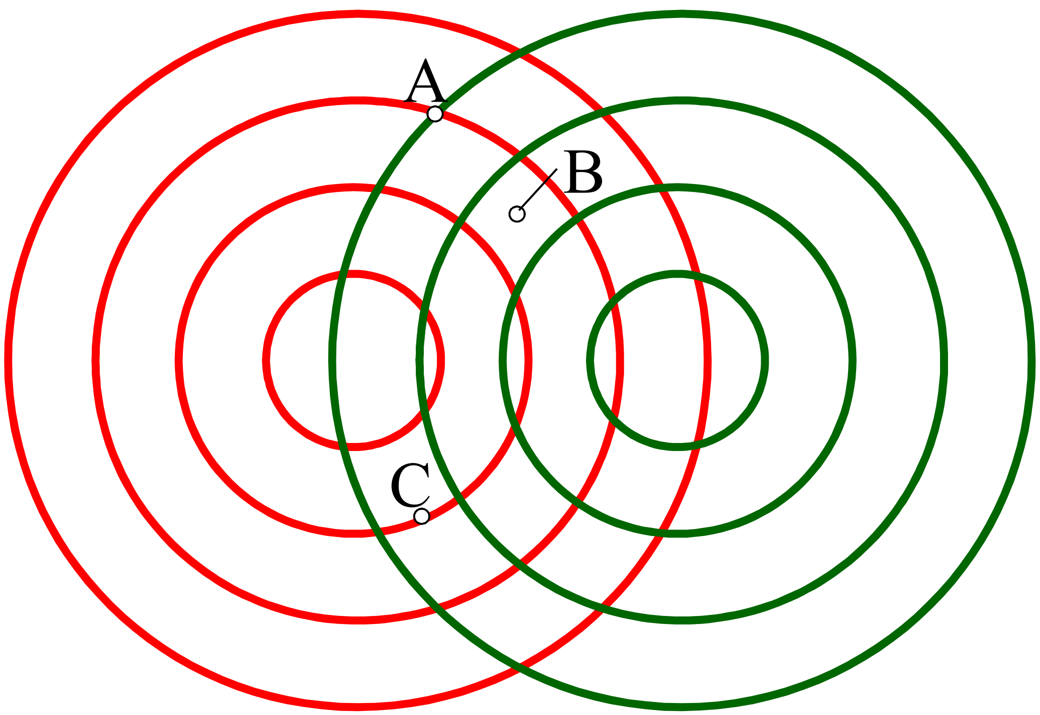
B: 2 troughs meet;
constructive interference

C: Crest meets trough;
destructive interference



Interference: Distance in Wavelengths

We've got two point sources emitting the same wavelength. If the difference in distances from the listener to the point sources is a multiple of the wavelength, constructive interference will occur. Examples: Point A is 3 λ from the red center and 4 λ from the green center, a difference of 1 λ. For B, the difference is zero. Since 1 and 0 are whole numbers, constructive interference happens at these points.



If the difference in distance is an odd multiple of half the wavelength, destructive interference occurs. Example: Point C is 3.5 λ from the green center and 2 λ from the red center. The difference is 1.5 λ , so destructive interference occurs there.

Sound Demo

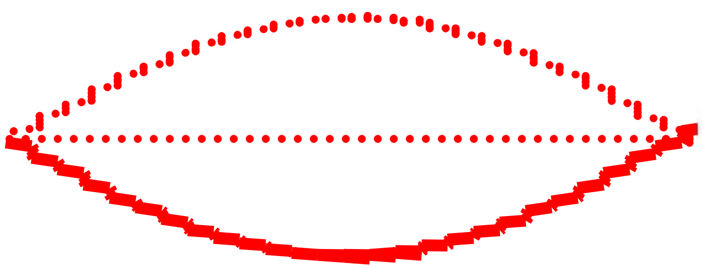
If they were visible, the wavefronts would look just as it did on the last slide, except they would be spheres instead of circles. You can experience the interference by leaning side to side from various places in the room. If you do this, you should hear the loudness fluctuate. This is because your head is moving through points of constructive interference (loud spots) and destructive interference (quiet regions, or “dead spots”). Turning one speaker off will eliminate this effect, since there will be no interference.

Noise Reduction

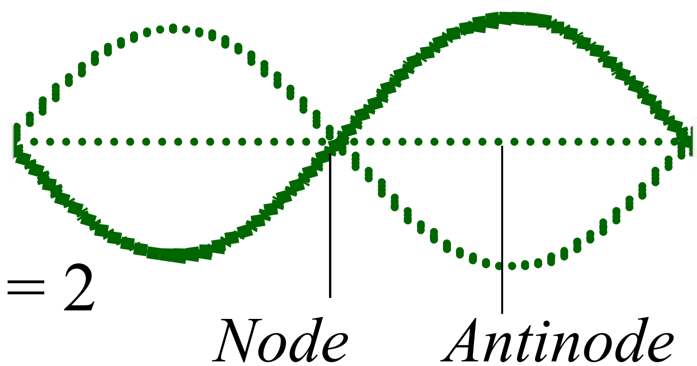
The concept of interference is used to reduce noise. For example, some pilots where special headphones that analyze engine noise and produce the inverse of those sounds. This waves produced by the headphones interfere destructively with the sound waves coming from the engine. As a result, the noise is reduced, but other sounds can still be heard, since the engine noise has a distinctive wave pattern, and only those waves are being cancelled out.

Standing Waves: 2 Fixed Ends

When a guitar string of length L is plucked, only certain frequencies can be produced, because only certain wavelengths can sustain themselves. Only standing waves persist. Many harmonics can exist at the same time, but the fundamental (n = 1) usually dominates. As we saw in the wave presentation, a standing wave occurs when a wave reflects off a boundary and interferes with itself in such a way as to produce nodes and antinodes. Destructive interference always occurs at a node. Both types occur at an antinode; they alternate.



n = 1 (fundamental)



n = 2

Wavelength Formula: 2 Fixed Ends

(string of length L)

The pattern is of the form:

$$\lambda = \frac{2\,L}{n}$$

where n = 1, 2, 3, ….

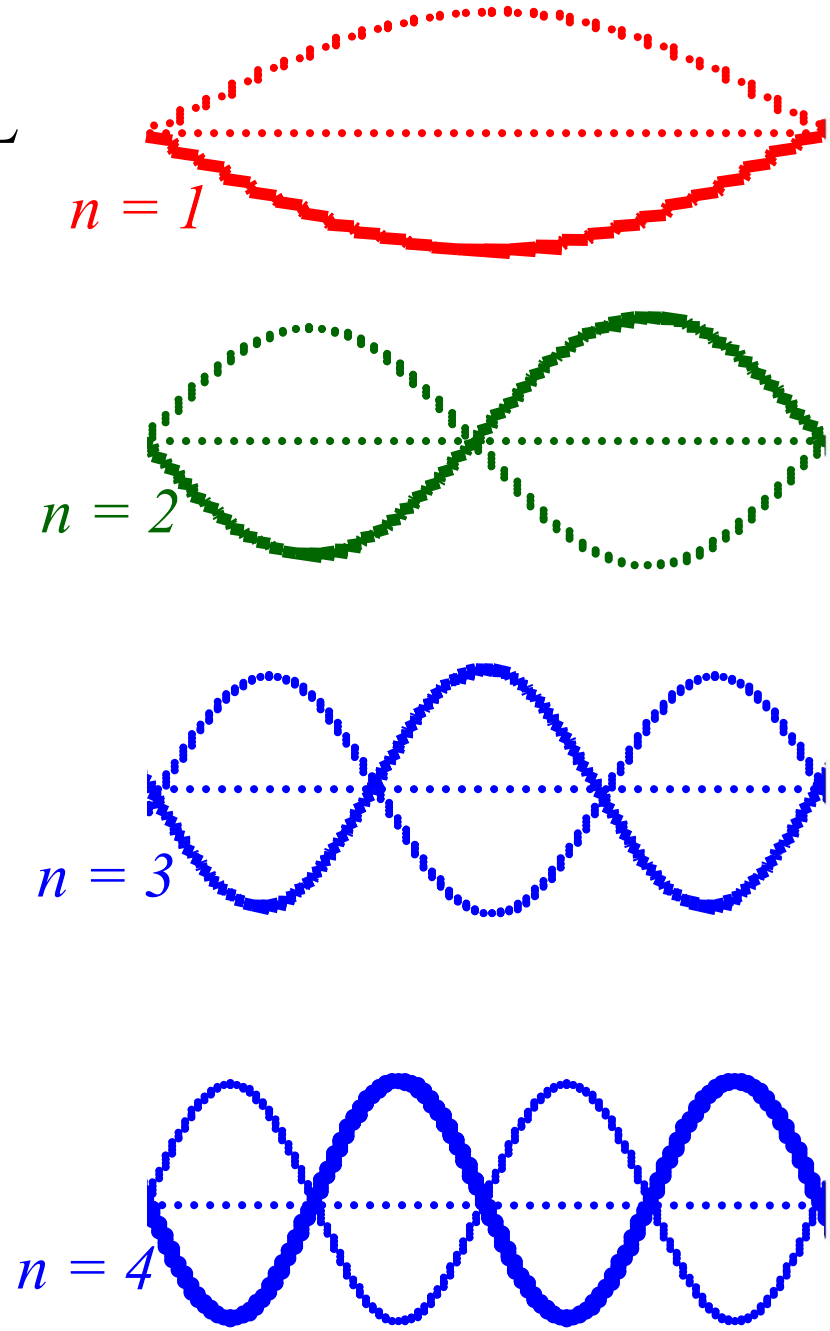
Thus, only certain wavelengths can exists. To obtain tones corresponding to other wavelengths, one must press on the string to change its length.

$\lambda = 2\,L$

$\lambda = L$

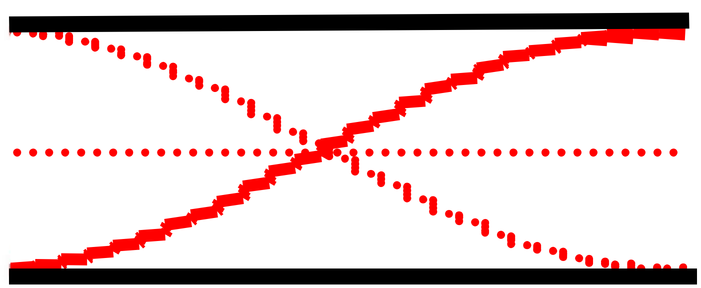
$\lambda = \frac{2}{3}L$

$\lambda = \frac{1}{2}L$



Standings Waves: 2 Open Ends

Like waves traveling on a string, sound waves traveling in a tube reflect back when they reach the end of the tube. (Much of the sound energy will exit the open tube, but some will reflect back.) If the wavelength is right, the reflected waves will combine with the original to create a standing wave. For a tube with two open ends, there will be an antinode at each end, rather than a node. (A closed end would correspond to a node, since it blocks the air from moving.) The pic shows the fundamental. Note: the air does not move like a guitar string moves; the curve represents the amount of vibration. Maximum vibration occurs at the antinodes. In the middle is a node where the air molecules don't vibrate at all.



n = 1 (fundamental)

Wavelength Formula: 2 Open Ends

(tube of length L)

As with the string, the pattern is:

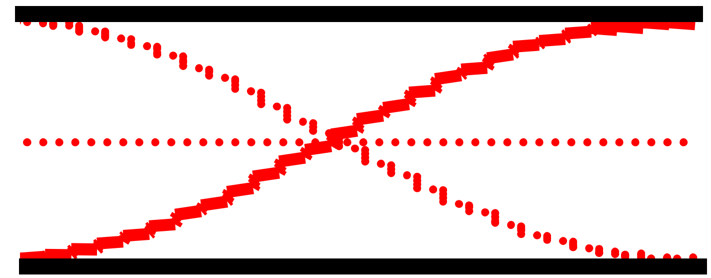
$$\lambda = \frac{2\,L}{n}$$

where n = 1, 2, 3, ….

Thus, only certain wave-lengths will reinforce each other (resonate). To obtain tones corresponding to other wavelengths, one must change the tube's length.

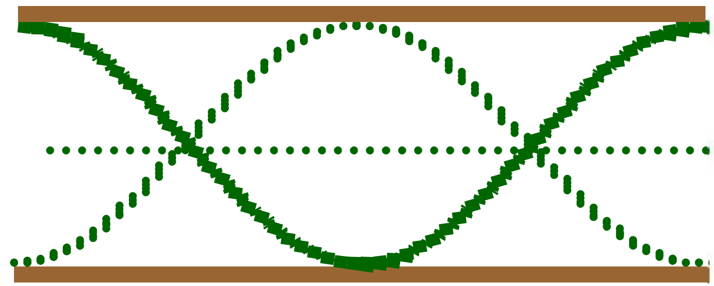
$\lambda = 2\,L$

n = 1



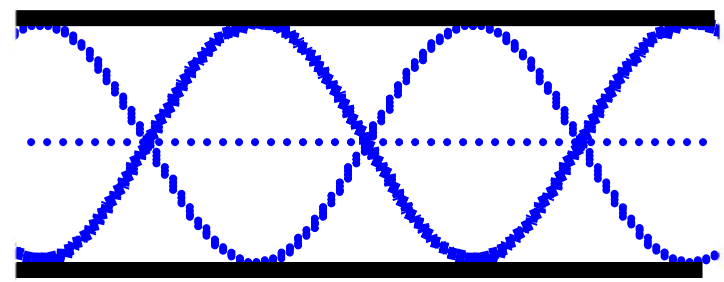
$\lambda = L$

n = 2



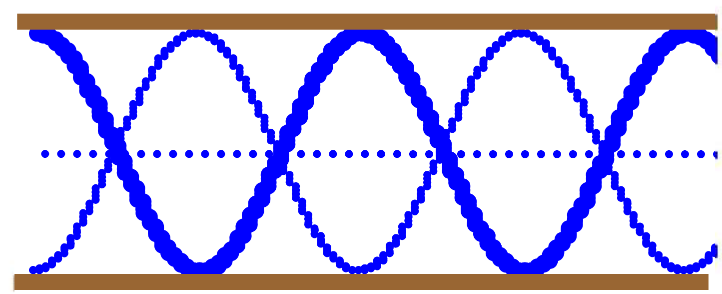
$\lambda = \frac{2}{3}L$

n = 3



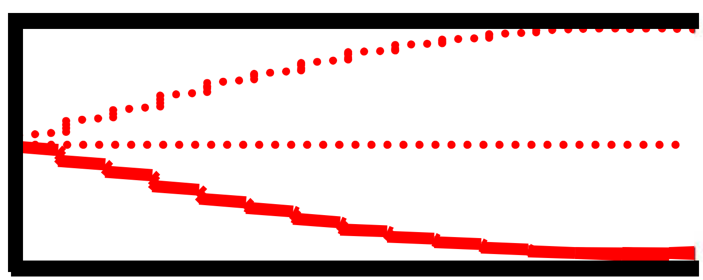
$\lambda = \frac{1}{2}L$

n = 4



Standings Waves: 1 Open End

If a tube has one open and one closed end, the open end is a region of maximum vibration of air molecules an antinode. The closed end is where no vibration occurs a node. At the closed end, only a small amount of the sound energy will be transmitted; most will be reflected. At the open end, of course, much more sound energy is transmitted, but a little is reflected. Only certain wavelengths of sound will resonate in this tube, which depends on it length.



n = 1 (fundamental)

Wavelength Formula: 1 Open End

(tube of length L)

The pattern is:

$$L = \frac{n\lambda}{4}$$

or,

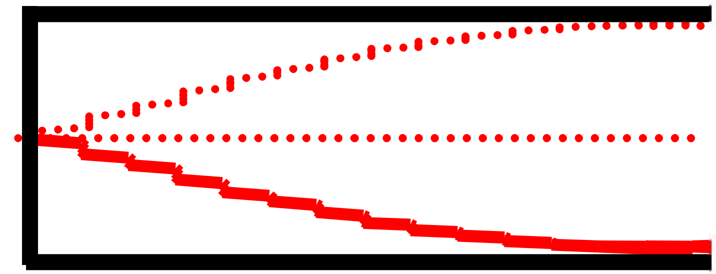
$$\lambda = \frac{4L}{n}$$

where n = 1, 3, 5, 7, ….

Note: only odd harmonics exist when only one end is open.

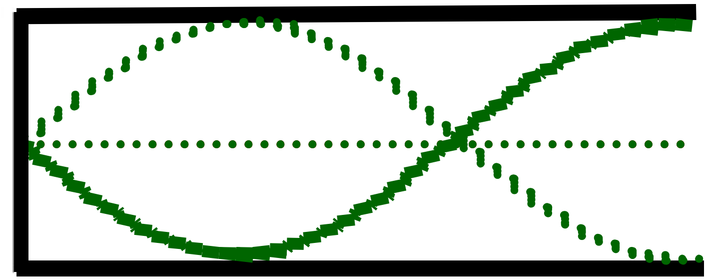
$$L = \frac{1}{4}\lambda$$

n = 1



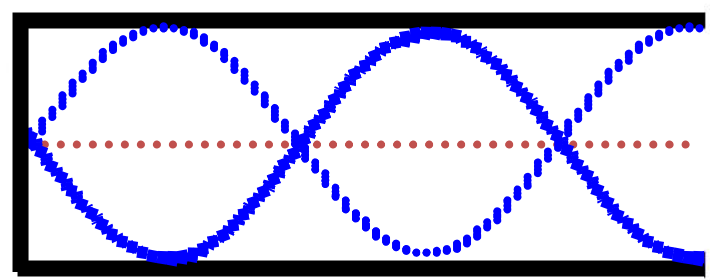
$$L = \frac{3}{4}\lambda$$

n = 3



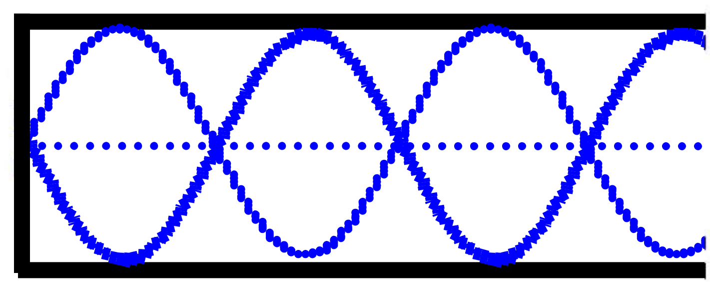
$$L = \frac{5}{4}\lambda$$

n = 5



$$L = \frac{7}{4}\lambda$$

n = 7



Acoustics

Acoustics sometimes refers to the science of sound. It can also refer to how well sounds traveling in enclosed spaces can be heard.

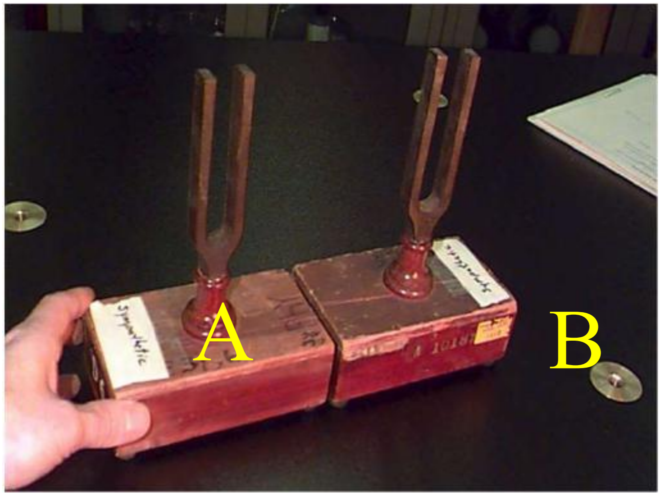
Note how the walls and ceiling are beveled to get sound waves reflect in different directions. This minimizes the odds of there being a "dead spot" somewhere in the audience.

The Great Hall in the Krannert Center is an example of excellent acoustics. Chicago Symphony Orchestra has even recorded there.

Tuning Forks & Resonance

Tuning forks produce sound when struck because, as the tines vibrate back and forth, they bump into neighboring air molecules (A speaker works in the same way). Touch a vibrating tuning fork to the surface of some water, and you'll see the splashing. The more frequently the tines vibrate, the higher the frequency of the sound. The harmonics pics would look just like those for a tube with one open end. Smaller tuning forks make a high pitch sound, since a shorter length means a shorter wavelength.

If a vibrating fork (*A*) is brought near one that is not vibrating (*B*), *A* will cause *B* to vibrate only if they made to produce the same frequency. This is an example of resonance. If the driving force (*A*) matches the natural frequency of *B*, then *A* can cause the amplitude of *B* to increase. (If you want to push someone on a swing higher and higher, you must push at the natural frequency of the swing.)



Resonance: Shattering a Glass

If the frequency of the sound matches the natural frequency of the glass, and if the amplitude is sufficient. The glass's natural frequency can be determined by flicking the glass with your finger and listening to the tone it makes. If the glass is being bombarded by sound waves of this freq-uency, the amplitude of the vibrating glass with grow and grow until the glass shatters.

Musical Instruments

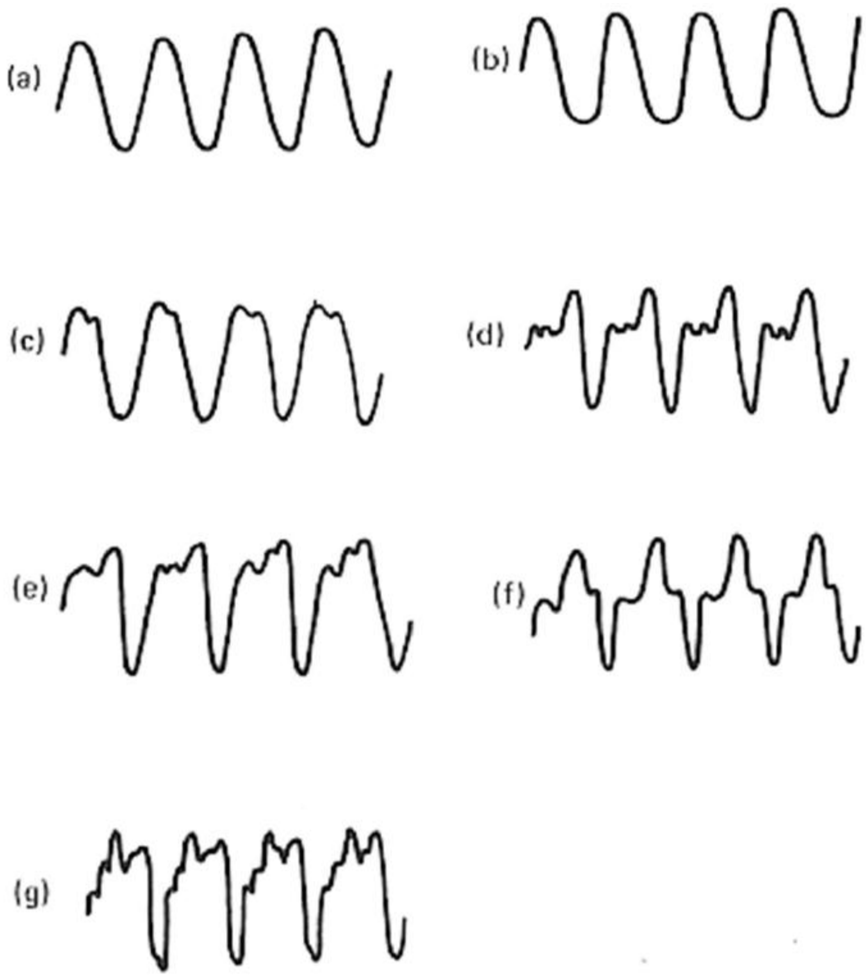
As a guitar, string instruments make use of vibrations on strings where each end is a vibrational node. The strings themselves don't move much air. So, either an electrical pickup and amplifier are needed, or the strings must transmit vibrations to the body of the instrument in which sound waves can resonate.

Other instruments make use of standing waves in tubes. A flute for example can be approximated as cylindrical tubes with two open ends. A clarinet has just one open end (The musician's mouth blocks air in a clarinet, forming a closed end, but a flutist blows air over a hole without blocking the movement of air in and out). Other instruments, like drums, produce sounds via standing waves on a surface, or membrane.

Complex Sounds

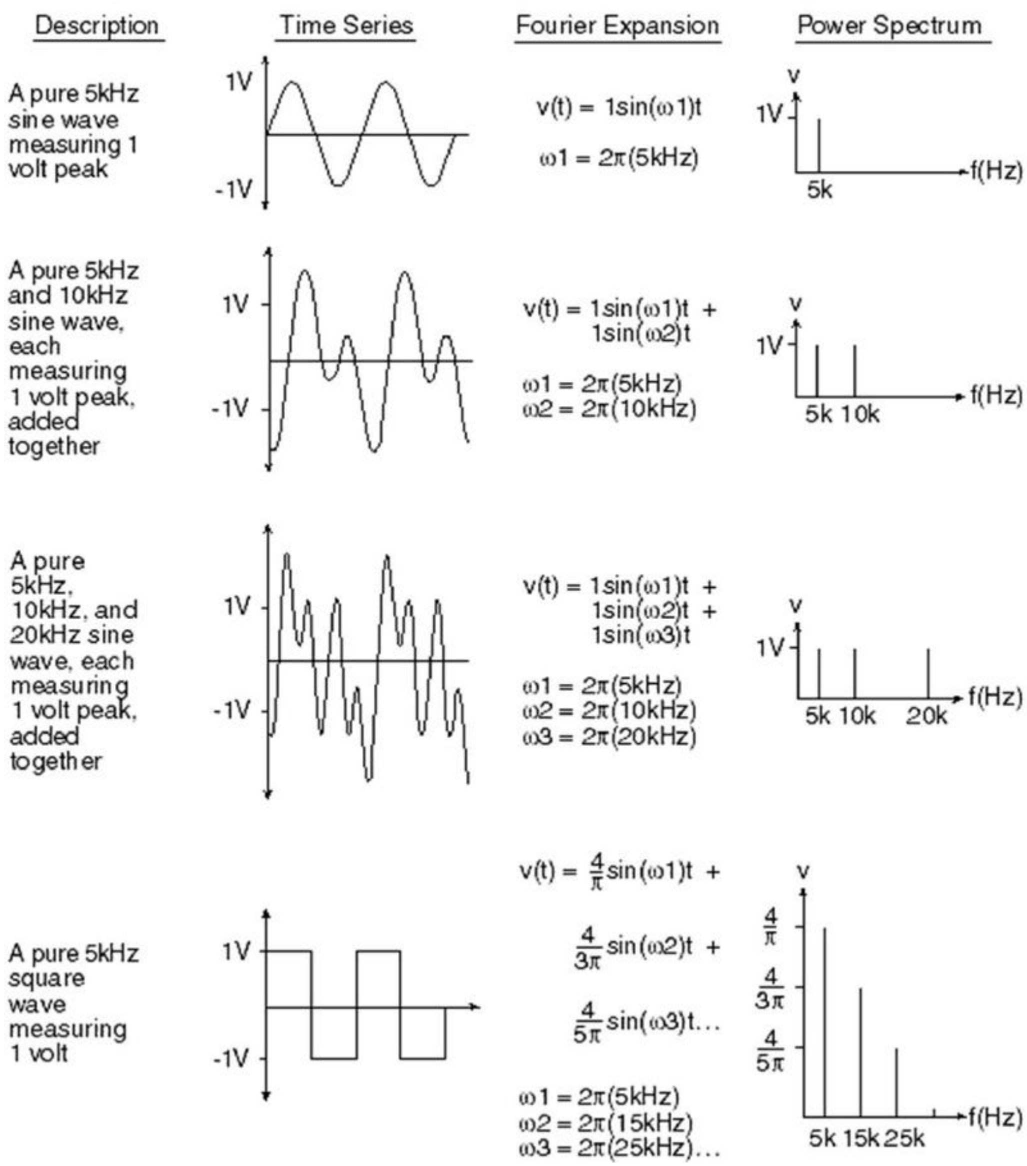
Real sounds are rarely as simple as the individual standing wave patterns we've seen on a string or in a tube. Why is it that two different instruments can play the exact same note at the same volume, yet still sound so different? This is because many different harmonics can exist at the same time in an instrument, and the wave patterns can be very complex. If only fundamental frequencies could be heard, instruments would sound more alike. The relative strengths of different harmonics is known as timbre (*tamber*). In other words, most sounds, including voices, are complex mixtures of frequencies. The sound made by a flute is predominately due to the first & second harmonics, so it's waveform is fairly simple. The sounds of other instruments are more complicated due to the presence of additional harmonics.

All Shapes of Waveforms



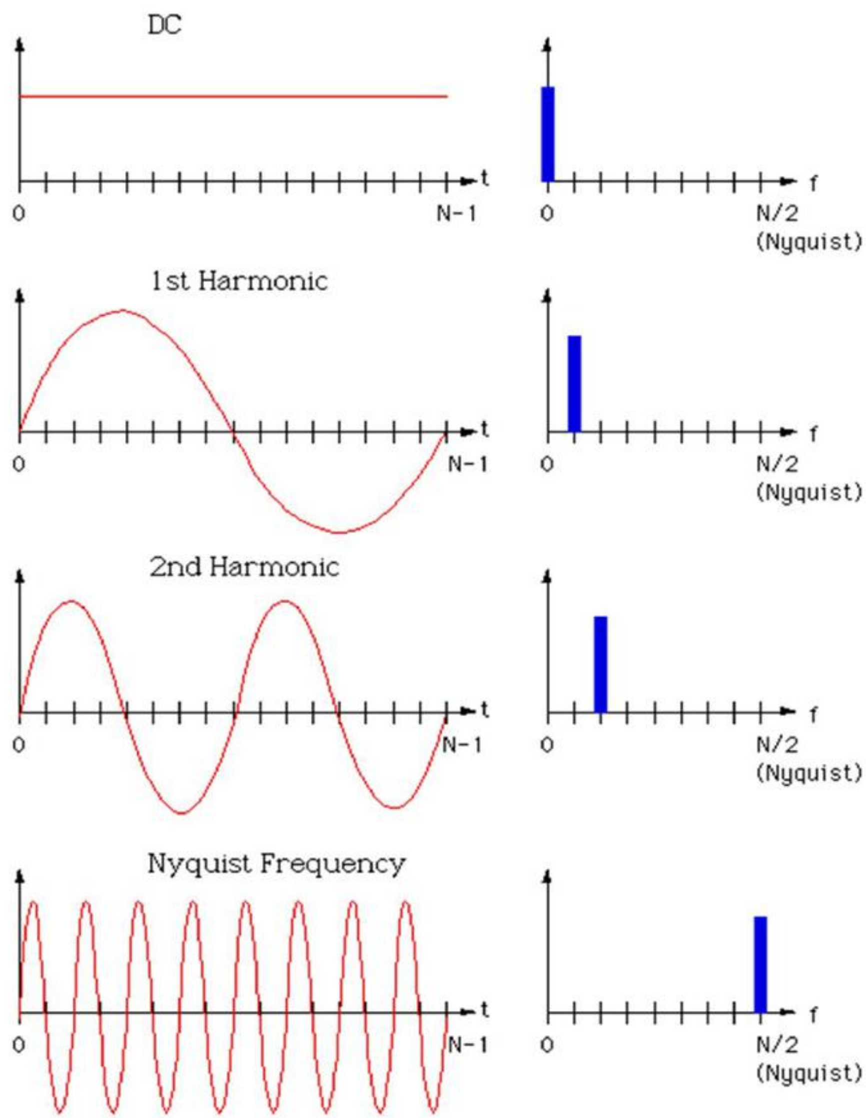
- Different Instruments have different waveforms
  - a: glockenspiel
  - b: soft piano
  - c: loud piano
  - d: trumpet
- More waveforms:
  - e: french horn
  - f: clarinet
  - g: violin
- Our ears are sensitive to the detailed shape of waveforms!

Composite Waveforms



- A single sine wave has only one frequency represented in the "power spectrum"
- Adding a "second harmonic" at twice the frequency makes a more complex waveform
- Throwing in the fourth harmonic, the waveform is even more sophisticated
- A square wave is composed of odd multiples of the fundamental frequency

How does our ear know?



- Our ears pick out frequency components of a waveform
- A DC (constant) signal has no wiggles, thus is at zero frequency
- A sinusoidal wave has a single frequency associated with it
- The faster the wiggles, the higher the frequency
- The height of the spike indicates how strong (amplitude) that frequency component is

Octaves & Ratios

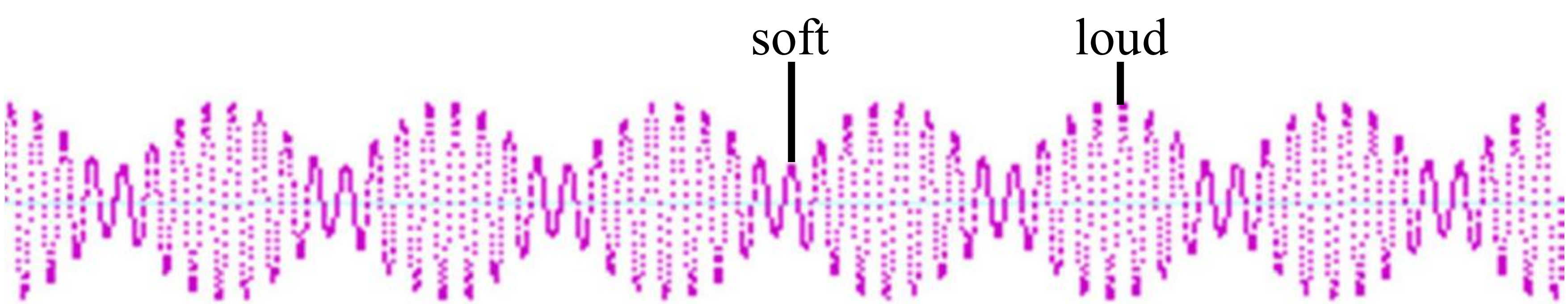
Some mixtures of frequencies are pleasing to the ear; others are not. Typically, a harmonious combo of sounds is one in which the frequencies are in some simple ratio. If a fundamental frequency is combined with the 2^{nd} harmonic, the ratio will be 1 : 2. Each is the same musical note, but the 2^{nd} harmonic is one octave higher. In other words, going up an octave means doubling the frequency.

Another simple (and therefore harmonious) ratio is 2 : 3. This can be produced by playing a C note (262 Hz) with a G note (392 Hz).

Beats

We've seen how many frequencies can combine to produce a complicated waveform. If two frequencies that are nearly the same combine, a phenomenon called beats occurs. The resulting waveform increases and decreases in amplitude in a periodic way, i.e., the sound gets louder and softer in a regular pattern. Hear Beats When two waves differ slightly in frequency, they are alternately in phase and out of phase. Suppose the two original waves have frequencies f_1 and f_2. Then their superposition (below) will have their average frequency and will get louder and softer with a frequency of $| f_1 - f_2 |$.

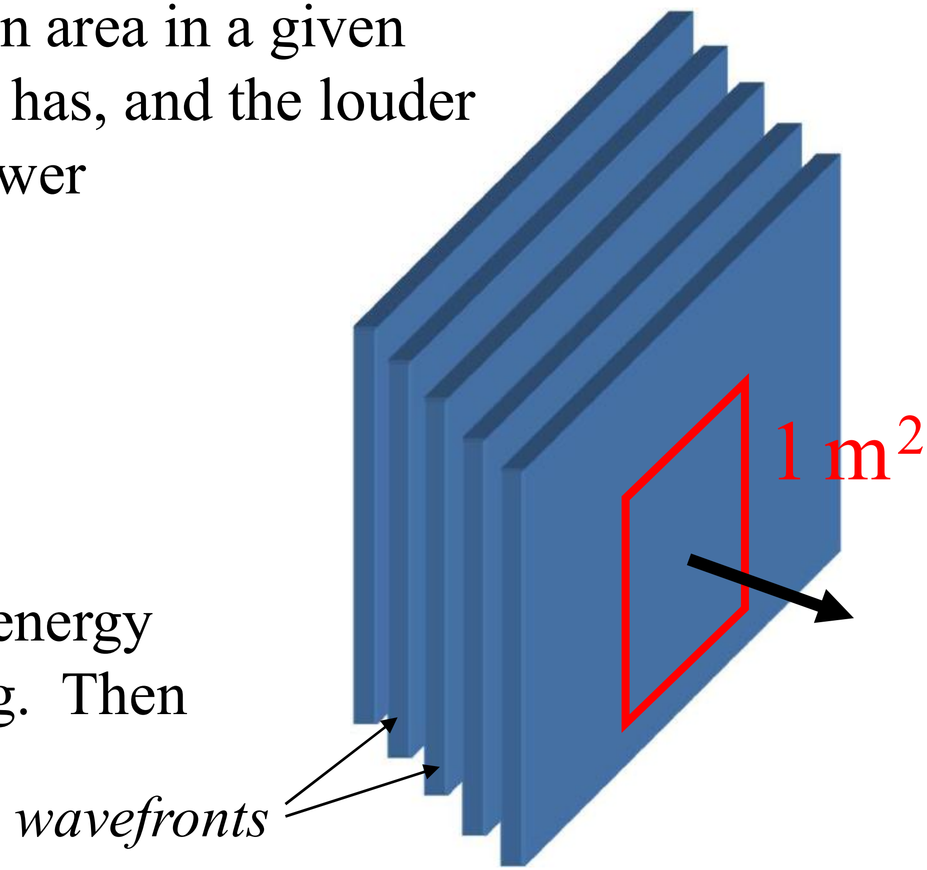
$$f_{beat} = | f_1 - f_2 | \qquad f_{combo} = (f_1 + f_2) / 2$$



Intensity

All waves carry energy. In a typical sound wave the pressure doesn't vary much from the normal pressure of the medium. Consequently, sound waves don't transmit a whole lot of energy. The more energy a sound wave transmits through a given area in a given amount of time, the more intensity it has, and the louder it will sound. That is, intensity is power per unit area:

$$I = \frac{P}{A}$$



Suppose that in one second the green wavefronts carry one joule of sound energy through the one square meter opening. Then the intensity at the red rectangle is $1\ W / m^2$. (1 Watt = 1 J / s.)

Threshold Intensity

The more intense a sound is, the louder it will be. Normal sounds carry small amounts of energy, but our ears are very sensitive. In fact, we can hear sounds with intensities as low as 10^{-12} W / m ^{2} ! This is called the threshold intensity, I $_0$.

$$I_0 = 10^{-12}\ W/m^2$$

This means that if we had enormous ears like Dumbo’s, say a full square meter in area, we could hear a sound delivering to this area an energy of only one trillionth of a joule each second! Since our ears are thousands of times smaller, the energy our ears receive in a second is thousands of times less.

Sound Level

The greater the intensity of a sound at a certain place, the louder it will sound. But doubling the intensity will not make it seem twice as loud. Experiments show that the intensity must increase by about a factor of 10 before the sound will seem twice as loud to us. A sound with a 100 times greater intensity will sound about 4 times louder. Therefore, we measure sound level (loudness) based on a logarithmic scale. The sound level in decibels (dB) is given by:

$$\beta = 10 \log \frac{I}{I_0} \quad \text{(in decibels)}$$

Note: According to this definition, a sound at the intensity level registers zero decibels:

$$10 \log (10^{-12} / 10^{-12}) = 10 \log (1) = 0 \text{ dB}$$

The Decibel Scale

The loudness of a given sound depends, of course, on the power of the source of the sound as well as the distance from the source.

Source	Decibels
Anything on the verge of being audible	0
Whisper	30
Normal Conversation	60
Busy Traffic	70
Niagara Falls	90
Train	100
Construction Noise	110
Rock Concert	120
Machine Gun	130
Jet Takeoff	150
Rocket Takeoff	180

Constant exposure leads to permanent hearing loss. (90–110)

← *Pain* (120)

← *Damage* (130)

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

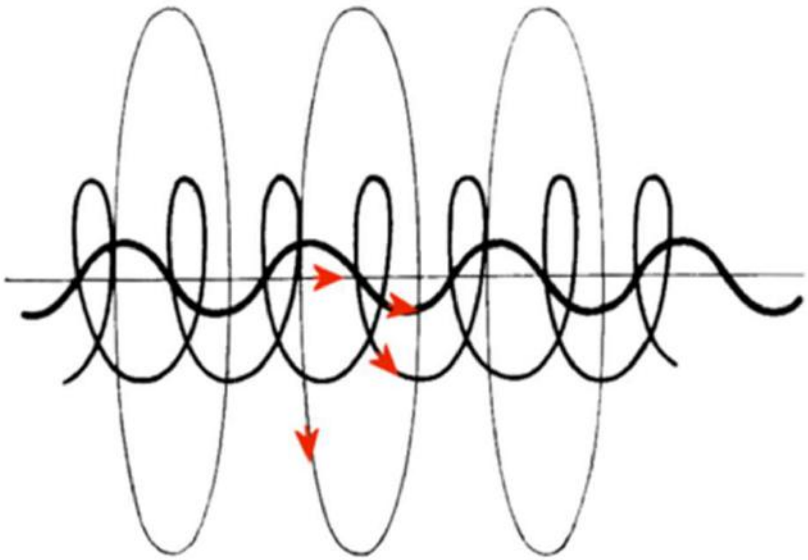
Electromagnetic & Light

Electromagnetic & Light

- Electromagnetic Waves
- Electromagnetic Spectrum and Frequencies
- Energy Carried by Electromagnetic Waves
- Momentum and Radiation Pressure of an Electromagnetic Wave
- Radio Communication
- Light

Electromagnetic Waves

- Do not need matter to transfer energy.
- Are made by vibrating electric charges and can travel through space by transferring energy between vibrating electric and magnetic fields.



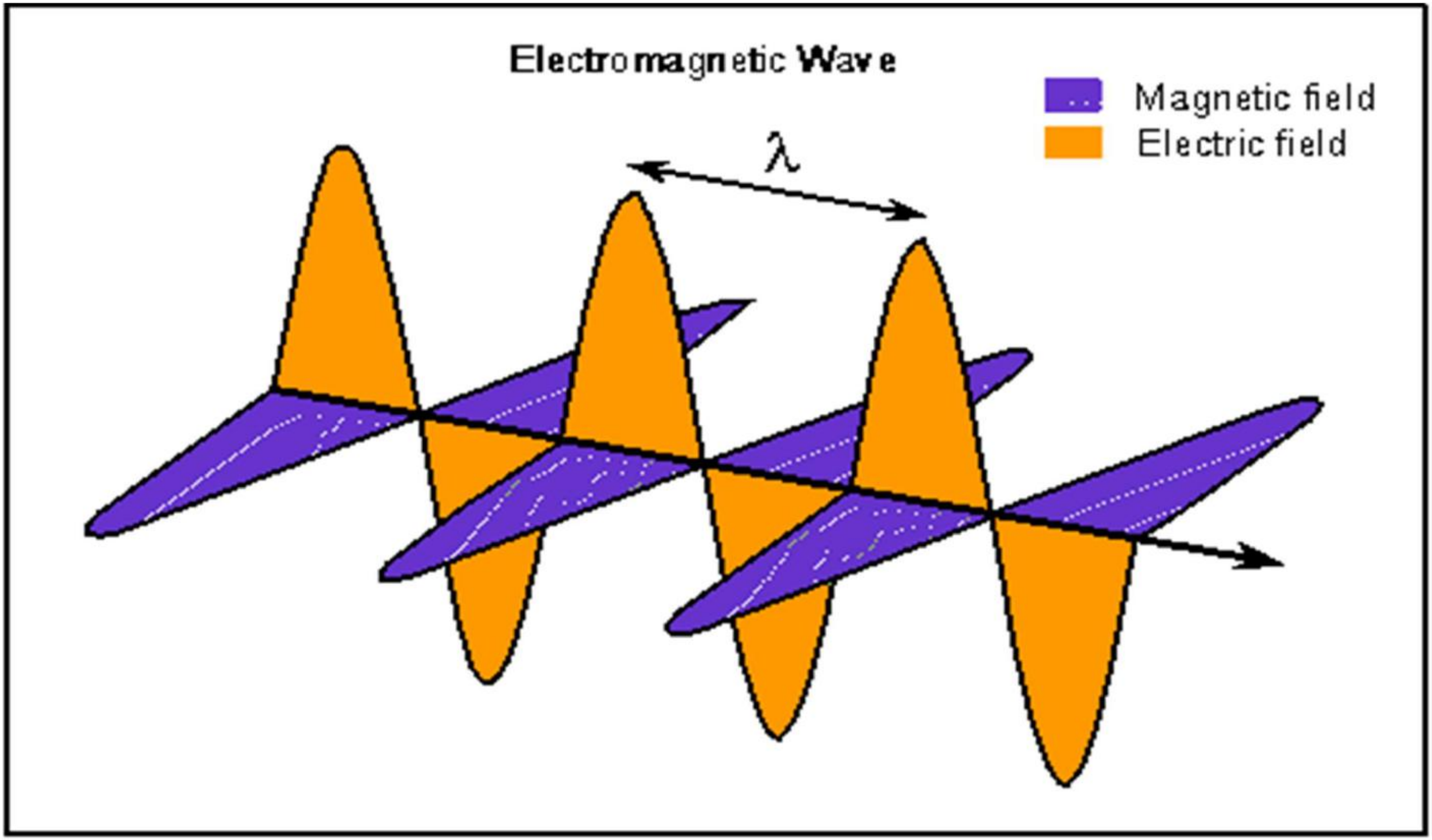
- Any moving electric charge is surrounded by an electric field and a magnetic field.

What happens when electric and magnetic fields change?

- A changing magnetic field creates a changing electric field.
- One example of this is a transformer which transfers electric energy from one circuit to another circuit.
  - In the main coil changing electric current produces a changing magnetic field
  - Which then creates a changing electric field in another coil producing an electric current
  - The reverse is also true.
- Making electromagnetic waves

Making Electromagnetic Waves

- When an electric charge vibrates, the electric field around it changes creating a changing magnetic field.
- The magnetic and electric fields create each other again and again.
- An EM wave travels in all directions. The figure only shows a wave traveling in one direction.
- The electric and magnetic fields vibrate at right angles to the direction the wave travels so it is a transverse wave.
- Please refer to picture on the next slide


Electromagnetic Wave
Magnetic field
Electric field
λ

Properties of EM Waves

- All matter contains charged particles that are always moving; therefore, all objects emit EM waves.
- The wavelengths become shorter as the temperature of the material increases.
- EM waves carry *radiant energy.*
- EM Wavelength= distance from crest to crest. EM Frequency= number of wavelengths that pass a given point in 1 s. As frequency increases, wavelength becomes smaller.
- What is the speed of EM waves?

What is the speed of EM waves?

- All EM waves travel 300,000 km/sec in space.
- EM waves usually travel slowest in solids and fastest in gases.

Material	Speed (km/s)
Vacuum	300,000
Air	<300,000
Water	226,000
Glass	200,000
Diamond	124,000

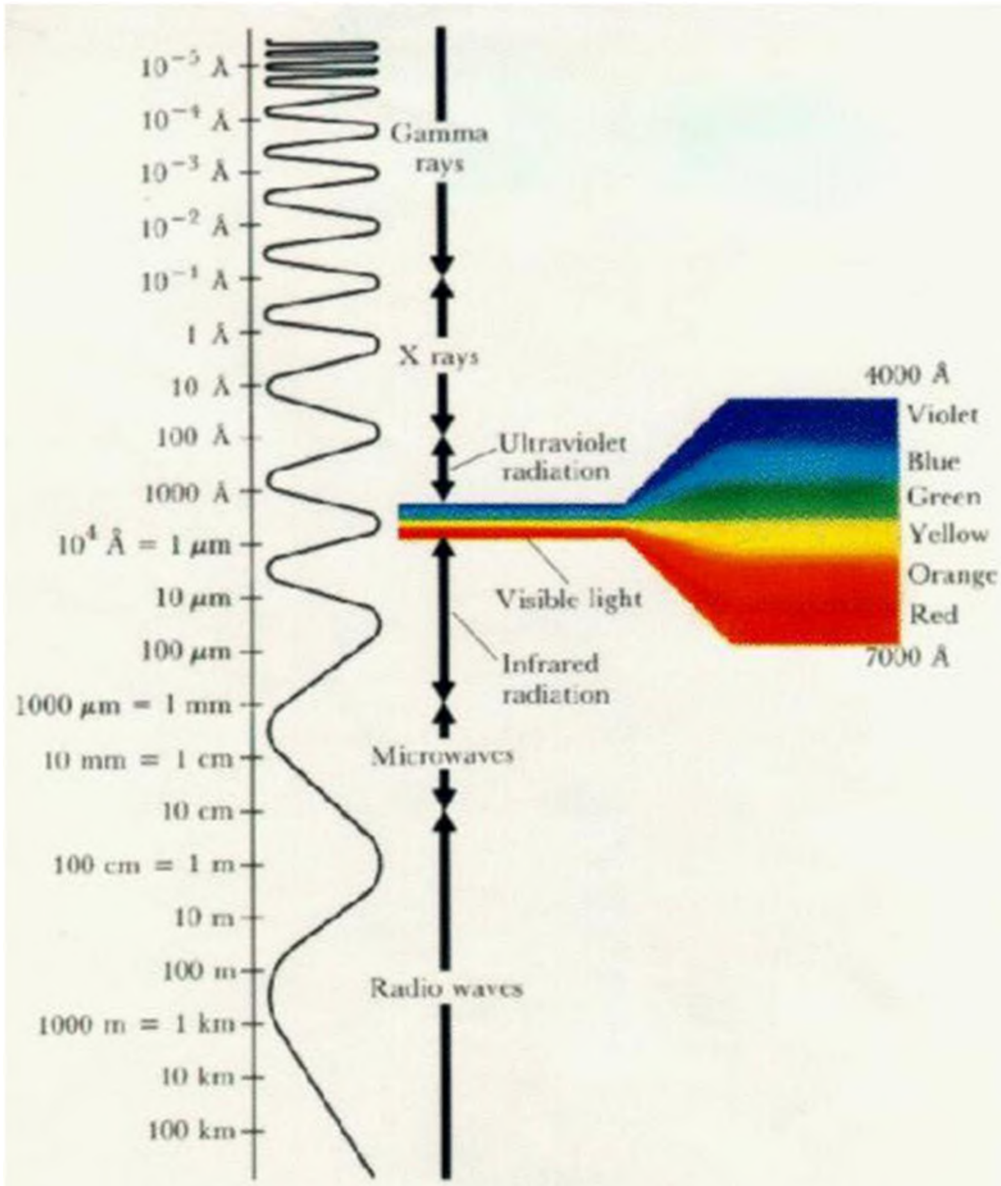
Can a wave be a particle?

- In 1887, Heinrich Hertz discovered that shining light on a metal caused electrons to be ejected.
- Whether or not electrons were ejected depended upon ***frequency*** not the amplitude of the light! Remember energy depends on amplitude.
- Years later, Albert Einstein explained Hertz's discovery: EM waves can behave as a particle called a ***photon*** whose energy depends on the frequency of the waves.

EM Characteristics

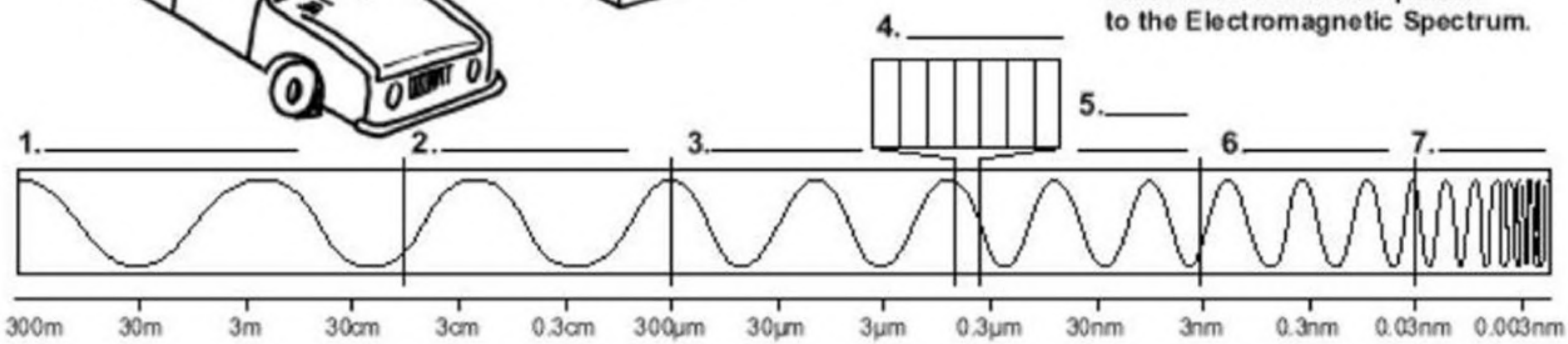
- Waves made by vibrating electric charges that can travel through space where there is no matter
- EM is kind of Transverse wave with alternating electric and magnetic fields
- EM sometimes behave as waves or as particles (photons)

Electromagnetic Spectrum



"Wavestown"

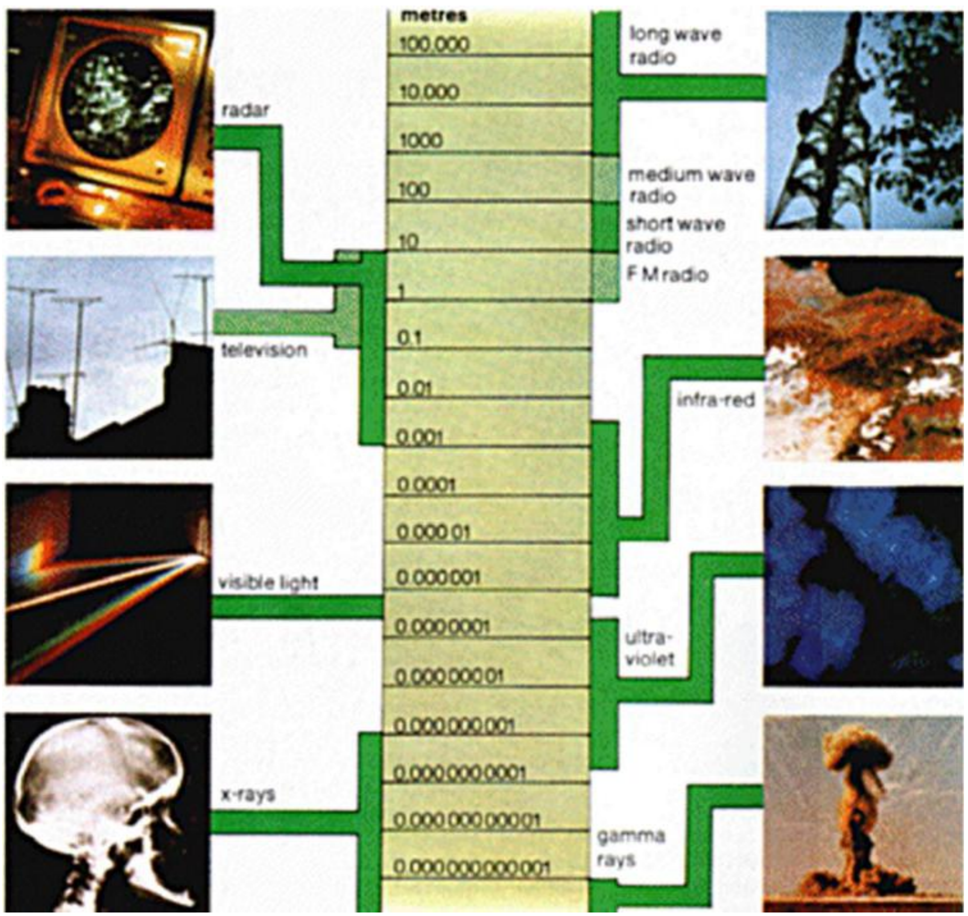
Label the chart below, then match the items in the picture to the Electromagnetic Spectrum.



Range of EM wave

- Frequencies is called the ***electromagnetic spectrum.***
- Different parts interact with matter in different ways.
- The ones humans can see are called visible light, a small part of the whole spectrum.
- Antennae of a radio detects radio waves. ***Radio waves*** are low frequency EM waves with wavelengths longer than 1mm. These waves must be turned into sound waves by a radio before human can hear them.

Range of Frequencies



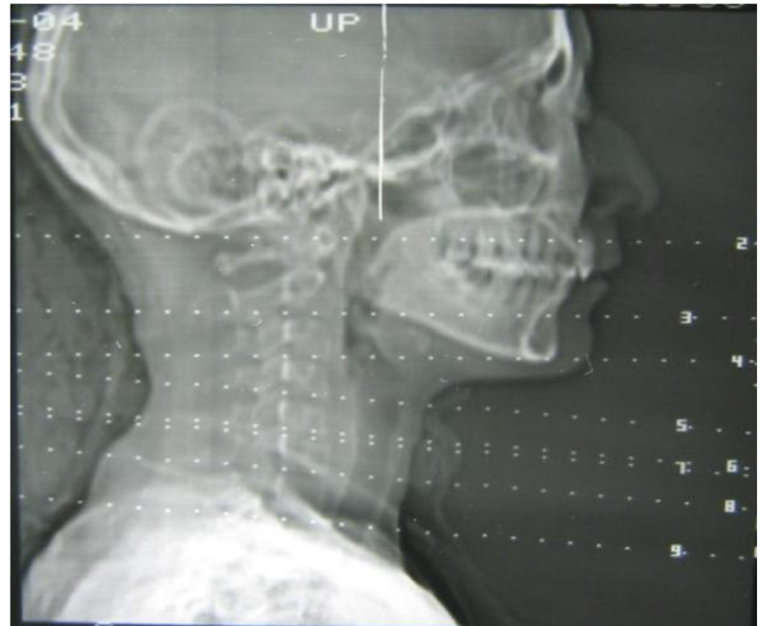
In order of increasing frequency and decreasing wavelength, the EM spectrum consists of: very long wave radio, used for communication with submarines; long, medium and short wave radio (used for AM broadcasting); FM radio, television and radar; infra-red (heat) radiation, which is recorded in the Earth photographs taken by survey satellites; visible light; ultraviolet light, which, while invisible, stimulates fluorescence in some materials; x rays & gamma rays used in medicine and released in radioactive decay

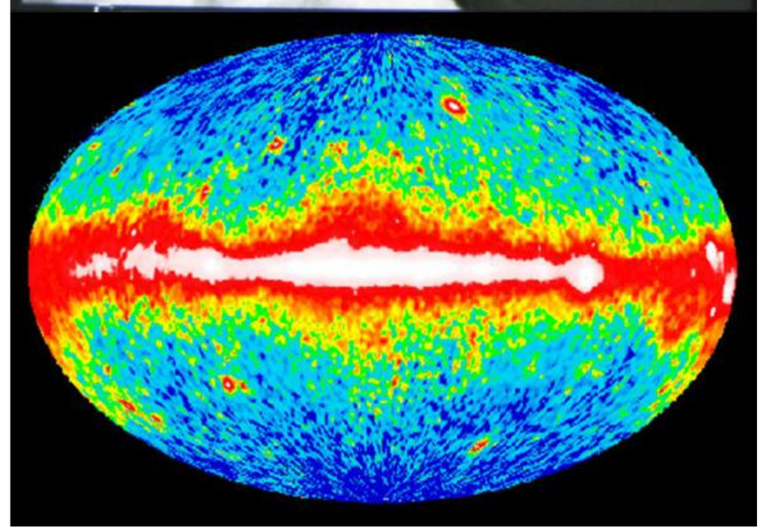
Infrared & UV Waves

- Infrared. EM with wavelengths between 1mm & 750 billionths of a meter. Used daily in remote controls, to read CD-ROMs. Every objects gives off infrared waves; hotter objects give off more than cooler ones. Satellites can ID types of plants growing in a region with infrared detectors.
- Ultraviolet. EM waves with wavelengths from about 400 billionths to 10 billionths of a meter. Have enough energy to enter skin cells
  - Longer wavelengths – UVA
  - Shorter wavelengths – UVB rays
  - Both can cause skin cancer

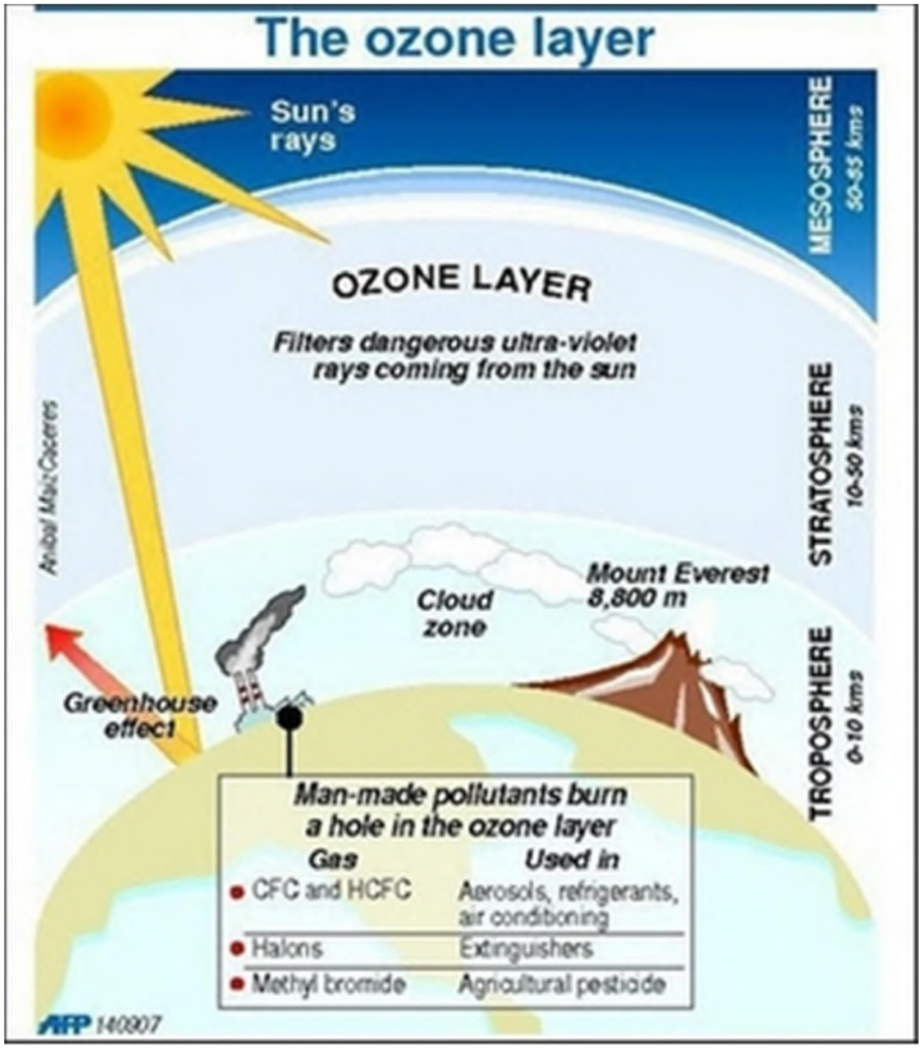
X Rays and Gamma Rays

- EM waves with shortest wavelength & highest frequency. High Energy- go through skin & muscle. High level exposure causes cancer.
- EM with wavelengths shorter than 10 trillionths of a meter. Highest energy, can travel through several centimeters of lead. Both can be used in radiation therapy to kill diseased cells.
- The composite image shows the all sky gamma ray background.





Ozone layer



- 20-50 km above earth
- Molecule of 3 O atoms
- Absorbs Sun's harmful UV rays
- Ozone layer decreasing due to CFCs in AC, refrigerators, & cleaning fluids

What are microwaves?

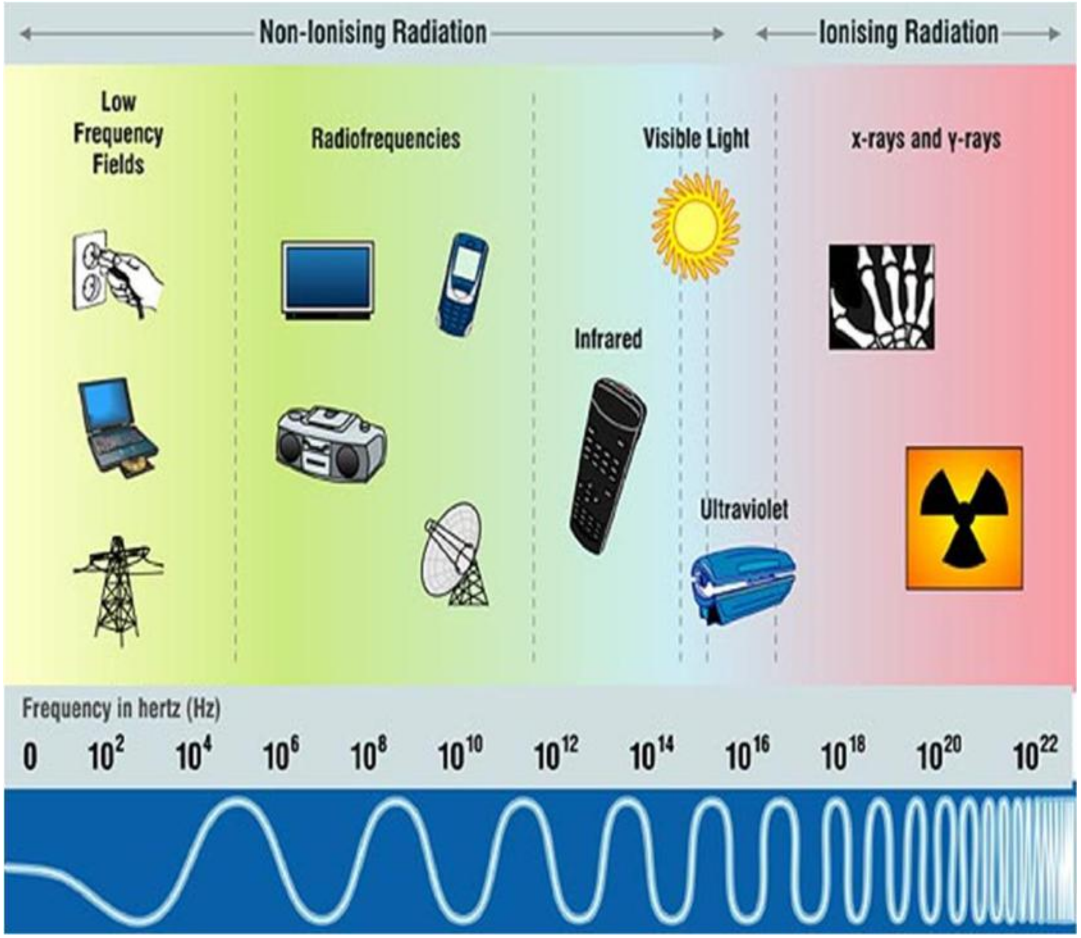
- ***Microwaves*** are radio waves with wavelengths less than 30 cm and higher frequency & shorter wavelength.
- Cell phones and satellites use microwaves between 1 cm & 20 cm for communication.
- In microwave ovens, a vibrating electric field causes water molecules to rotate billions of times per second causing friction, creating TE which heats the food.

What is magnetic resonance imaging?

- MRI was developed in the 1980s to use radio waves to diagnose illnesses with a strong magnet and a radio wave emitter and a receiver. Protons in H atoms of the body act like magnets lining up with the field. This releases energy which the receiver detects and creates a map of the body's tissues.

Can UV radiation be useful?

- Helps body make vitamin D for healthy bones and teeth
- Used to sterilize medical supplies & equip
- Detectives use fluorescent powder (absorbs UV & glows) to find fingerprints



Maxwell's Equations

$$\oint \vec{E} \cdot d\vec{A} = \frac{q_{enclosed}}{\varepsilon_o}$$

$$\oint \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \vec{B} \cdot d\vec{s} = \mu_o I_{encl} + \mu_o \varepsilon \frac{d\Phi_E}{dt}$$

These four equations provide a complete description of electromagnetism.

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

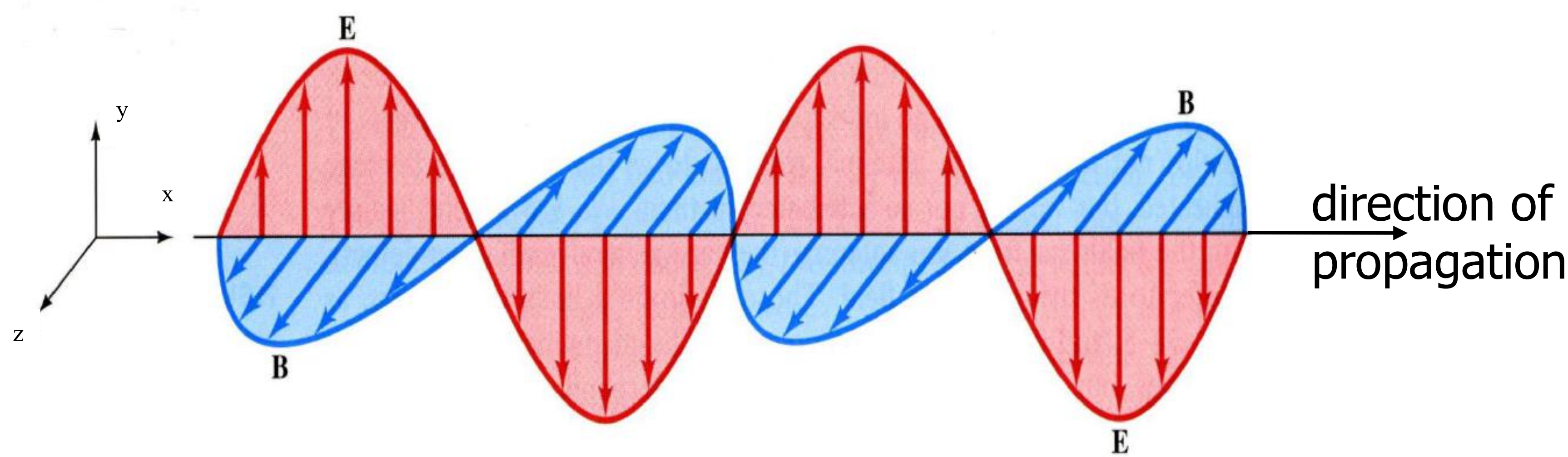
$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt}$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c^2}\frac{d\vec{E}}{dt} + \mu_0 \vec{J}$$

Production of Electromagnetic Waves

- Apply a sinusoidal voltage to an antenna.
- Charged particles in the antenna oscillate sinusoidally.
- The accelerated charges produce sinusoidally varying electric and magnetic fields, which extend throughout space.
- The fields do not instantaneously permeate all space, but propagate at the speed of light.



Electric and Magnetic Field Amplitudes

- The solutions of Maxwell's equations are wave-like with both E and $\vec{B}$ satisfying a wave equation.

$$E_y = E_{max}\sin(kx - \omega t) \qquad B_z = B_{max}\sin(kx - \omega t)$$

- Electromagnetic waves travel through empty space with the speed of light $C = 1/(\mu_0\varepsilon_0)^{1/2}$. E_{max} and B_{max} are the electric and magnetic field **amplitudes**.
- The components of the electric and magnetic fields of plane EM waves are perpendicular to each other and perpendicular to the direction of wave propagation. The latter property says that EM waves are transverse waves. The magnitudes of E and B in empty space are related by E/B = c.

$$\frac{E_{max}}{B_{max}} = \frac{E}{B} = \frac{\omega}{k} = c$$

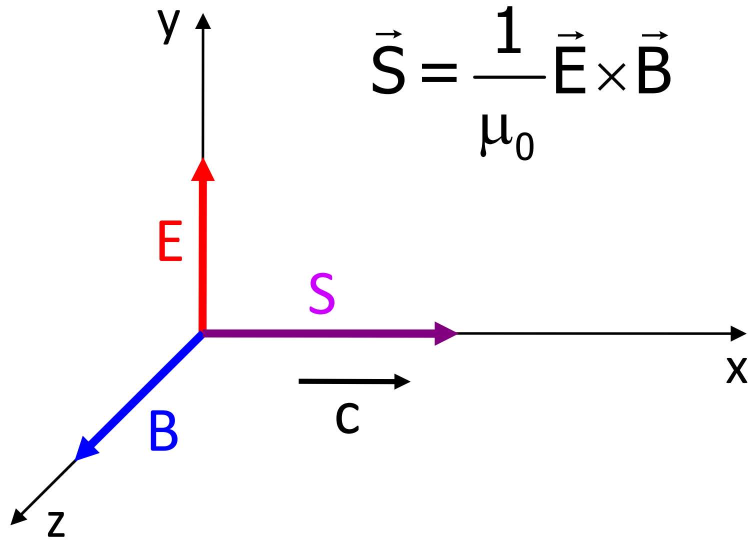
Energy Carried by EM Waves

Electromagnetic waves carry energy, and as they propagate through space they can transfer energy to objects in their path. The rate of flow of energy in an electromagnetic wave is described by a vector S**,** called the **Pointing vector**.*

$$\vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$$

The magnitude S represents the rate at which energy flows through a unit surface area perpendicular to the direction of wave propagation.

Thus, S represents **power per unit area**. The direction of S is along the direction of wave propagation. The units of S are **J/(s·m^2) =W/m^2**.



$$\vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$$

For an EM wave $\left|\vec{E}\times\vec{B}\right| = EB$

so $S = \dfrac{EB}{\mu_0}$.

Because B = E/c we can write

$$S = \frac{E^2}{\mu_0 c} = \frac{cB^2}{\mu_0}.$$

These equations for S apply at any instant of time and represent the instantaneous rate at which energy is passing through a unit area.

$$S = \frac{EB}{\mu_0} = \frac{E^2}{\mu_0 c} = \frac{cB^2}{\mu_0}$$

EM waves are sinusoidal.

$$E_y = E_{max} \sin(kx - \omega t)$$

$$B_z = B_{max} \sin(kx - \omega t)$$

The average of S over one or more cycles is called the **wave intensity I**.

The time average of $\sin^2(kx - \omega t)$ is ½, so

$$I = S_{average} = \langle S \rangle = \frac{E_{max} B_{max}}{2\mu_0} = \frac{E_{max}^2}{2\mu_0 c} = \frac{cB_{max}^2}{2\mu_0}$$

Energy Density

The **energy densities** (energy per unit volume) associated with electric field and magnetic fields are:

$$u_E = \frac{1}{2}\varepsilon_0 E^2 \qquad\qquad u_B = \frac{1}{2}\frac{B^2}{\mu_0}$$

Using B = E/c and c = $1/(\mu_0\varepsilon_0)^{½}$ we can write

$$u_B = \frac{1}{2}\frac{B^2}{\mu_0} = \frac{1}{2}\frac{\left(E/c\right)^2}{\mu_0} = \frac{1}{2}\frac{\mu_0\varepsilon_0 E^2}{\mu_0} = \frac{1}{2}\varepsilon_0 E^2$$

$$u_B = u_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\frac{B^2}{\mu_0}$$

$$u_B = u_E = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\frac{B^2}{\mu_0}$$

For an electromagnetic wave, the instantaneous energy density associated with the magnetic field equals the instantaneous energy density associated with the electric field.

Hence, in a given volume the energy is equally shared by the two fields. The total energy density is equal to the sum of the energy densities associated with the electric and magnetic fields:

$$u = u_B + u_E = \varepsilon_0 E^2 = \frac{B^2}{\mu_0}$$

When we average this instantaneous energy density over one or more cycles of an electromagnetic wave, we again get a factor of ½ from the time average of $\sin^2(kx - \omega t)$.

$$\langle u_E \rangle = \frac{1}{4}\varepsilon_0 E_{max}^2 \ , \ \ \langle u_B \rangle = \frac{1}{4}\frac{B_{max}^2}{\mu_0}, \quad \text{and} \quad \langle u \rangle = \frac{1}{2}\varepsilon_0 E_{max}^2 = \frac{1}{2}\frac{B_{max}^2}{\mu_0}$$

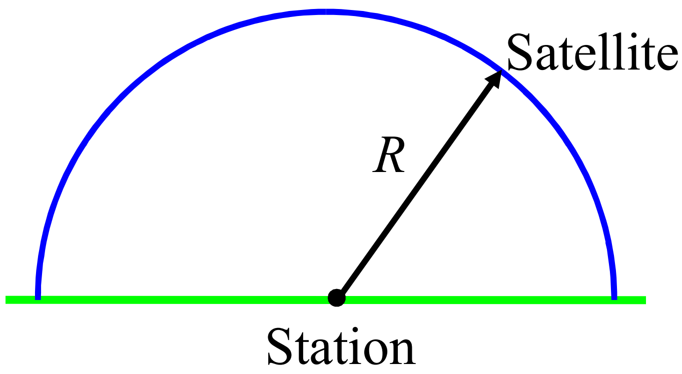
Recall

$$S_{average} = \langle S \rangle = \frac{1}{2}\frac{E_{max}^2}{\mu_0 c} = \frac{1}{2}\frac{cB_{max}^2}{\mu_0} \quad \text{so we see that} \quad \langle S \rangle = c\langle u \rangle.$$

The intensity of an electromagnetic wave equals the average energy density multiplied by the speed of light.

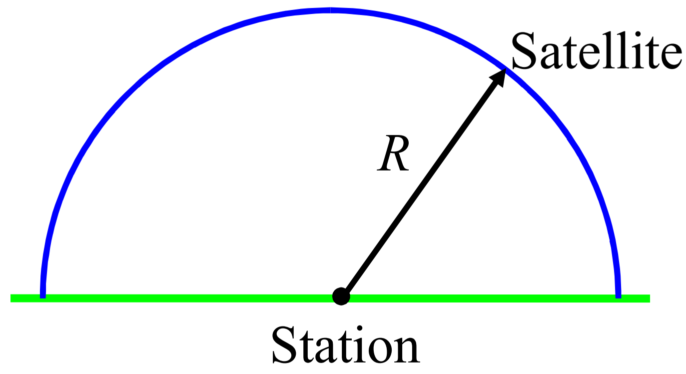
Example: a radio station on the surface of the earth radiates a sinusoidal wave with an average total power of 50 kW. Assuming the wave is radiated equally in all directions above the ground, find the amplitude of the electric and magnetic fields detected by a satellite 100 km from the antenna.

All the radiated power passes through the **hemispherical surface*** so the average power per unit area (the intensity) is



$$I = \left(\frac{\text{power}}{\text{area}}\right)_{\text{average}} = \frac{P}{2\pi R^2} = \frac{\left(5.00\times10^4\ \text{W}\right)}{2\pi\left(1.00\times10^5\ \text{m}\right)^2} = 7.96\times10^{-7}\ \text{W/m}^2$$

$$I = \langle S \rangle = \frac{1}{2}\frac{E_{max}^2}{\mu_0 c}$$



$$E_{max} = \sqrt{2\mu_0 cI}$$

$$= \sqrt{2\left(4\pi\times10^{-7}\right)\left(3\times10^{8}\right)\left(7.96\times10^{-7}\right)}$$

$$= 2.45\times10^{-2}\ \mathrm{V/m}$$

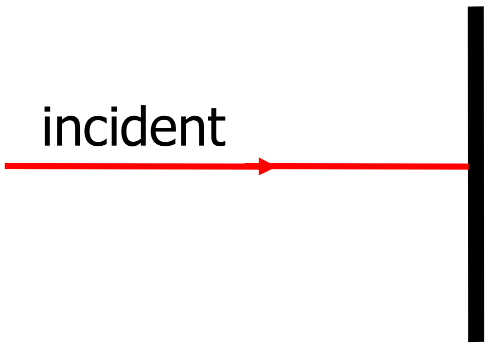
$$B_{max} = \frac{E_{max}}{c} = \frac{\left(2.45\times10^{-2}\ \mathrm{V/m}\right)}{\left(3\times10^{8}\ \mathrm{m/s}\right)} = 8.17\times10^{-11}\ \mathrm{T}$$

Momentum Carried by EM Waves

EM waves carry linear momentum as well as energy. When this momentum is absorbed at a surface pressure is exerted on that surface. If we assume that EM radiation is incident on an object for a time Δt and that the radiation is entirely absorbed by the object, then the object gains energy ΔU in time Δt.

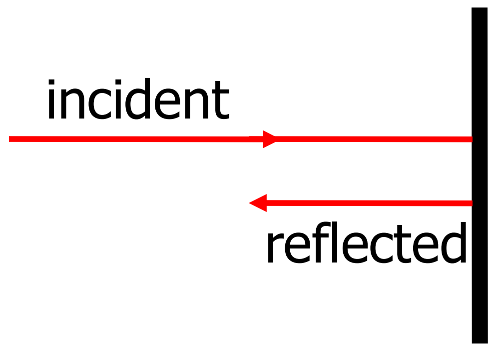
Maxwell showed that the momentum change of the object is then:

$$|\Delta p| = \frac{\Delta U}{c} \quad \text{(total absorption)}$$



The direction of the momentum change of the object is in the direction of the incident radiation.

If instead of being totally absorbed the radiation is totally reflected by the object, and the reflection is along the incident path, then the magnitude of the momentum change of the object is twice that for total absorption.



$$|\Delta p| = \frac{2\Delta U}{c} \quad \text{(total reflection along incident path)}$$

The direction of the momentum change of the object is again in the direction of the incident radiation.

Radiation Pressure

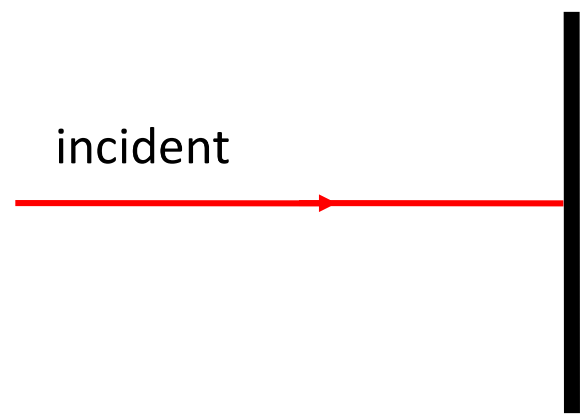
The radiation pressure on the object is defined as the force per unit area:

$$P = \frac{F}{A}$$

From Newton's 2nd Law (F = dp/dt) we have: $$P = \frac{F}{A} = \frac{1}{A}\frac{dp}{dt}$$

For total absorption, $$\Delta p = \frac{\Delta U}{c}$$

So $$P = \frac{1}{A}\frac{dp}{dt} = \frac{1}{A}\frac{d}{dt}\left(\frac{U}{c}\right) = \frac{1}{c}\left(\frac{dU/dt}{A}\right) = \frac{S}{c}$$



(Equations involve magnitudes of vector quantities)

This is the instantaneous radiation pressure in the case of total absorption:

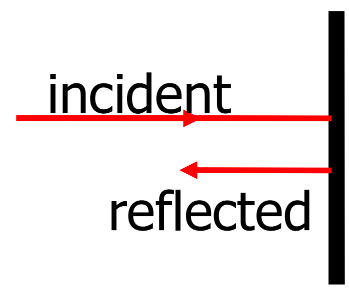
$$P = \frac{S}{c}$$

For the average radiation pressure, replace S by $\langle S \rangle = S_{avg} = I$:

$$P_{rad} = \frac{I}{c} \quad \text{(total absorption)}$$

Following similar arguments it can be shown that:

$$P_{rad} = \frac{2I}{c} \quad \text{(total reflection)}$$



Example: a satellite orbiting the earth has solar energy collection panels with a total area of 4.0 m2. If the sun's radiation is incident perpendicular to the panels and is completely absorbed find the average solar power absorbed and the average force associated with the radiation pressure. The intensity (I or S average) of sunlight prior to passing through the earth's atmosphere is 1.4 kW/m2.

$$\text{Power} = IA = \left(1.4\times10^{3}\ {}^{W}\!/\!{}_{m^2}\right)\left(4.0\ m^2\right) = 5.6\times10^{3}\ W = 5.6\ kW$$

Assuming total absorption of the radiation:

$$P_{rad} = \frac{S_{average}}{c} = \frac{I}{c} = \frac{\left(1.4\times10^{3}\ {}^{W}\!/\!{}_{m^2}\right)}{\left(3\times10^{8}\ {}^{m}\!/\!{}_{s}\right)} = 4.7\times10^{-6}\,Pa$$

$$F = P_{rad}A = \left(4.7\times10^{-6}\ {}^{N}\!/\!{}_{m^2}\right)\left(4.0\ m^2\right) = 1.9\times10^{-5}\,N$$

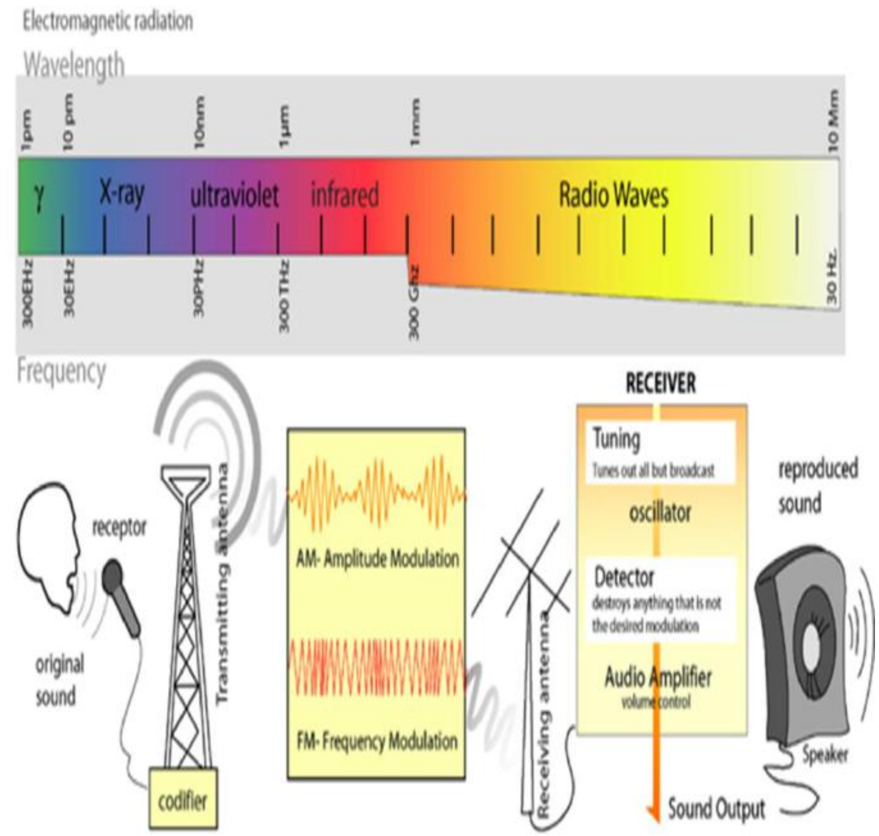
Caution! The letter P (or p) has been used in this lecture for power, pressure, and momentum!

Radio Communication

- Radio stations change sound to EM waves & then your radio receiver changes the EM waves back to sound waves again. Each station broadcasts at a certain frequency which you tune in by choosing their frequency. ***Carrier wave***- the frequency of the EM wave that a station uses.
- Microphones convert sound waves to a changing electric current or electronic signal containing the words & music.
- The modified carrier wave vibrates electrons in the station's antennae creating a radio wave that travels out in all directions at the speed of light to your radio antennae.
- The vibrating electrons produce a changing electric current which your radio separates the carrier wave from the signal to make the speakers vibrate creating sound waves.

Radio & TV

- AM Radio. In AM amplitude changes but frequency does not. AM frequencies range from 540,000 Hz to 1,6000,000 Hz usually listed in kHz.
- FM Radio. In FM radio stations transmit broadcast information by changing the frequency of the carrier wave. The strength of FM waves is always the same and is in megahertz. Mega=million.
- TV Uses radio waves to send electronic signals in a carrier wave. Sound is sent by FM; color and brightness is sent at the same time by AM signals.



Cathode-ray Tube

- Many TVs and computer monitors display images on a CRT, a sealed vacuum tube in which beams of electrons are produced.
- Color TV produces 3 electron beams inside the CRT which strike the inside of the screen that is covered with more than 100,000 rectangular spots.
- There are 3 types of spots, red, green and blue. The electron beams move back and forth across the screen.
- The signal from the TV station controls how bright each spot is. Three spots together can form any color.
- You see a full color image on the TV.

Telephones

- Sound waves→ microphone→ electric signal→ radio waves→ transmitted to and from microwave tower → receiver→ electric signal → speaker→ sound wave

Cordless Phones & Pagers

- Cell phones and cordless telephones are ***transceivers,*** device that transmits one signal & receives another radio signal from a base unit. You can talk and listen at the same time because the two signals are at different frequencies.

- A pager is a small radio receiver with a phone number. A caller leaves a message at a terminal with a call-back number. At the terminal, the message is turned into an electronic signal transmitted by radio wave. Newer pagers can send and receive messages.

Communications Satellites

- Thousands of satellites orbit Earth. A radio or TV station sends microwave signals to the satellite which amplifies the signal and sends it back to a different place on Earth. Satellite uses different frequencies to send & receive.

Global Positioning System (GPS)

- GPS is a system of 24 satellites, ground monitoring stations and portable receivers that determine your exact location on Earth. GPS receiver measures the time it takes for radio waves to travel from 4 different satellites to the receiver. The system is owned and operated by the US Department of Defense, but the microwaves can be used by anyone.

Light

- Normally, "light" refers to the type of electromagnetic wave that stimulates the retina of our eyes.

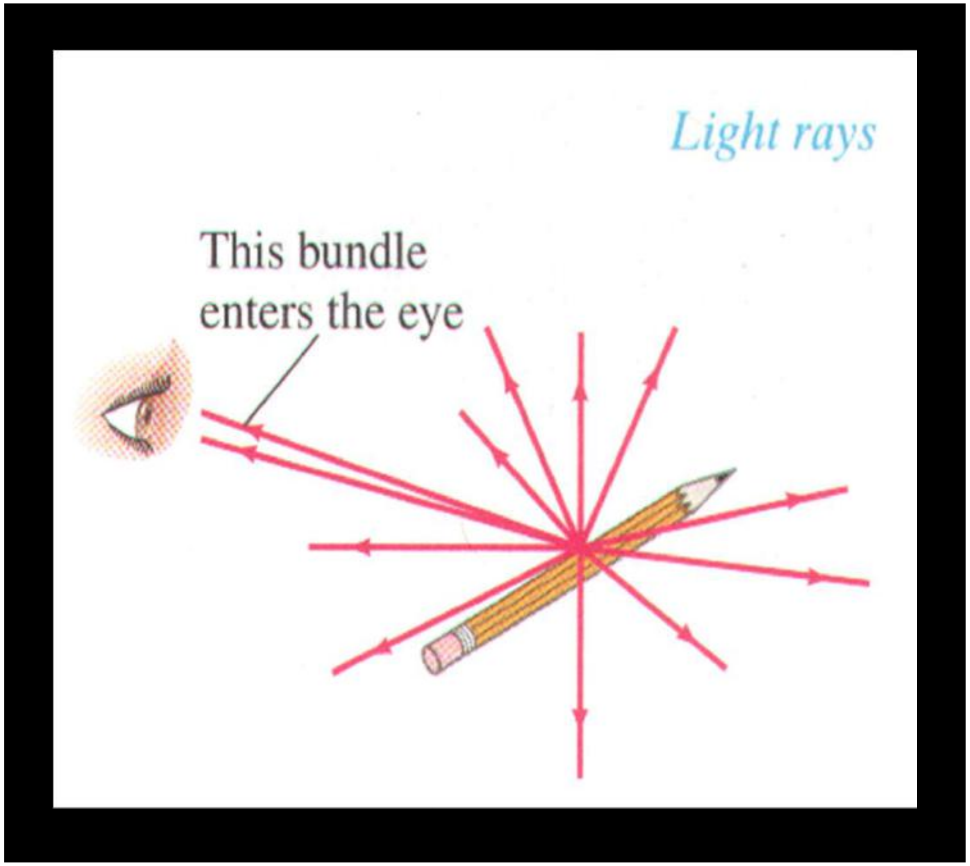
- Light acts like a wave except when it acts like particles.

- Light is a type of electromagnetic wave and travels with the speed $c = 2.9979 \times 10^8$ m/s in a vacuum. (Just use 3×10^8!)

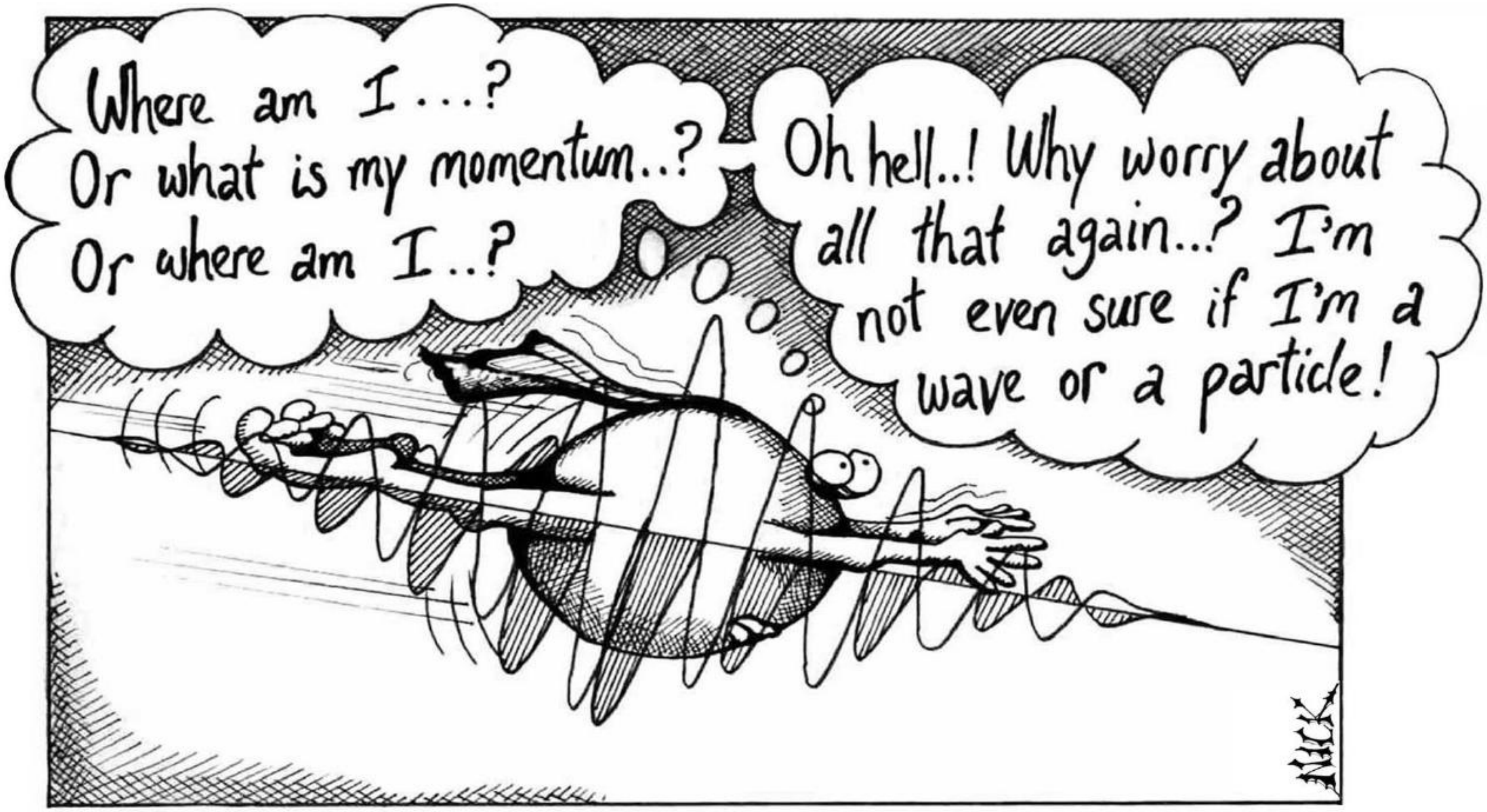
- A light ray is an infinitely thin beam of light. Of course, there really isn't such a thing, but the concept helps us visualize properties of light.

Light Ray

- Light rays from some external source strike an object and reflect off it in all directions.
- We only see those light rays that reflect in the direction of our eyes.
- If we can see something, it must be reflecting light!
- Zillions of rays are simultaneously reflected in all directions from any point of an object.



Intermezzo: Light, Waves or Particles?



Photon self-identity problems.

Geometric Optics

Although light is actually an electromagnetic **wave**, it generally travels in straight lines (like particles do!).

We can describe many properties of light by assuming that it travels in straight-line paths in the form of rays.

A **ray** is a straight line along which light is propagated. In other contexts, the definition of ray might be extended to include bent or curved lines.

Basic Physics 2
Lecture Module

Rahadian N, S.Si. M.Si.

Introduction to Modern Physics

Introduction to Modern Physics

- Preface
- Triumph of Classical Physics
- Complications & Discoveries
- The Beginning of Modern Physics
- Fields of Modern Physics

Preface

- "Modern" – 20th Century. By the end of the 19th century it seemed that all the laws of physics were known, and the motion of the planets was understood

- However, there were a few problems where classical physics (pre-20th century) didn't seem to work. It became obvious that Newton's laws could not explain atomic level phenomena

- Modern Physics has very some unintuitive ideas. And understanding the ideas of modern physics requires the knowledge of the classical physics.

Triumph of Classical Physics: The Conservation Laws

- **Conservation of energy**: The total sum of energy (in all its forms) is conserved in all interactions.
- **Conservation of linear momentum**: In the absence of external forces, linear momentum is conserved in all interactions.
- **Conservation of angular momentum**: In the absence of external torque, angular momentum is conserved in all interactions.
- **Conservation of charge**: Electric charge is conserved in all interactions.

Conservation Laws in The Modern Context

- We will establish the **conservation of mass** as part of the **conservation of energy**

- In addition to the classical conservation laws, two modern results will include:
  - The conservation of baryons and leptons
  - The fundamental invariance principles for time reversal, distance, and parity

- The three fundamental forces are introduced
  - **Gravitational**: $\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$
  - **Electroweak**
    - **Weak**: Responsible for nuclear beta decay and effective only over distances of ~10^{-15} m
    - **Electromagnetic**: $\vec{F}_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$ (Coulomb force)
  - **Strong**: Responsible for "holding" the nucleus together and effective less than ~10^{-15} m

Unification

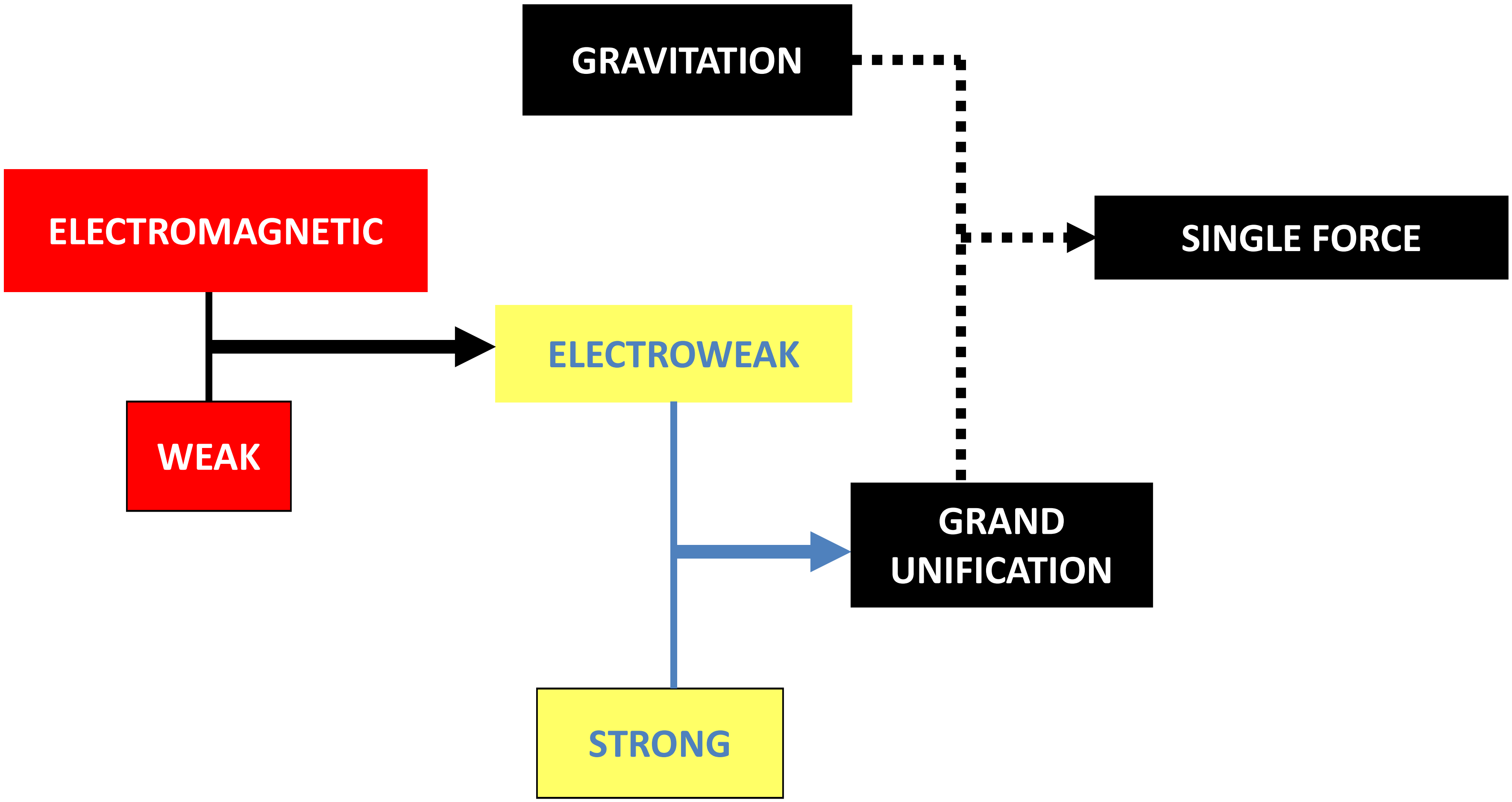
- Unification of inertial mass m_i and gravitational mass m_g
  - $m_i = m_g = m$
  - Where the same m responds to Newtonian force and also induces the gravitational force

- This is more appropriately referred to as the principle of equivalence in the theory of general relativity

- Maxwell unified the electric and magnetic forces as fundamentally the same force; now referred to as the **electromagnetic force**

- In the 1970's Glashow, Weinberg, and Salem proposed the equivalence of the electromagnetic and the weak forces (at high energy); now referred to as the **electroweak interaction**

Goal: Unification of All Forces into a Single Force



Complications & Discoveries

- Three fundamental problems:
  - The question of the existence of an electromagnetic medium.
  - The problem of observed differences in the electric and magnetic field between stationary and moving reference systems .
  - The failure of classical physics to explain blackbody radiation.

- Additional Discoveries Contribute to the Complications
  - Discovery of x-rays
  - Discovery of radioactivity
  - Discovery of the electron
  - Discovery of the Zeeman effect

The Beginning of Modern Physics

- These new discoveries and the many resulting complications required a revision of the fundamental physical assumptions that culminated in the huge successes of the classical foundations

- To this end the introduction of the modern theory of relativity and quantum mechanics becomes the starting point of this most fascinating revision

Fields of Modern Physics

Classical Physics and Atom

Quantum mechanics

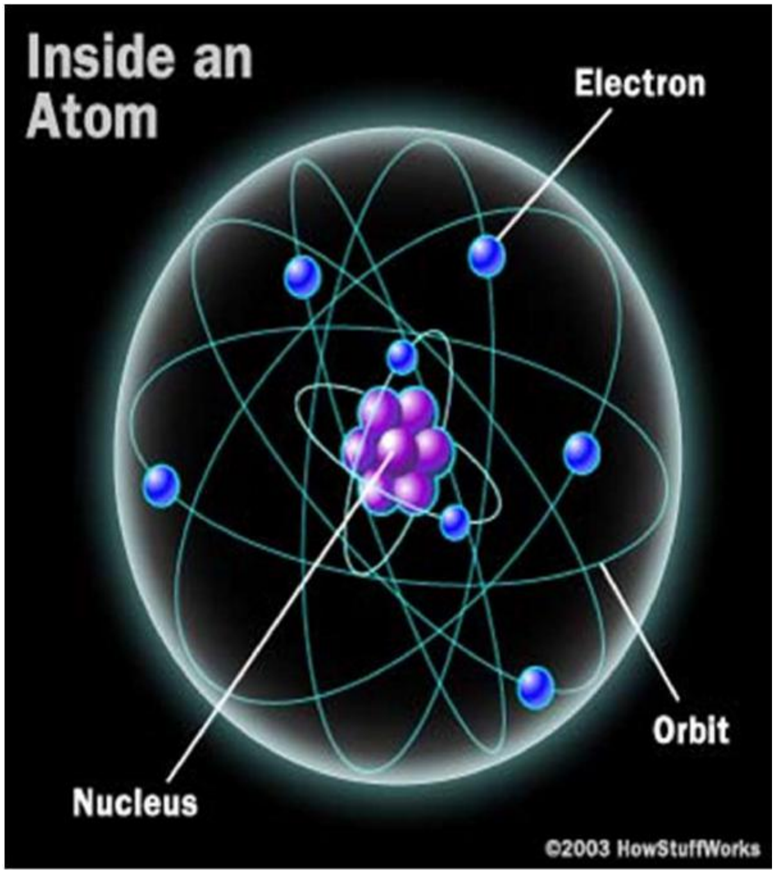
Gravity and Standard Model

Nuclear and Particle physics

Cosmology and Astrophysics

Revolutions in Other Fields

Introduction to Classical Physics & Atom



- According to the laws of mechanics and electricity and magnetism, an orbiting electron in an atom should continually radiate away energy as electromagnetic waves.
- Very quickly the electron would loose all of its energy and there would be no atoms!

The Atomic Theory of Matter

- Initiated by Democritus and Leucippus (~450 B.C.)
  (first to us the Greek *atomos*, meaning "indivisible")

- In addition to fundamental contributions by Boyle, Charles, and Gay-Lussac, Proust (1754 – 1826) proposes the **law of definite proportions**

- Dalton advances the **atomic theory of matter** to explain the law of definite proportions

- Avogadro proposes that all gases at the same temperature, pressure, and volume contain the ***same number of molecules (atoms)***; viz. 6.02×10^{23} atoms

- Cannizzaro (1826 – 1910) makes the distinction between atoms and molecules advancing the ideas of Avogadro.

Further Advances in Atomic Theory

- Maxwell derives the speed distribution of atoms in a gas
- Robert Brown (1753 – 1858) observes microscopic "random" motion of suspended grains of pollen in water
- Einstein in the 20^{th} century explains this random motion using atomic theory

Overwhelming Evidence for Existence of Atoms

- Ernst Mach (1838 – 1916) opposes the theory on the basis of logical positivism, i.e., atoms being *"unseen" place into question their reality.* And Wilhelm Ostwald (1853 – 1932) supports this premise but on experimental results of radioactivity, discrete spectral lines, and the formation of molecular structures

- Max Planck (1858 – 1947) advances the concept to explain blackbody radiation by use of submicroscopic "quanta"

- Boltzmann requires existence of atoms for his advances in statistical mechanics

- Albert Einstein (1879 – 1955) uses molecules to explain Brownian motion and determines the approximate value of their size and mass

- Jean Perrin (1870 – 1942) experimentally verifies Einstein's predictions

Introduction to Quantum Mechanics

- Radiation
- Light is made of particles. The need for a quantification
  1) Black-body radiation
  2) Atomic Spectroscopy
  3) Photoelectric Effect
- Wave–particle duality
  1) Compton Effect
  2) Electron Diffraction Davisson and Germer
  3) Young's Double Slit Experiment
- Louis de Broglie relation for a photon from relativity
- A new mathematical tool: Wave functions and operators
- Measurable physical quantities and associated operators – Correspondence principle
- The Schrödinger Equation
- The Uncertainty principle

Classical Point of View

- In Newtonian mechanics, the laws are written in terms of PARTICLE TRAJECTORIES.
- A PARTICLE is an indivisible mass point object that has a variety of properties that can be measured, which we call observables. The observables specify the state of the particle (position and momentum).
- A SYSTEM is a collection of particles, which interact among themselves via internal forces, and can also interact with the outside world via external forces. The STATE OF A SYSTEM is a collection of the states of the particles that comprise the system.
- All properties of a particle can be known to infinite precision.
- Conclusions:
  – TRAJECTORY ➔ state descriptor of Newtonian physics,
  – EVOLUTION OF THE STATE ➔ Use Newton's second law
  – PRINCIPLE OF CAUSALITY ➔ Two identical systems with the same initial conditions, subject to the same measurement will yield the same result.

The Quantum Mechanics View

- All matter (particles) has wave-like properties
  - so-called particle-wave *duality*
- Particle-waves are described in a probabilistic manner
  - electron doesn't whiz around the nucleus, it has a probability distribution describing where it might be found
  - allows for seemingly impossible "quantum tunneling"
- Some properties come in dual packages: can't know both simultaneously to arbitrary precision
  - called the Heisenberg Uncertainty Principle
  - not simply a matter of measurement precision
  - position/momentum and energy/time are example pairs
- The act of "measurement" fundamentally alters the system
  - called entanglement: information exchange alters a particle's state

Classical Mechanics and Quantum Mechanics

Mechanics: the study of the behavior of physical bodies when subjected to forces or displacements

Classical Mechanics: describing the motion of macroscopic objects.

Macroscopic: measurable or observable by naked eyes

Quantum Mechanics: describing behavior of systems at atomic length scales and smaller .

Basics of Quantum Mechanics

- Classical mechanics (Newton's mechanics) and Maxwell's equations (electromagnetics theory) can explain MACROSCOPIC phenomena such as motion of billiard balls or rockets.

- Quantum mechanics is used to explain microscopic phenomena such as photon-atom scattering and flow of the electrons in a semiconductor.

- Quantum mechanics is a collection of postulates based on a huge number of experimental observations.

- The differences between the classical and quantum mechanics can be understood by examining both
  - The classical point of view
  - The quantum point of view

- Quantum particles can act as both particles and waves → WAVE-PARTICLE DUALITY

- Quantum state is a conglomeration of several possible outcomes of measurement of physical properties → Quantum mechanics uses the language of PROBABILITY theory (random chance)

- An observer cannot observe a microscopic system without altering some of its properties. Neither one can predict how the state of the system will change.

- QUANTIZATION of energy is yet another property of "microscopic" particles.

Heisenberg Uncertainty Principle

- One cannot unambiguously specify the values of particle's position and its momentum for a microscopic particle, i.e.

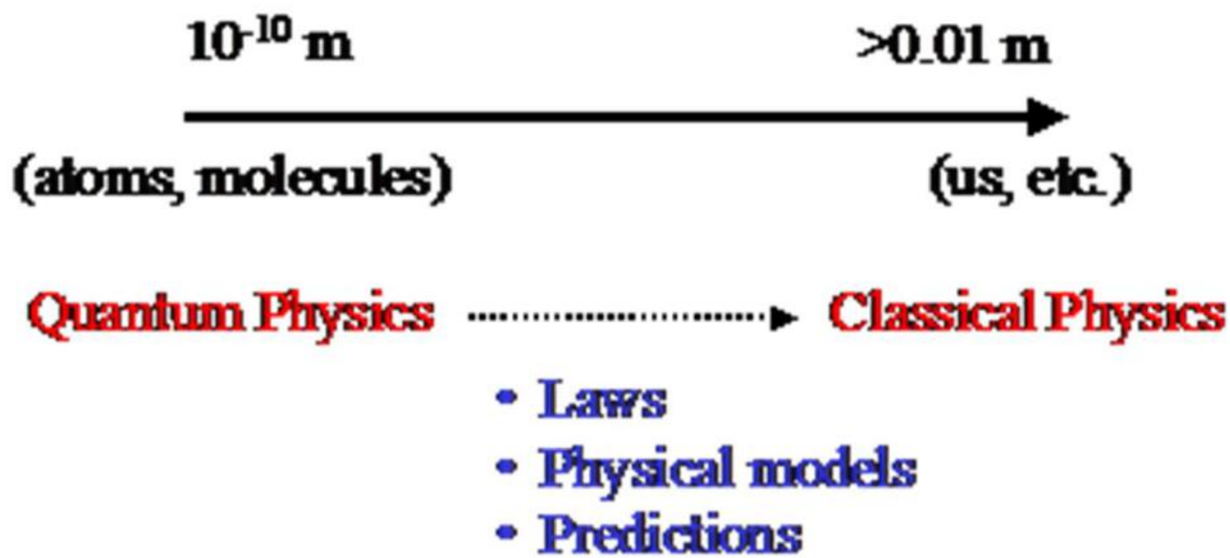
$$\Delta x(t_0) \cdot \Delta p_x(t_0) \geq \frac{1}{2}\frac{h}{2\pi}$$

- Position and momentum are, therefore, considered as incompatible variables.

- The Heisenberg uncertainty principle strikes at the very heart of the classical physics => the particle trajectory.

The Correspondence Principle

When Quantum physics is applied to macroscopic systems, it must reduce to the classical physics. Therefore, the nonclassical phenomena, such as uncertainty and duality, must become undetectable. Niels Bohr codified this requirement into his Correspondence principle:



Light: Particle-Wave

- The behavior of a "microscopic" particle is very different from that of a classical particle:
  - ➔ in some experiments it resembles the behavior of a classical wave (not localized in space)
  - ➔ in other experiments it behaves as a classical particle (localized in space)

- Corpuscular theories of light treat light as though it were composed of particles, but can not explain DIFRACTION and INTERFERENCE.

- Maxwell's theory of electromagnetic radiation can explain these two phenomena, which was the reason why the corpuscular theory of light was abandoned.

Particle-Wave Duality

- Waves as particles:
  - Max Plank work on black-body radiation, in which he assumed that the molecules of the cavity walls, described using a simple oscillator model, can only exchange energy in quantized units.
  - 1905 Einstein proposed that the energy in an electromagnetic field is not spread out over a spherical wavefront, but instead is localized in individual clumbs - quanta. Each quantum of frequency n travels through space with speed of light, carrying a discrete amount of energy and momentum =photon => used to explain the photoelectric effect, later to be confirmed by the *x*-ray experiments of Compton.

- Particles as waves
  - Double-slit experiment, in which instead of using a light source, one uses the electron gun. The electrons are diffracted by the slit and then interfere in the region between the diaphragm and the detector.
  - Aharonov-Bohm effect

Gravity

- Gravity is best described by Einstein's Relativity, which requires continuous fields. Einstein said that the universe is space and time woven into a fabric, and this fabric bends and indents like a trampoline. Lets say we put a heavy ball like the sun on this trampoline, it indents. Now lets say we add the earth, the earth will roll into the indentation. Now lets give the earth a spin when we roll it. It will spin around the sun in a circular pattern, or an orbit. That's all gravity is.

- The universe isn't alone, gravity is just an incident, and atoms aren't solid. Whether or not you want to combine the theories I'll leave it up to you, and remember, these are just theories.

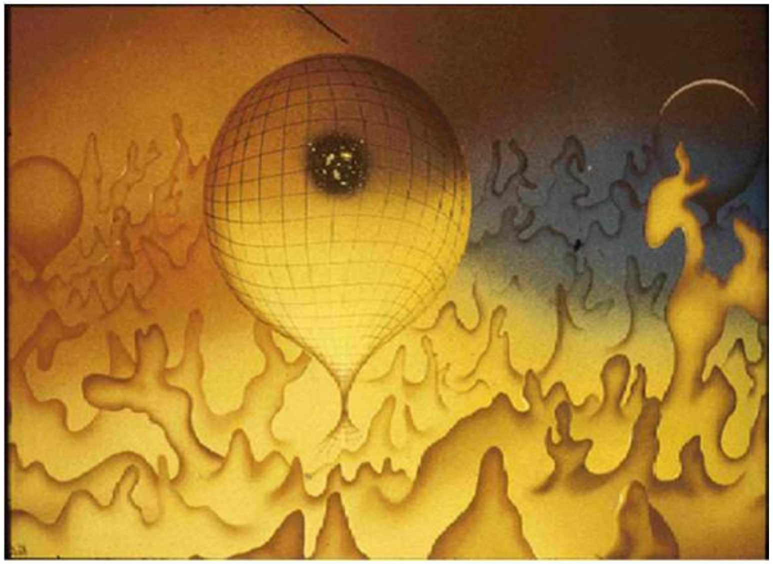
- Einstein's theory of gravity is built on the principle that the speed of light is constant, as an object speeds up its clock runs faster, the effects of gravity cannot be distinguished from the effects of acceleration in the absence of gravity, and everyone's a relative.

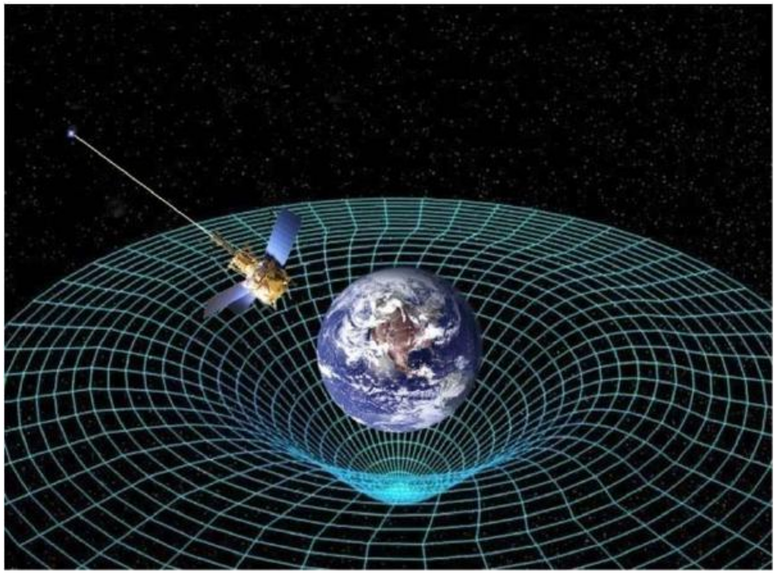
The Standard Model

- The Standard Model uses the discrete fields of Quantum Mechanics, as required by Heisenberg's Uncertainty Principle.

- Attempts to explain all phenomena of particle physics in terms of properties and interactions of a small number of three distinct types.

- Leptons: spin-1/2. Quarks: spin-1/. Bosons: spin-1; force carriers. These are assumed to be elementary.





Nuclear Physics

- Nuclear physics is physics study of structure, properties, and interactions of atomic nuclei at fundamental level.
- Nucleus – contains almost all mass of ordinary matter in a tiny volume
- Understanding behavior of nuclear matter under normal conditions and conditions far from normal a major challenge extreme conditions existed in the early universe, exist now in the core of stars, and can be created in the laboratory during collisions between nuclei (TRIUMF).
- Nuclear scientists investigate by measuring the properties, shapes, and decays of nuclei at rest and in collisions.

Particle Physics

- Particle physics is journey into the heart of matter, a branch of physics that studies the elementary constituents of matter and radiation, and the interactions between them. It is also called "high energy physics", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators

- Particle physics studies these very small building block particles and works out how they interact to make the universe look and behave the way it does. Everything in the universe, from stars and planets, to us is made from the same basic building blocks - particles of matter. Some particles were last seen only billionths of a second after the Big Bang. Others form most of the matter around us today.

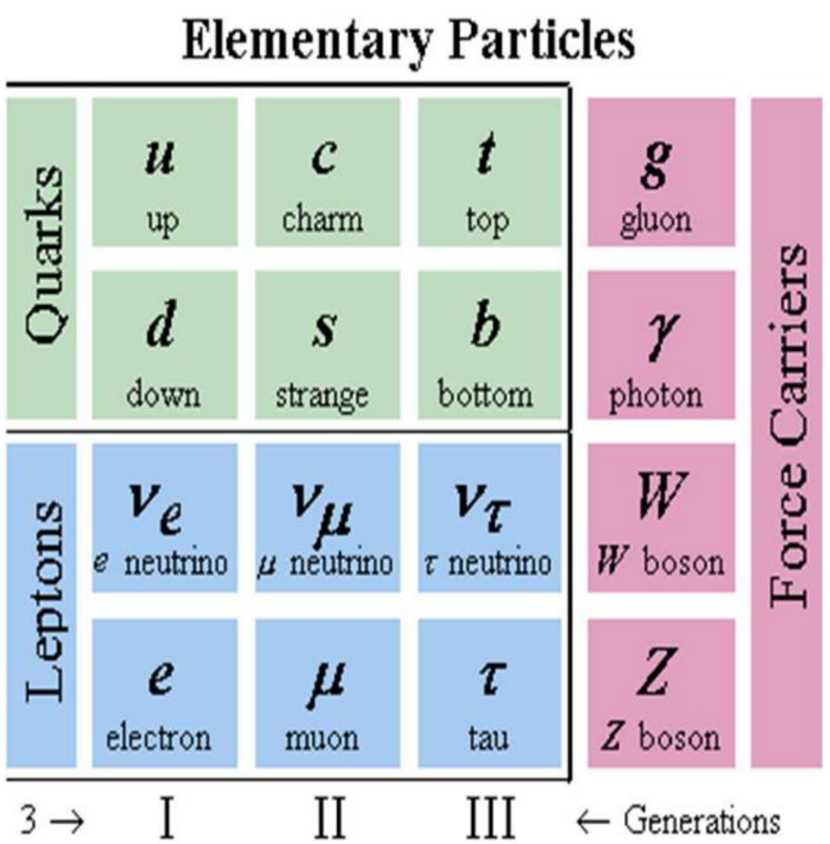
Fundamental Forces

- There are four forces.

- Each is associated with force-carrying particles:
  - Electromagnetic force: photon
  - Weak force: W boson, Z boson
  - Strong force: gluon
  - Gravitational force: graviton (maybe)

- The Standard Model describes all of them except the gravitational force.

- The Standard Model and Relativity can be used to describe some fundamental forces, but there is no theory which can describes all fundamental forces.



Interactions

- Electromagnetic

  e^- (lepton) bound in the atoms by the electromagnetic force

- Weak interaction

  Neutrino observed in beta decay.

- Strong interaction

  Quarks are bound in together by the strong force in nucleons. Nuclear forces bind nucleons into nuclei.

- Gravitation

  Gravitational interaction between the elementary particles is in practice very small compared to the other three.

The forces of elementary particle physics are associated with the exchange of particles. An interaction between particles is characterized by both its strength and its range.

forces	strength	range (fm)	exchange particle	mass (eV)	charge	spin
gravitational	$6x10^{-39}$	infinite	graviton?	0	0	2
weak	$1x10^{-6}$	$2x10^{-3}$	$W\pm$, Z	$91x10^{9}$	± 1,0	1
electromagnetic	$7x10^{-3}$	infinite	photon	0	0	1
strong	1	1.5	pion	$35x10^{6}$	0	1

1 fm = 10^{-15} m

Force between two objects can be described as exchange of a particle – particle transfers momentum and energy between the two objects, and is said to mediate the interaction graviton – not yet observed pions or pi mesons – between nucleons

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

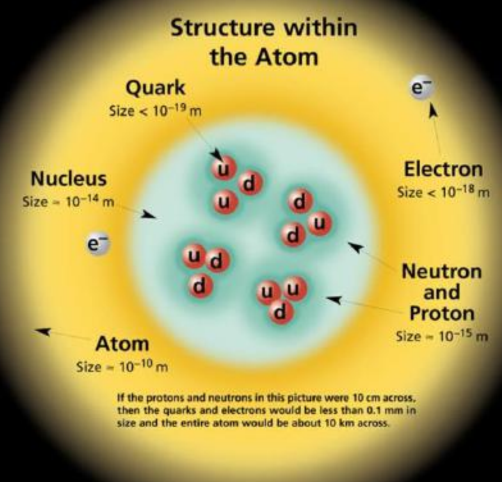
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

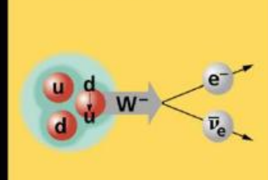
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

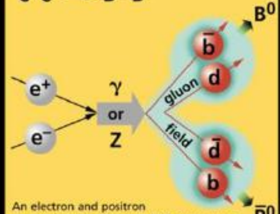
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



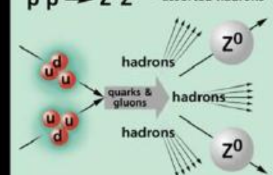
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

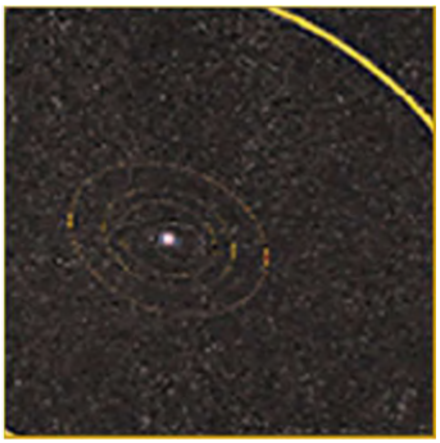
http://CPEPweb.org

Introduction to Cosmology

- The cosmological principle Underpinning of (theoretical) cosmology
- *The belief that the universe is very smooth on extremely large scales (>100 Mpc)*
- Only fairly recently it has been possible to provide convincing observational evidence supporting the smoothness of the matter distribution on large scales
    1. Cosmic Microwave Background
    2. Large scale galaxy (cluster) distribution
- Implies two important properties of our universe
    1. Homogeneity : Universe looks the same at each point
    2. Isotropy: Universe looks the same in all directions

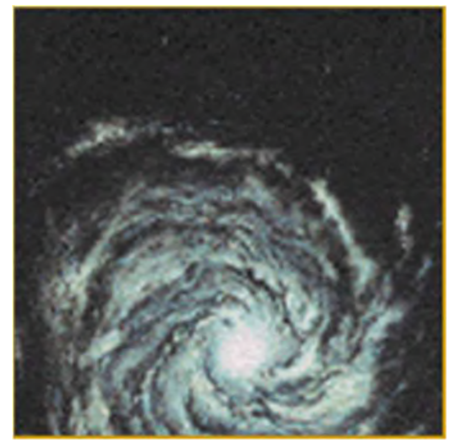
Cosmological distances

Alternative unit : 1 parsec ~ 3.261 lyr
Nearest similar galaxy : Andromeda ~ 770 kpc



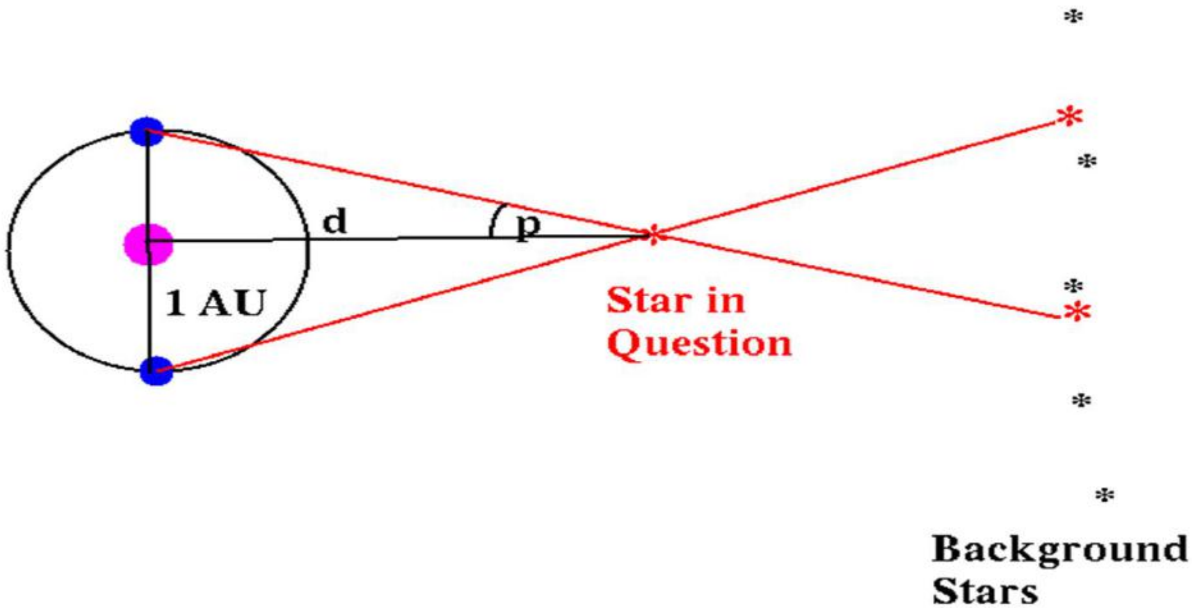
Mean distance Earth-Sun. 1 Astronomical Unit (AU) ~ 10^{11} meters

Nearest stars
Few light years
~ 10^{16} meters



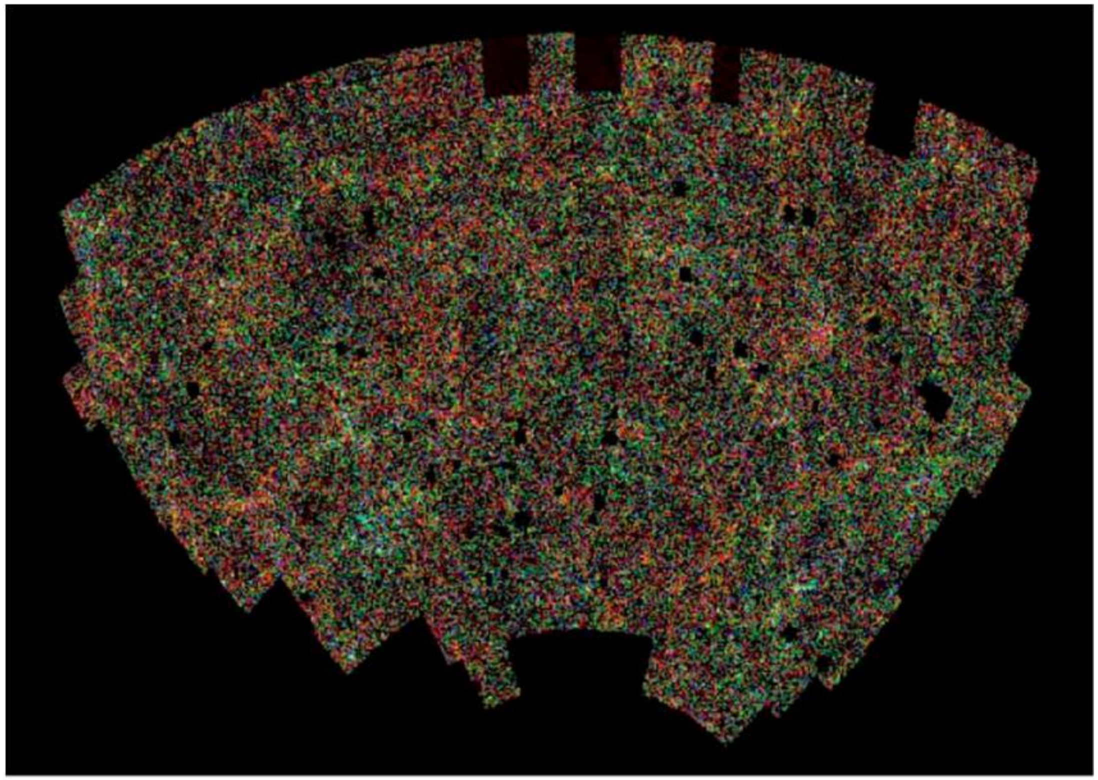
Milky Way galaxy
size ~ 13 kpc
~ 10^{20} meters

What is a parsec?



1 pc = 1 AU / tan(1 arcsecond)
1 arcsecond = 360 degrees / 3600

Typical galaxy group volume ~ cubic Million parsecs
Cosmologist's favorite unit: Megaparsec (Mpc) ~ 10^{22} meters



APM Survey picture of a large part of the sky, about 30 degrees across, showing almost a million galaxies out to a distance of about 2 billion light years.
MAP990047

Clusters, superclusters of galaxies and voids ~ 100 Mpc
Even larger scales > 100 Mpc: Universe appears smooth!

Astrophysics

- Astrophysics is the part of astronomy that deals with the interaction of matter, and heavenly bodies with interstellar space.

- There are many different theories in astrophysics, but my main topics will be String Theory and Quantum Theory.

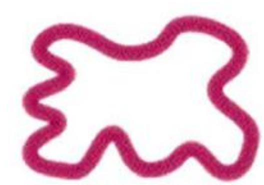
Quantum and String Theory

- In Quantum Theory, atoms aren't solid. There more like a thought. So you never really touch anything. The atoms repel each other before you touch it or you'd go through every thing. Since matter is like a thought it can be altered. Lets say if you believe with every fiber of your being you will walk on water, you'll walk on water.

- According to Einstein there are four dimensions: length, width, depth, and time. In string theory there are the four dimensions stated by Einstein plus seven others, but the most important of the eleven is dimensions is eleventh dimension. The eleventh dimension is what holds the universe together.

String Theory

- String theory suggests that the elementary particles are one-dimensional strings as opposed to zero-dimensional point particles.
- All known elementary particles are made up of one building block: the string.
- The resonance of each string determines the properties (mass, charge, spin, etc.) of the particle, thus different resonant frequencies correspond to different particles.
- Strings are on the order of the Planck length (10^{-35} m), or 10^{20} times smaller than the diameter of an atomic nucleus!

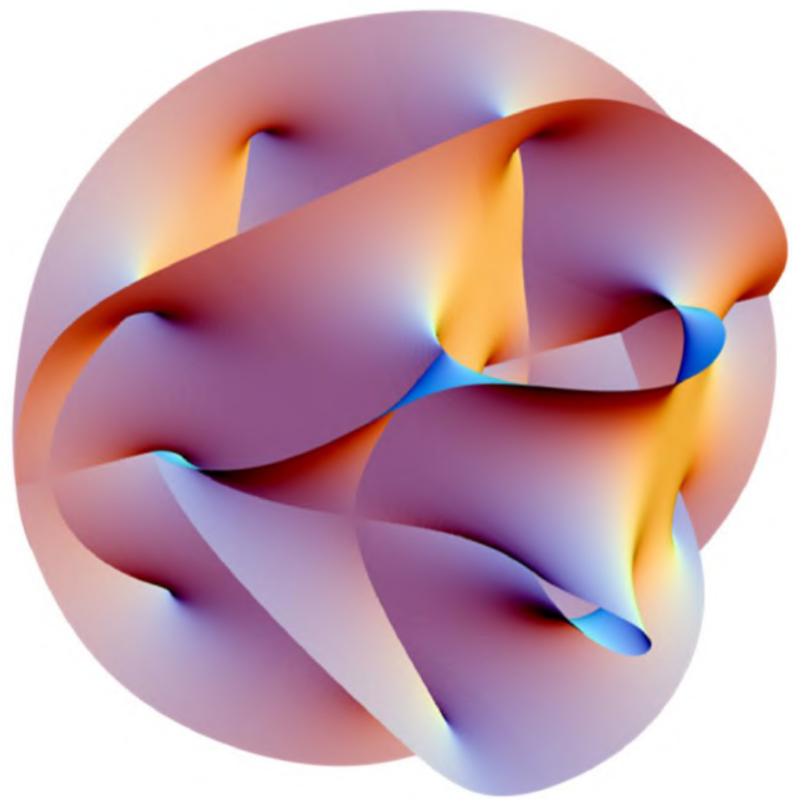


The Five Main String Theories

- **Type I:** Supersymmetry between forces and matter, open and closed strings; group symmetry is SO(32)
- **Type IIA:** Supersymmetry between forces and matter, closed strings, open strings bound to D-branes, massless fermions spin both ways (achiral).
- **Type IIB:** Supersymmetry between forces and matter, closed strings, open strings bound to D-branes; massless fermions only spin one way (chiral).
- **Type HO:** Supersymmetry between forces and matter, closed strings, heterotic (right moving and left moving strings differ), group symmetry is SO(32).
- **Type HE:** Supersymmetry between forces and matter, closed strings, heterotic (right moving and left moving strings differ), group symmetry is $E8 \times E8$.

Predictions of String Theory

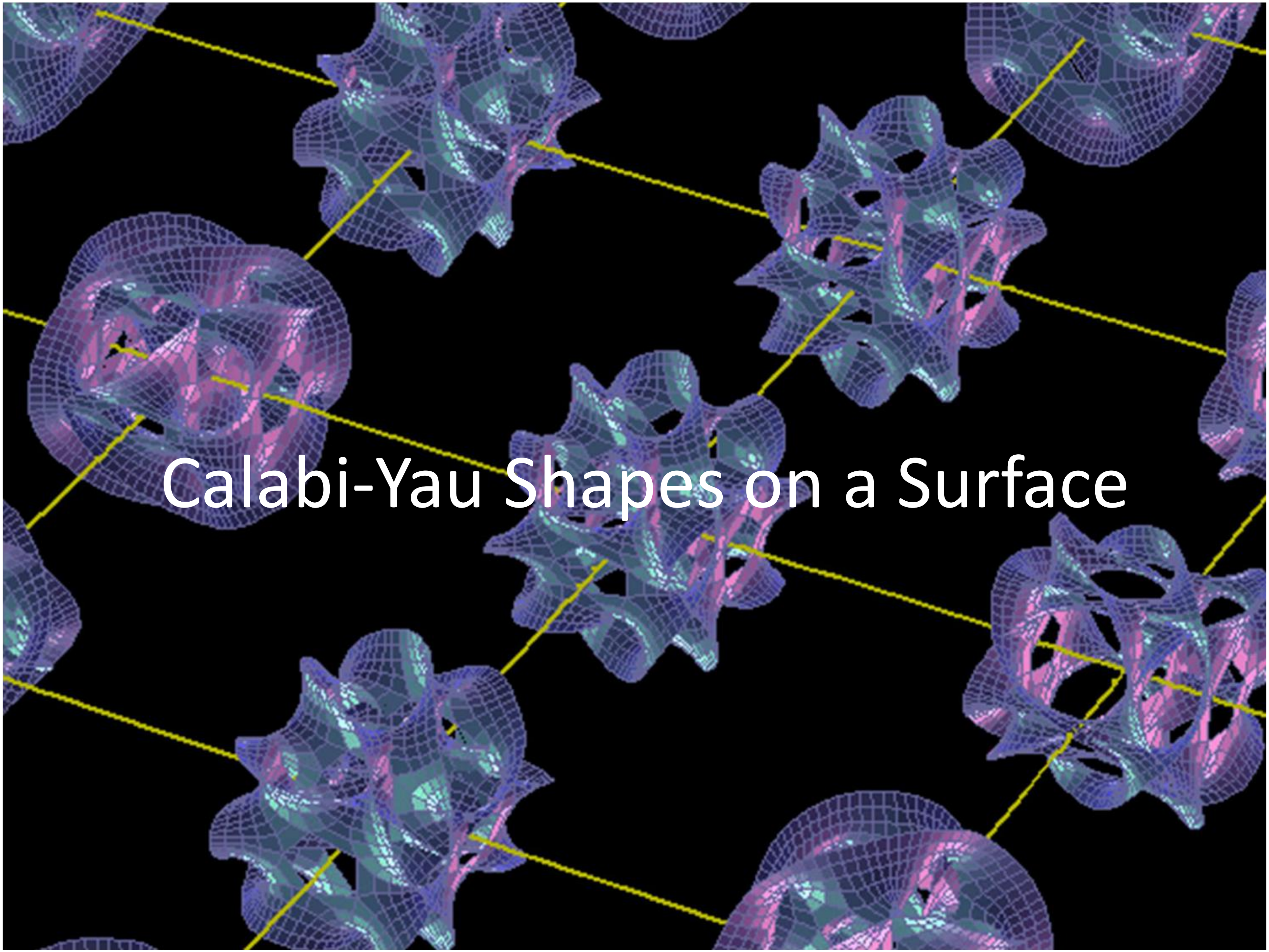
- The five main theories suggest an 11-dimensional universe, composed of 3 space dimensions, 1 time dimension and 6 (or 7) spatially coiled dimensions!
- These coiled dimensions form the Calabi-Yau manifolds.
- String theory states that our universe began from one single explosion, which created all matter.



Alternate Universes

- String Theory states that our universe began from one single explosion, which created all matter. But there was a problem. Where did all this matter come from? This was the singularity. That is where the eleventh dimension comes in. Theoretically there an infinite number of universes in the eleventh dimension, and there is so little space that when the universes move they most often collide, and when they do they create a massive explosion creating an entirely new universe. This explosion is the Big Bang Theory.

- The universe isn't alone, gravity is just an incident, and atoms aren't solid. Whether or not you want to combine the theories I'll leave it up to you, and remember, these are just theories.


Calabi-Yau Shapes on a Surface