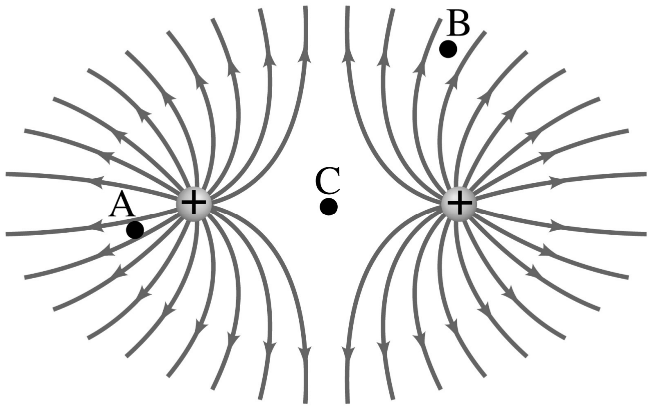
Chapter 16

Electric Charge and Electric Field



Units of Chapter 16

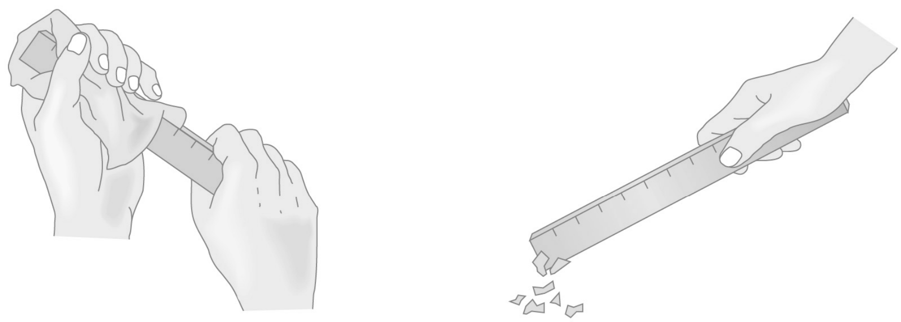
- Static Electricity; Electric Charge and Its Conservation
- Electric Charge in the Atom
- Insulators and Conductors
- Induced Charge; the Electroscope
- Coulomb's Law
- Solving Problems Involving Coulomb's Law and Vectors
- The Electric Field

Units of Chapter 16

- Field Lines
- Electric Fields and Conductors
- Photocopy Machines and Computer Printers Use Electrostatics

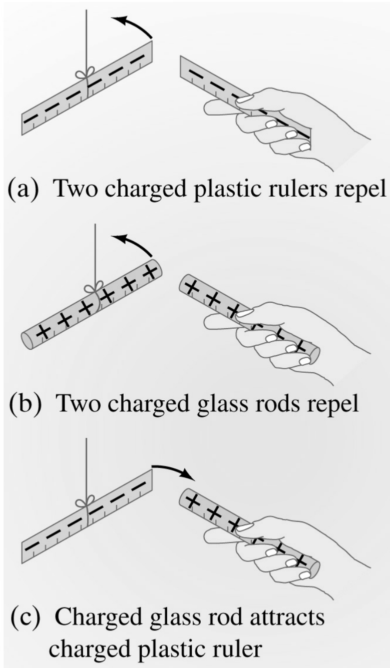
16.1 Static Electricity; Electric Charge and Its Conservation

Objects can be charged by rubbing



(a) (b)

16.1 Static Electricity; Electric Charge and Its Conservation



Charge comes in two types, positive and negative; like charges repel and opposite charges attract

16.1 Static Electricity; Electric Charge and Its Conservation

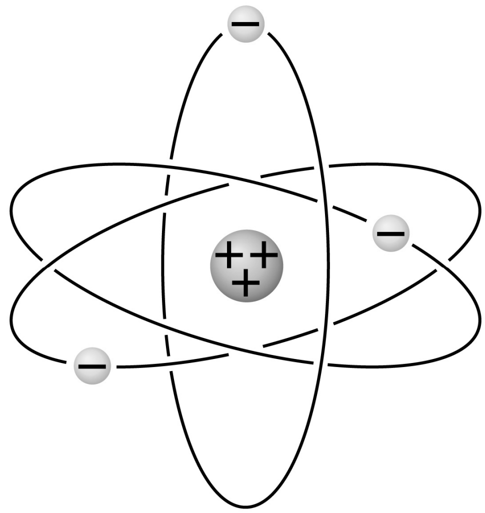
Electric charge is conserved – the arithmetic sum of the total charge cannot change in any interaction.

16.2 Electric Charge in the Atom

Atom:

Nucleus (small, massive, positive charge)

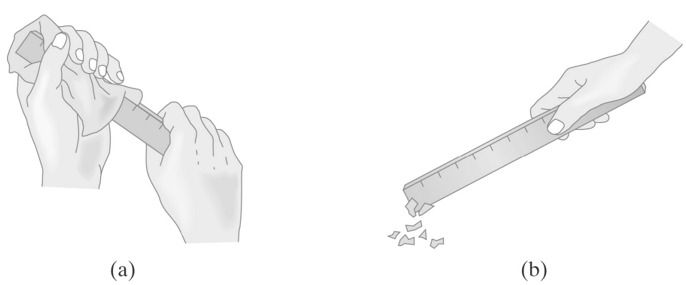
Electron cloud (large, very low density, negative charge)



16.2 Electric Charge in the Atom

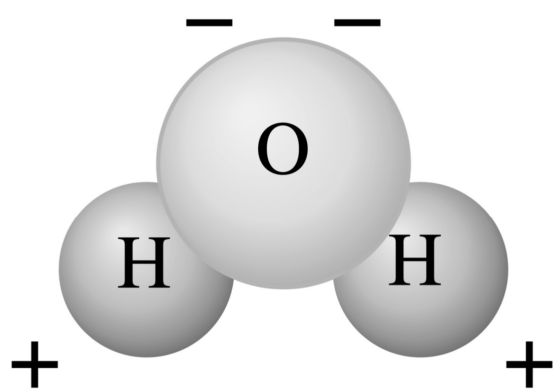
Atom is electrically neutral.

Rubbing charges objects by moving electrons from one to the other.



16.2 Electric Charge in the Atom

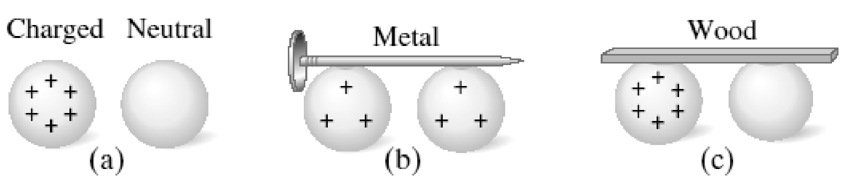
Polar molecule: neutral overall, but charge not evenly distributed



16.3 Insulators and Conductors

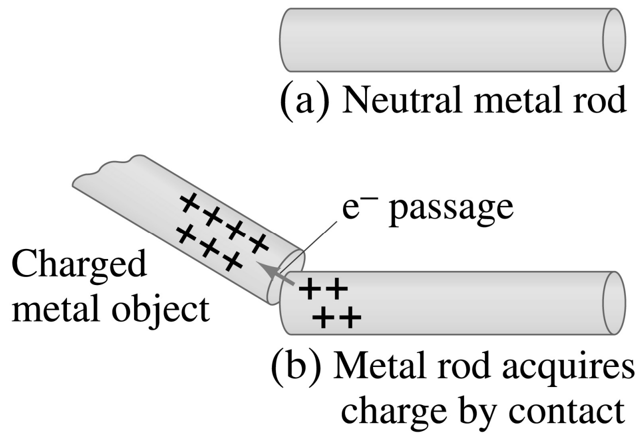
Conductor:	Insulator:
Charge flows freely	Almost no charge flows
Metals	Most other materials

Some materials are semiconductors.



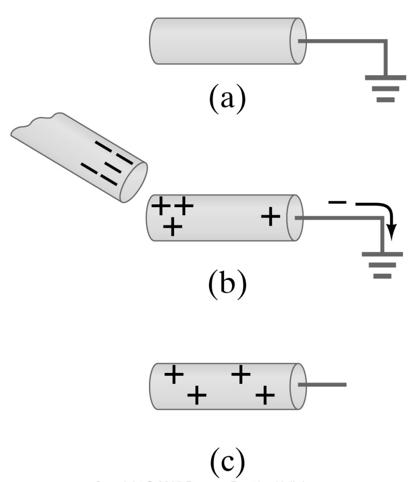
16.4 Induced Charge; the Electroscope

Metal objects can be charged by conduction:



16.4 Induced Charge; the Electroscope

They can also be charged by induction:



16.4 Induced Charge

inductive charging –

uses the electromagnetic field to transfer energy between two objects.

A charging station sends energy through inductive coupling to an electrical device, which stores the energy in the batteries.

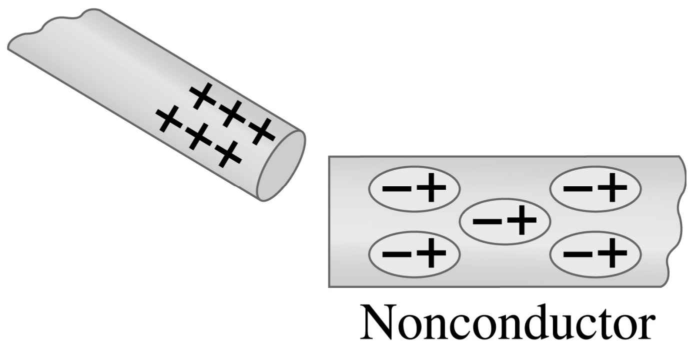
Because there is a small gap between the two coils, inductive charging is one kind of short-distance wireless energy transfer.

16.4 Induced Charge

HP/Palm "Touchstone" charger for HP/Palm Pre, Pixi and TouchPad, and Phillips Sonicare toothbrush.

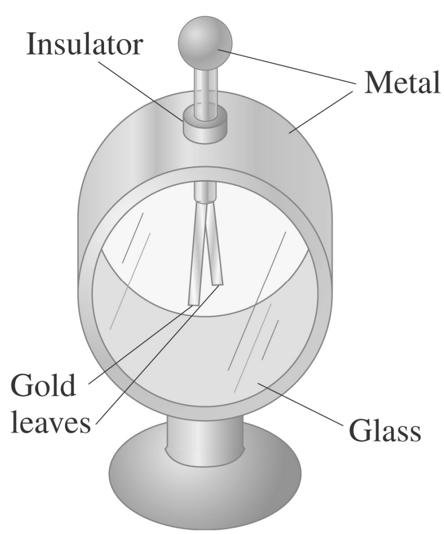
16.4 Induced Charge; the Electroscope

Nonconductors won't become charged by conduction or induction, but will experience charge separation:



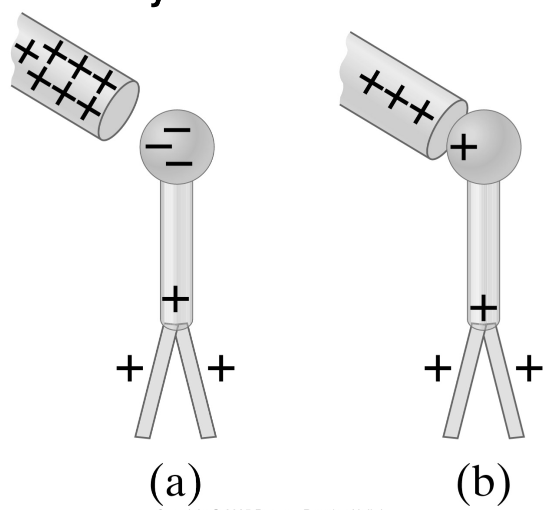
16.4 Induced Charge; the Electroscope

The electroscope can be used for detecting charge:



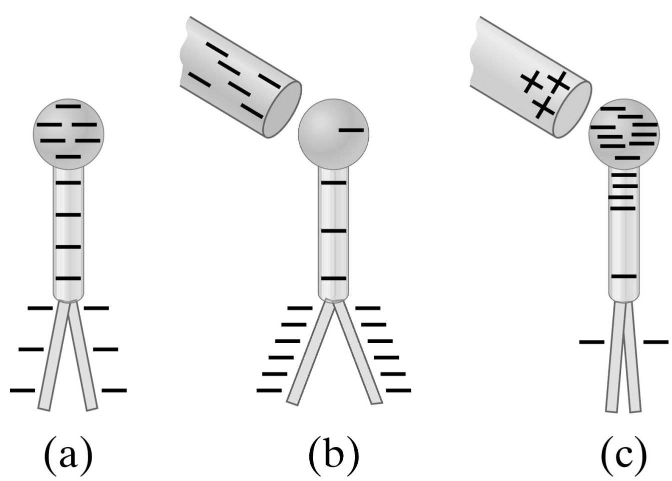
16.4 Induced Charge; the Electroscope

The electroscope can be charged either by conduction or by induction.



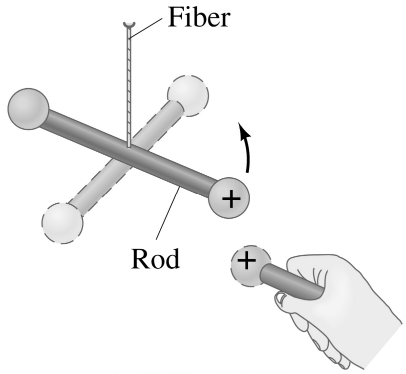
16.4 Induced Charge; the Electroscope

The charged electroscope can then be used to determine the sign of an unknown charge.



16.5 Coulomb’s Law

Experiment shows that the electric force between two charges is proportional to the product of the charges and inversely proportional to the distance between them.



Sound familiar?

Think about a past topic that this is like.

16.5 Coulomb’s Law

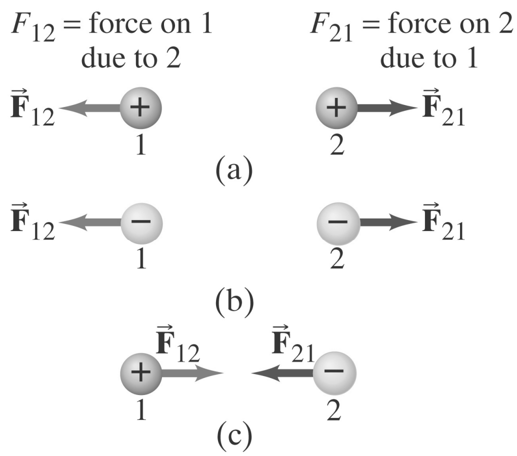
Coulomb’s law:

$$F = k\frac{Q_1 Q_2}{r^2} \quad \textbf{(16-1)}$$

This equation gives the magnitude of the force.

16.5 Coulomb's Law

The force is along the line connecting the charges, and is attractive if the charges are opposite, and repulsive if they are the same.



16.5 Coulomb's Law

Unit of charge: coulomb, C

The proportionality constant in Coulomb's law is then:

$$k = 8.988 \times 10^9\ \mathrm{N \cdot m^2/C^2}$$

Charges produced by rubbing are typically around a microcoulomb:

$$1\ \mu\mathrm{C} = 10^{-6}\ \mathrm{C}$$

16.5 Coulomb's Law

Charge on the electron:

$$e = 1.602 \times 10^{-19}\ \text{C}$$

Electric charge is quantized in units of the electron charge.

16.5 Coulomb's Law

The proportionality constant k can also be written in terms of ϵ_0, the permittivity of free space:

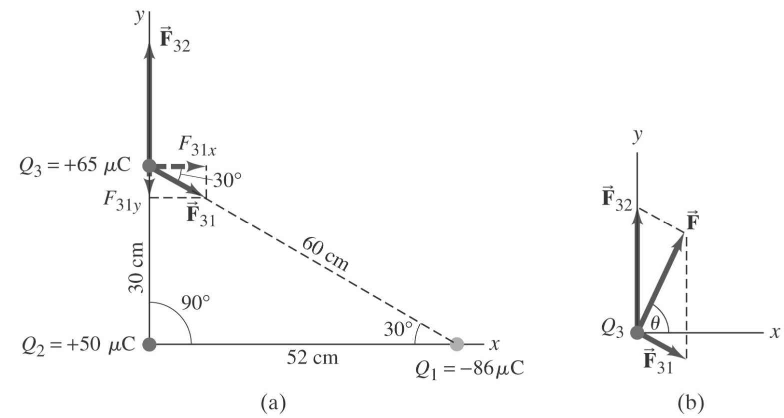
$$F = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r^2}$$

$$\epsilon_0 = \frac{1}{4\pi k} = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2 \qquad \textbf{(16-2)}$$

16.5 Coulomb's Law

Coulomb's law strictly applies only to point charges.

Superposition: for multiple point charges, the forces on each charge from every other charge can be calculated and then added as vectors.



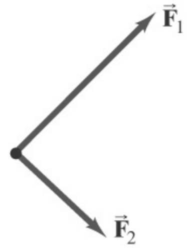
16.6 Solving Problems Involving Coulomb's Law and Vectors

The net force on a charge is the vector sum of all the forces acting on it.

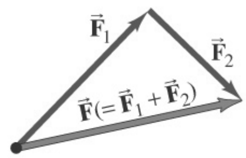
$$\vec{\mathbf{F}}_{\text{net}} = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \cdots$$

16.6 Solving Problems Involving Coulomb's Law and Vectors

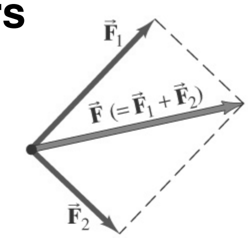
Vector addition review:



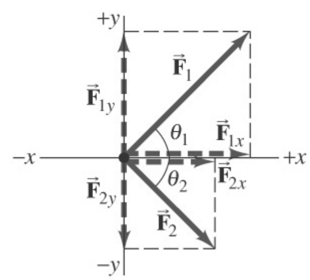
(a) Two forces acting on an object.



(b) The total, or net, force is $\vec{F} = \vec{F}_1 + \vec{F}_2$ by the tail-to-tip method of adding vectors.



(c) $\vec{F} = \vec{F}_1 + \vec{F}_2$ by the parallelogram method.



(d) $\vec{F}_1$ and $\vec{F}_2$ resolved into their x and y components.

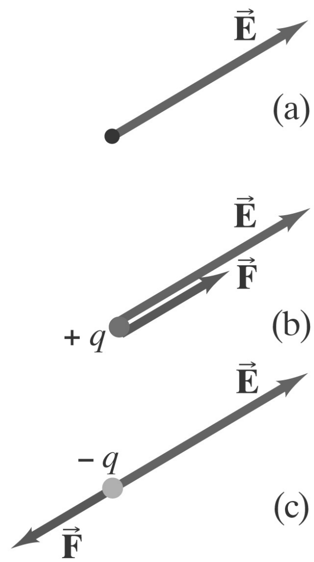
16.6 Solving Problems Involving Coulomb's Law and Vectors

16-4, page 448 - Electric Forces

16.7 The Electric Field

The electric field is the force on a small charge, divided by the charge:

$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}}{q} \qquad \textbf{(16-3)}$$



16.7 The Electric Field

For a point charge:

$$E = k\frac{Q}{r^2} \qquad \textbf{(16-4a)}$$

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2} \qquad \textbf{(16-4b)}$$

16.7 The Electric Field

Force on a point charge in an electric field:

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} \qquad \text{(16-5)}$$

Superposition principle for electric fields:

$$\vec{\mathbf{E}} = \vec{\mathbf{E}}_1 + \vec{\mathbf{E}}_2 + \cdots$$

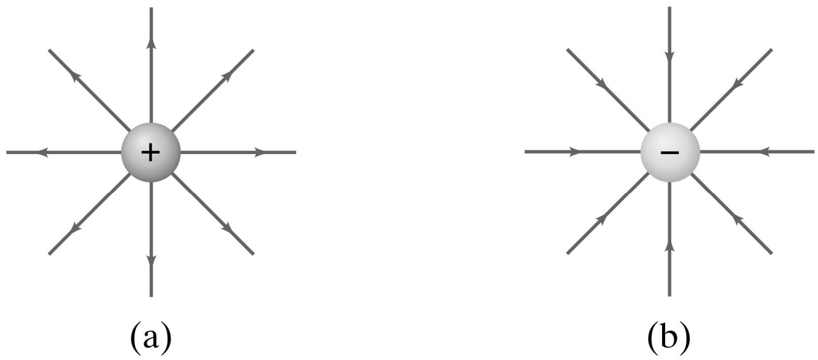
16.7 The Electric Field

Problem solving in electrostatics: electric forces and electric fields

1. **Draw a diagram; show all charges, with signs, and electric fields and forces with directions**
2. **Calculate forces using Coulomb's law**
3. **Add forces vectorially to get result**

16.8 Field Lines

The electric field can be represented by field lines. These lines start on a positive charge and end on a negative charge.



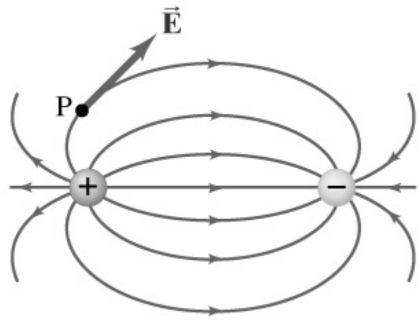
16.8 Field Lines

The number of field lines starting (ending) on a positive (negative) charge is proportional to the magnitude of the charge.

The electric field is stronger where the field lines are closer together.

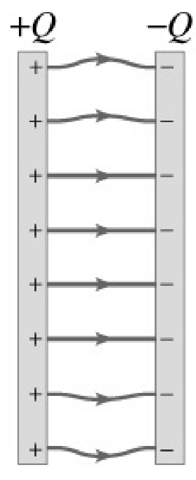
16.8 Field Lines

Electric dipole: two equal charges, opposite in sign:



(a)

16.8 Field Lines



(d)

The electric field between two closely spaced, oppositely charged parallel plates is constant.

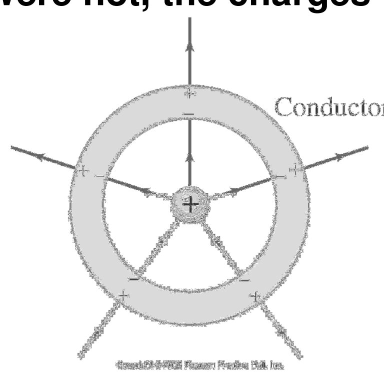
16.8 Field Lines

Summary of field lines:

1. **Field lines indicate the direction of the field; the field is tangent to the line.**
2. **The magnitude of the field is proportional to the density of the lines.**
3. **Field lines start on positive charges and end on negative charges; the number is proportional to the magnitude of the charge.**

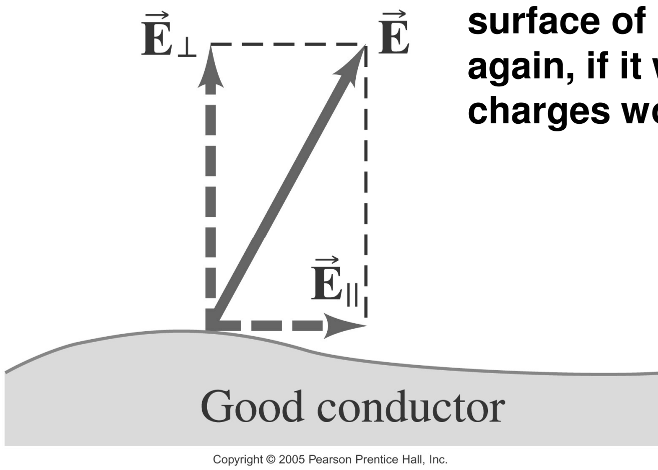
16.9 Electric Fields and Conductors

The static electric field inside a conductor is zero – if it were not, the charges would move.



The net charge on a conductor is on its surface.

16.9 Electric Fields and Conductors



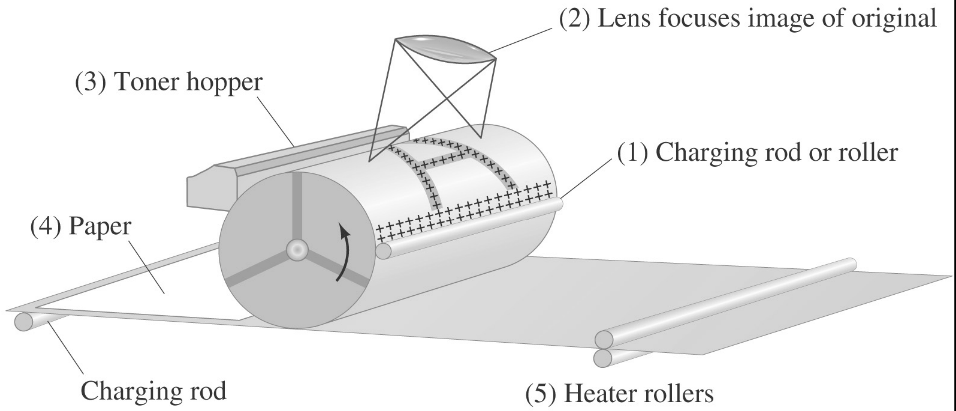
The electric field is perpendicular to the surface of a conductor – again, if it were not, charges would move.

16.12 Photocopy Machines and Computer Printers Use Electrostatics

Photocopy machine:

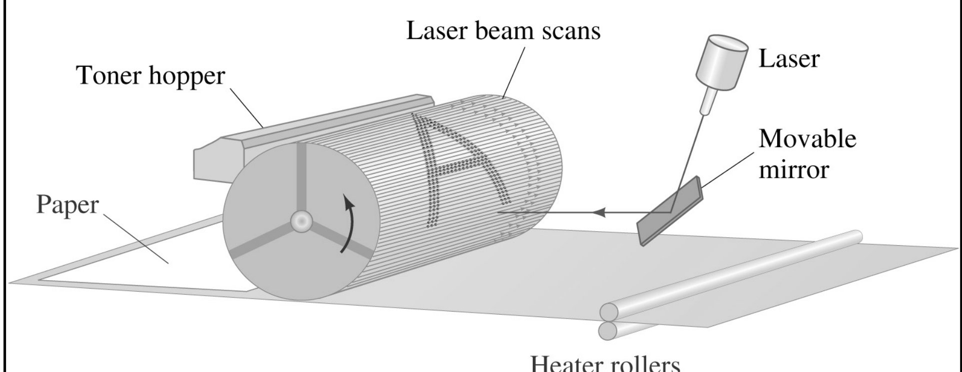
- **drum is charged positively**
- **image is focused on drum**
- **only black areas stay charged and therefore attract toner particles**
- **image is transferred to paper and sealed by heat**

16.12 Photocopy Machines and Computer Printers Use Electrostatics



16.12 Photocopy Machines and Computer Printers Use Electrostatics

Laser printer is similar, except a computer controls the laser intensity to form the image on the drum



Summary of Chapter 16

- Two kinds of electric charge – positive and negative
- Charge is conserved
- Charge on electron:

$$e = 1.602 \times 10^{-19}\ \mathrm{C}$$

- Conductors: electrons free to move
- Insulators: nonconductors

Summary of Chapter 16

- Charge is quantized in units of e
- Objects can be charged by conduction or induction
- Coulomb's law: $F = k\dfrac{Q_1 Q_2}{r^2}$

- Electric field is force per unit charge:

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

Summary of Chapter 16

- **Electric field of a point charge:** $E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}$
- **Electric field can be represented by electric field lines**
- **Static electric field inside conductor is zero; surface field is perpendicular to surface**
- **Electric flux:** $\Phi_E = EA\cos\theta$
- **Gauss's law:**

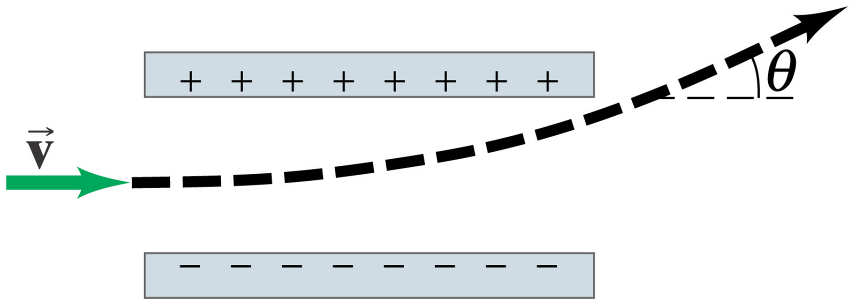
$$\sum_{\substack{\text{closed}\\\text{surface}}} E_\perp \, \Delta A = \frac{Q_{\text{encl}}}{\epsilon_0}$$

Homework

- Chp 16 Problems: # 5, 7, 9, 23, 25, 27, 31

Chapter 17

Electric Potential



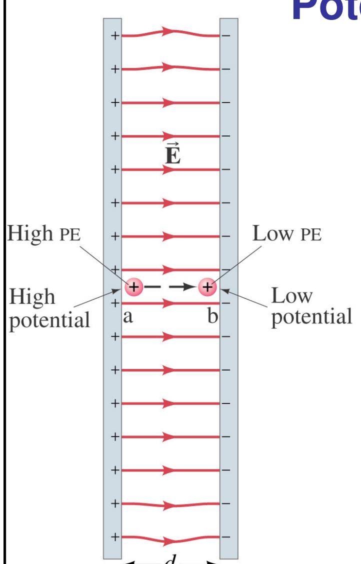
Units of Chapter 17

- Electric Potential Energy and Potential Difference
- Relation between Electric Potential and Electric Field
- Equipotential Lines
- The Electron Volt, a Unit of Energy
- Electric Potential Due to Point Charges
- Potential Due to Electric Dipole; Dipole Moment

Units of Chapter 17

- Capacitance
- Dielectrics
- Storage of Electric Energy
- Cathode Ray Tube: TV and Computer Monitors, Oscilloscope
- The Electrocardiogram (ECG or EKG)

17.1 Electrostatic Potential Energy and Potential Difference



The electrostatic force is conservative – potential energy can be defined

Change in electric potential energy is negative of work done by electric force:

$$\mathrm{PE_b} - \mathrm{PE_a} = -qEd \qquad \textbf{(17-1)}$$

17.1 Electrostatic Potential Energy and Potential Difference

Electric potential is defined as potential energy per unit charge:

$$V_a = \frac{PE_a}{q} \qquad (17\text{-}2a)$$

Unit of electric potential: the volt (V).

1 V = l J/C.

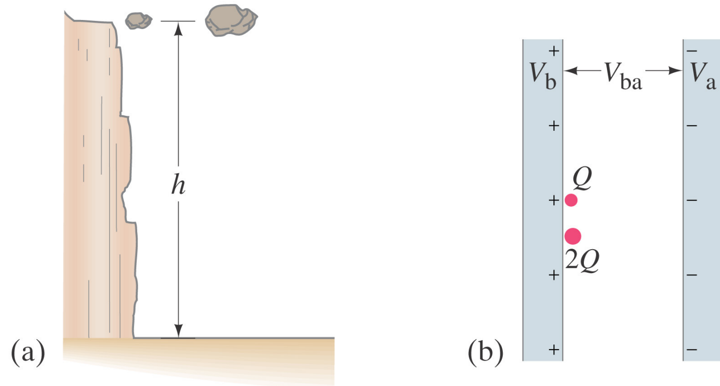
17.1 Electrostatic Potential Energy and Potential Difference

Only changes in potential can be measured, allowing free assignment of $V = 0$.

$$V_{ba} = V_b - V_a = \frac{PE_b - PE_a}{q} = -\frac{W_{ba}}{q} \qquad (17\text{-}2b)$$

17.1 Electrostatic Potential Energy and Potential Difference

Analogy between gravitational and electrical potential energy:



17.2 Relation between Electric Potential and Electric Field

Work is charge multiplied by potential:

$$W = -q(V_b - V_a) = -qV_{ba}$$

Work is also force multiplied by distance:

$$W = Fd = qEd$$

17.2 Relation between Electric Potential and Electric Field

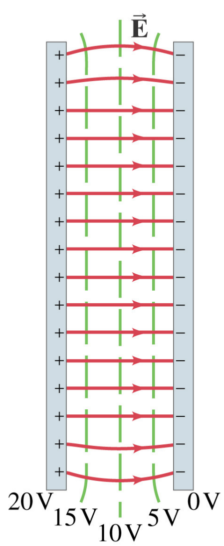
Solving for the field,

$$E = -\frac{V_{\mathrm{ba}}}{d} \qquad \textbf{(17-4b)}$$

If the field is not uniform, it can be calculated at multiple points:

$$E_x = -\Delta V / \Delta x$$

17.3 Equipotential Lines

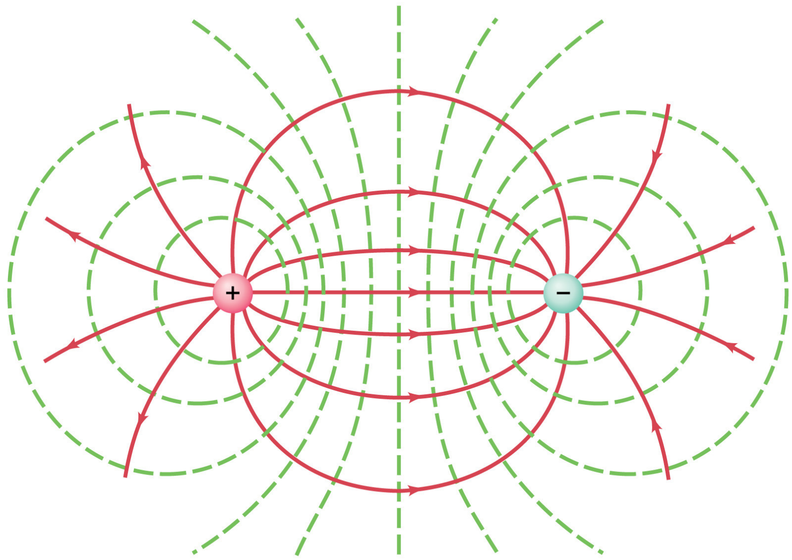


An equipotential is a line or surface over which the potential is constant.

Electric field lines are perpendicular to equipotentials.

The surface of a conductor is an equipotential.

17.3 Equipotential Lines



17.4 The Electron Volt, a Unit of Energy

One electron volt (eV) is the energy gained by an electron moving through a potential difference of one volt.

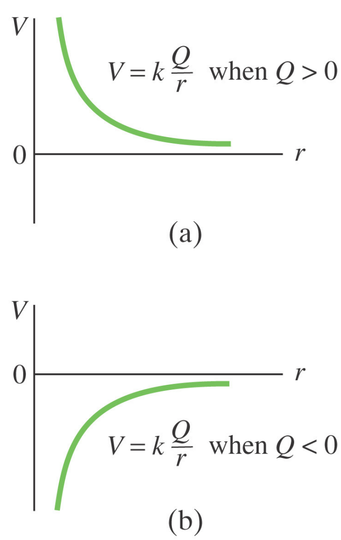
$$1\ \mathrm{eV} = 1.6 \times 10^{-19}\ \mathrm{J}$$

17.5 Electric Potential Due to Point Charges

The electric potential due to a point charge can be derived using calculus.

$$V = k\frac{Q}{r} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r} \qquad \textbf{(17-5)}$$

17.5 Electric Potential Due to Point Charges



These plots show the potential due to (a) positive and (b) negative charge.

17.5 Electric Potential Due to Point Charges

Using potentials instead of fields can make solving problems much easier – potential is a scalar quantity, whereas the field is a vector.

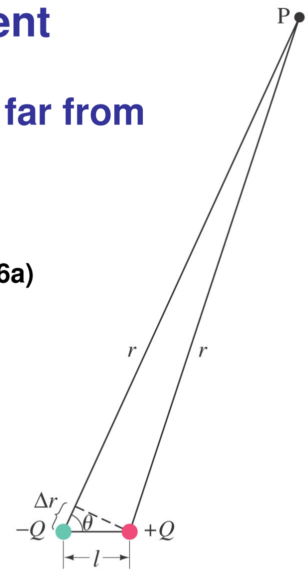
17.6 Potential Due to Electric Dipole; Dipole Moment

The potential due to an electric dipole is just the sum of the potentials due to each charge, and can be calculated exactly.

17.6 Potential Due to Electric Dipole; Dipole Moment

Approximation for potential far from dipole:

$$V \approx \frac{kQl\cos\theta}{r^2} \qquad \text{(17-6a)}$$



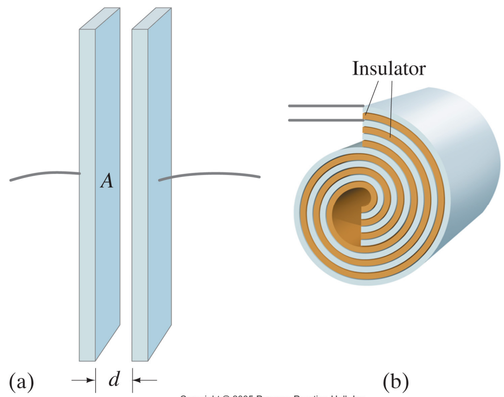
17.6 Potential Due to Electric Dipole; Dipole Moment

Or, defining the dipole moment $p = Ql$,

$$V \approx \frac{kp\cos\theta}{r^2} \qquad \text{(17-6b)}$$

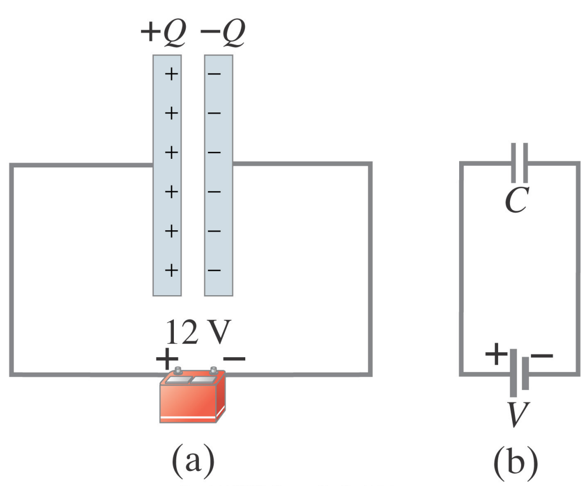
17.7 Capacitance

A capacitor consists of two conductors that are close but not touching. A capacitor has the ability to store electric charge.



17.7 Capacitance

Parallel-plate capacitor connected to battery. (b) is a circuit diagram.



17.7 Capacitance

When a capacitor is connected to a battery, the charge on its plates is proportional to the voltage:

$$Q = CV \qquad \text{(17-7)}$$

The quantity C is called the capacitance.

Unit of capacitance: the farad (F)

1 F = 1 C/V

17.7 Capacitance

The capacitance does not depend on the voltage; it is a function of the geometry and materials of the capacitor.

For a parallel-plate capacitor:

$$C = \epsilon_0 \frac{A}{d} \qquad \text{(17-8)}$$

17.8 Dielectrics

A dielectric is an insulator, and is characterized by a dielectric constant K.

Capacitance of a parallel-plate capacitor filled with dielectric:

$$C = K\epsilon_0 \frac{A}{d} \tag{17-9}$$

TABLE 17–3 Dielectric constants (at 20°C)

Material	Dielectric constant K	Dielectric strength (V/m)
Vacuum	1.0000	
Air (1 atm)	1.0006	3×10^6
Paraffin	2.2	10×10^6
Polystyrene	2.6	24×10^6
Vinyl (plastic)	2–4	50×10^6
Paper	3.7	15×10^6
Quartz	4.3	8×10^6
Oil	4	12×10^6
Glass, Pyrex	5	14×10^6
Rubber, neoprene	6.7	12×10^6
Porcelain	6–8	5×10^6
Mica	7	150×10^6
Water (liquid)	80	
Strontium titanate	300	8×10^6

17.8 Dielectrics

Dielectric strength is the maximum field a dielectric can experience without breaking down.

17.8 Dielectrics

The molecules in a dielectric tend to become oriented in a way that reduces the external field.

17.8 Dielectrics

This means that the electric field within the dielectric is less than it would be in air, allowing more charge to be stored for the same potential.

17.9 Storage of Electric Energy

A charged capacitor stores electric energy; the energy stored is equal to the work done to charge the capacitor.

$$\text{PE} = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C} \qquad \text{(17-10)}$$

17.9 Storage of Electric Energy

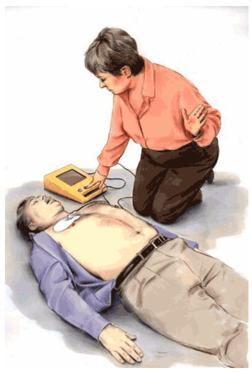
The energy density, defined as the energy per unit volume, is the same no matter the origin of the electric field:

$$\text{energy density} = \frac{\text{PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2 \qquad \text{(17-11)}$$

The sudden discharge of electric energy can be harmful or fatal. Capacitors can retain their charge indefinitely even when disconnected from a voltage source – be careful!

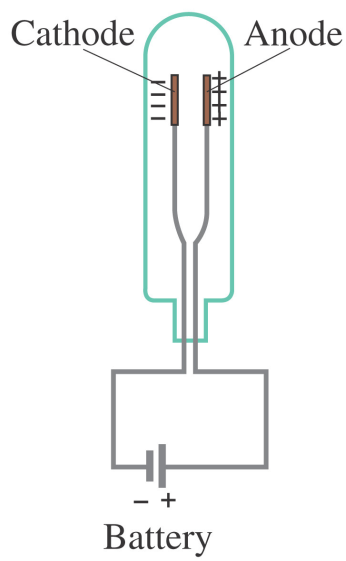
17.9 Storage of Electric Energy

Heart defibrillators use electric discharge to shock and stop an irregular heart beat. The heart will oftentimes reset. An AED can do this and can save lives.



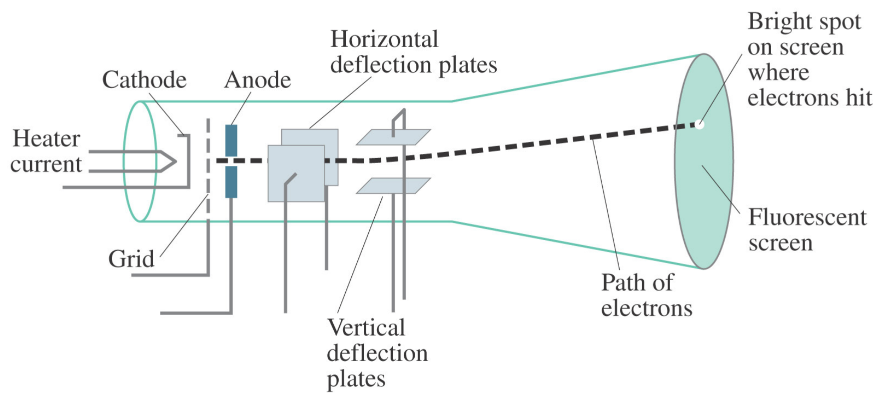
17.10 Cathode Ray Tube: TV and Computer Monitors, Oscilloscope

A cathode ray tube contains a wire cathode that, when heated, emits electrons. A voltage source causes the electrons to travel to the anode.



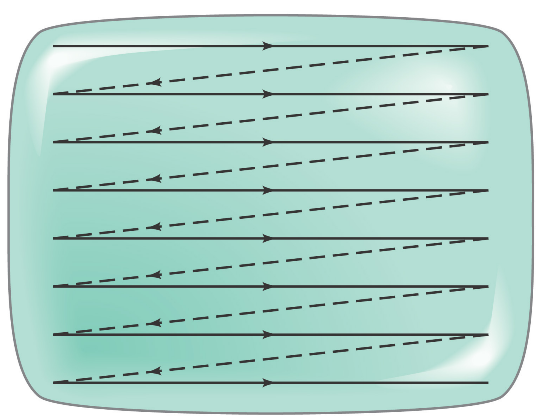
17.10 Cathode Ray Tube: TV and Computer Monitors, Oscilloscope

The electrons can be steered using electric or magnetic fields.



17.10 Cathode Ray Tube: TV and Computer Monitors, Oscilloscope

Televisions and computer monitors (except for LCD and plasma models) have a large cathode ray tube as their display. Variations in the field steer the electrons on their way to the screen.

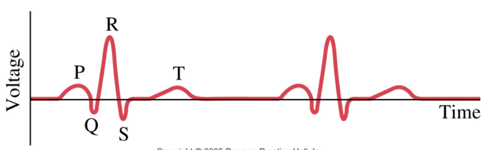


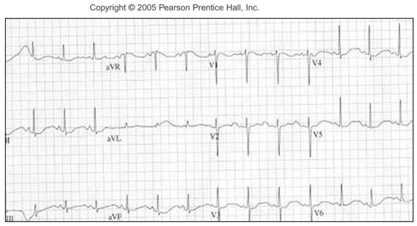
17.10 Cathode Ray Tube: TV and Computer Monitors, Oscilloscope

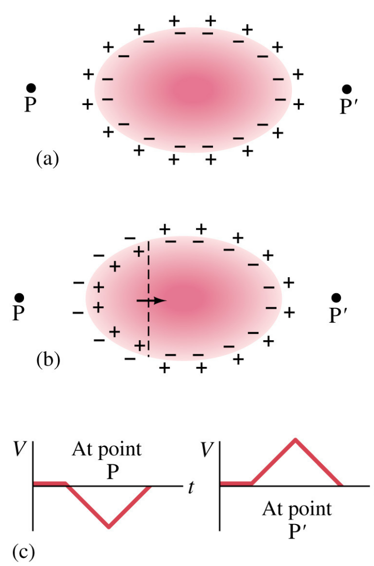
An oscilloscope displays en electrical signal on a screen, using it to deflect the beam vertically while it sweeps horizontally.

17.11 The Electrocardiogram (ECG or EKG)

The electrocardiogram detects heart defects by measuring changes in potential on the surface of the heart.







Summary of Chapter 17

• Electric potential energy:

$$PE_b - PE_a = -qEd$$

• Electric potential difference: work done to move charge from one point to another

• Relationship between potential difference and field:

$$E = -\frac{V_{ba}}{d}$$

Summary of Chapter 17

• Equipotential: line or surface along which potential is the same

• Electric potential of a point charge:

$$V = k\frac{Q}{r} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r}$$

• Electric dipole potential: $V \approx \frac{kp\cos\theta}{r^2}$

Summary of Chapter 17

• Capacitor: nontouching conductors carrying equal and opposite charge

•Capacitance:

$$Q = CV$$

• Capacitance of a parallel-plate capacitor:

$$C = \epsilon_0 \frac{A}{d}$$

Summary of Chapter 17

• A dielectric is an insulator

• Dielectric constant gives ratio of total field to external field

• Energy density in electric field:

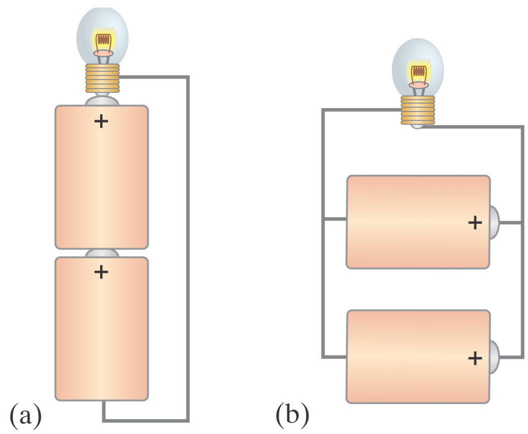
$$\text{energy density} = \frac{\text{PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2$$

Homework

- Chp 17 Problems: # 3, 5, 15, 21, 35, 37, 43, 47

Chapter 18

Electric Currents



Units of Chapter 18

- The Electric Battery
- Electric Current
- Ohm's Law: Resistance and Resistors
- Resistivity
- Electric Power

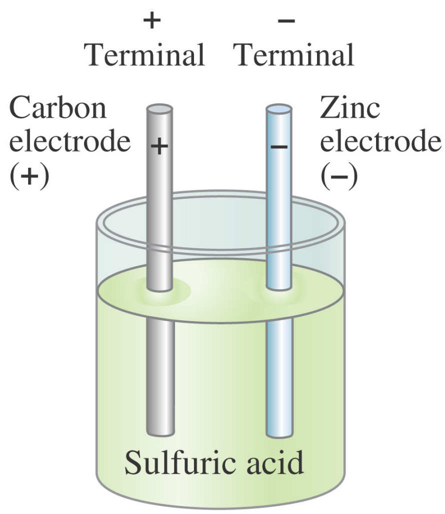
Units of Chapter 18

- Power in Household Circuits
- Alternating Current
- Microscopic View of Electric Current
- Superconductivity
- Electrical Conduction in the Human Nervous System

18.1 The Electric Battery

Volta discovered that electricity could be created if dissimilar metals were connected by a conductive solution called an electrolyte.

This is a simple electric cell.



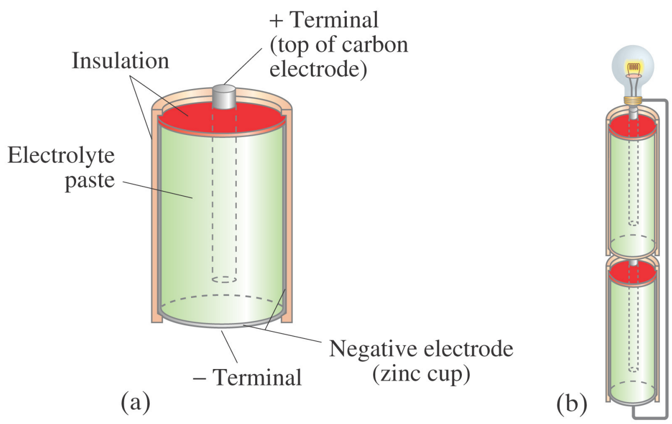
18.1 The Electric Battery

A battery transforms chemical energy into electrical energy.

Chemical reactions within the cell create a potential difference between the terminals by slowly dissolving them. This potential difference can be maintained even if a current is kept flowing, until one or the other terminal is completely dissolved.

18.1 The Electric Battery

Several cells connected together make a battery, although now we refer to a single cell as a battery as well.



18.2 Electric Current

Electric current is the rate of flow of charge through a conductor:

$$I = \frac{\Delta Q}{\Delta t} \qquad \text{(18-1)}$$

Unit of electric current: the ampere, A.

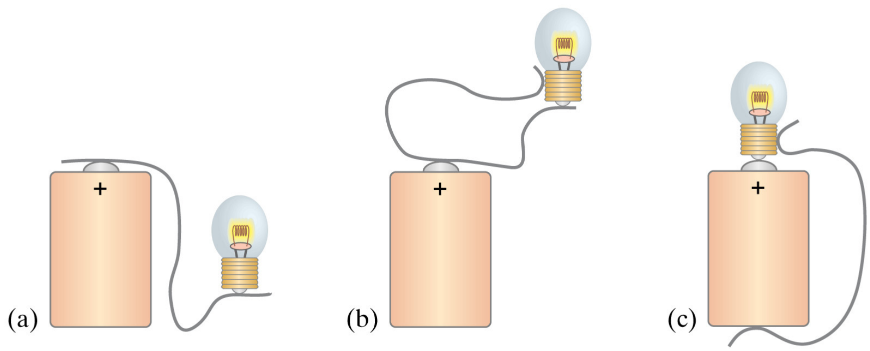
1 A = 1 C/s.

18.2 Electric Current

A complete circuit is one where current can flow all the way around. Note that the schematic drawing doesn't look much like the physical circuit!

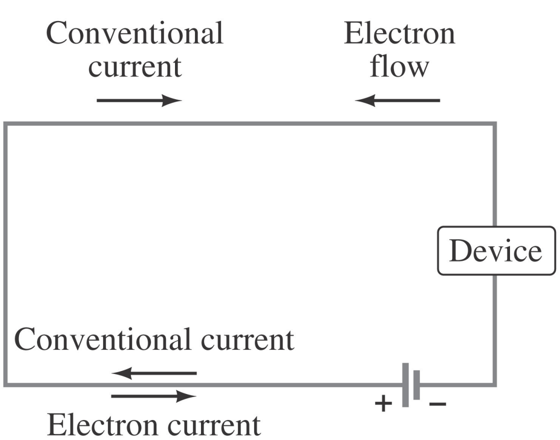
18.2 Electric Current

In order for current to flow, there must be a path from one battery terminal, through the circuit, and back to the other battery terminal. Only one of these circuits will work:



18.2 Electric Current

By convention, current is defined as flowing from + to -. Electrons actually flow in the opposite direction, but not all currents consist of electrons.



18.3 Ohm's Law: Resistance and Resistors

Experimentally, it is found that the current in a wire is proportional to the potential difference between its ends:

$$I \propto V$$

18.3 Ohm's Law: Resistance and Resistors

The ratio of voltage to current is called the resistance:

$$R = \frac{V}{I} \qquad \text{(18-2a)}$$

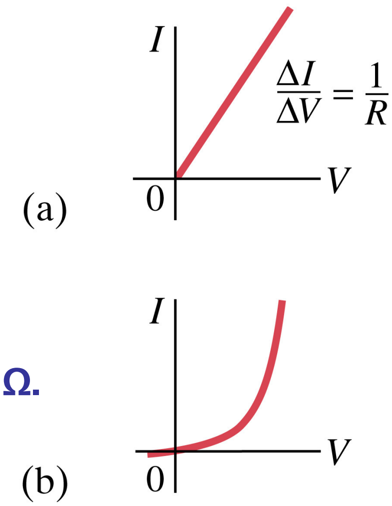
$$V = IR \qquad \text{(18-2b)}$$

18.3 Ohm's Law: Resistance and Resistors

In many conductors, the resistance is independent of the voltage; this relationship is called Ohm's law. Materials that do not follow Ohm's law are called nonohmic.

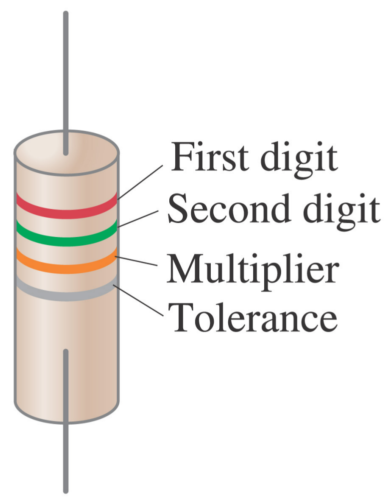
Unit of resistance: the ohm, Ω.

1 Ω = 1 V/A.



18.3 Ohm's Law: Resistance and Resistors

Standard resistors are manufactured for use in electric circuits; they are color-coded to indicate their value and precision.



18.3 Ohm's Law: Resistance and Resistors

Resistor Color Code

Color	Number	Multiplier	Tolerance
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold		10^{-1}	5%
Silver		10^{-2}	10%
No color			20%

18.3 Ohm's Law: Resistance and Resistors

Some clarifications:

• Batteries maintain a (nearly) constant potential difference; the current varies.

• Resistance is a property of a material or device.

• Current is not a vector but it does have a direction.

• Current and charge do not get used up. Whatever charge goes in one end of a circuit comes out the other end.

18.4 Resistivity

The resistance of a wire is directly proportional to its length and inversely proportional to its cross-sectional area:

$$R = \rho \frac{L}{A} \qquad \text{(18-3)}$$

The constant *ρ*, the resistivity, is characteristic of the material.

18.4 Resistivity

TABLE 18–1 Resistivity and Temperature Coefficients (at 20°C)

Material	Resistivity, ρ ($\Omega \cdot$ m)	Temperature Coefficient, α (C°)$^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100×10^{-8}	0.0004
Semiconductors†		
Carbon (graphite)	$(3–60) \times 10^{-5}$	−0.0005
Germanium	$(1–500) \times 10^{-3}$	−0.05
Silicon	0 .1–60	−0.07
Insulators		
Glass	$10^{9} – 10^{12}$	
Hard rubber	$10^{13} – 10^{15}$	

† Values depend strongly on the presence of even slight amounts of impurities.

18.4 Resistivity

For any given material, the resistivity increases with temperature:

$$\rho_T = \rho_0\left[1 + \alpha\left(T - T_0\right)\right] \qquad \text{(18-4)}$$

Semiconductors are complex materials, and may have resistivities that decrease with temperature.

18.5 Electric Power

Power, as in kinematics, is the energy transformed by a device per unit time:

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{QV}{t}$$

$$P = IV \qquad \text{(18-5)}$$

18.5 Electric Power

The unit of power is the watt, W.

For ohmic devices, we can make the substitutions:

$$P = IV = I(IR) = I^2R \qquad \text{(18-6a)}$$

$$P = IV = \left(\frac{V}{R}\right)V = \frac{V^2}{R} \qquad \text{(18-6b)}$$

18.5 Electric Power

What you pay for on your electric bill is not power, but energy – the power consumption multiplied by the time.

We have been measuring energy in joules, but the electric company measures it in kilowatt-hours, kWh.

$$\text{One kWh} = (1000\ \text{W})(3600\ \text{s}) = 3.60 \times 10^6\ \text{J}$$

18.6 Power in Household Circuits

The wires used in homes to carry electricity have very low resistance. However, if the current is high enough, the power will increase and the wires can become hot enough to start a fire.

To avoid this, we use fuses or circuit breakers, which disconnect when the current goes above a predetermined value.

18.6 Power in Household Circuits

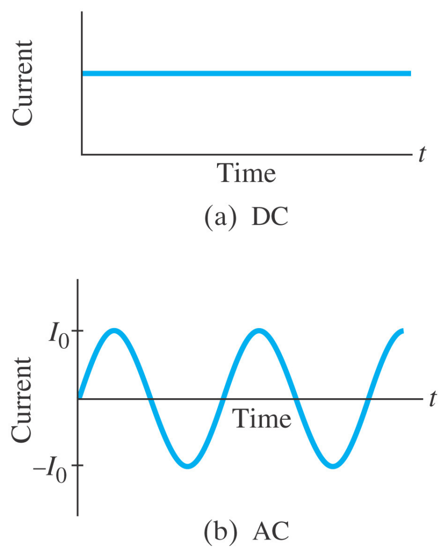
Fuses are one-use items – if they blow, the fuse is destroyed and must be replaced.

18.6 Power in Household Circuits

Circuit breakers, which are now much more common in homes than they once were, are switches that will open if the current is too high; they can then be reset.

18.7 Alternating Current

Current from a battery flows steadily in one direction (direct current, DC). Current from a power plant varies sinusoidally (alternating current, AC).



18.7 Alternating Current

The voltage varies sinusoidally with time:

$$V = V_0 \sin 2\pi f t = V_0 \sin \omega t$$

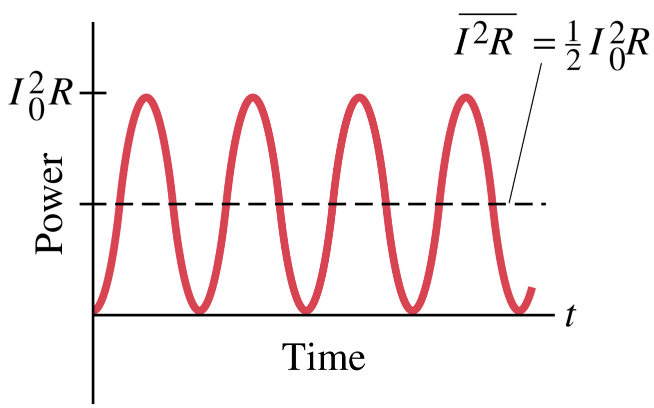
as does the current:

$$I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t \qquad \textbf{(18-7)}$$

18.7 Alternating Current

Multiplying the current and the voltage gives the power:

$$P = I^2 R = I_0^2 R \sin^2 \omega t$$



18.7 Alternating Current

Usually we are interested in the average power:

$$\overline{P} = \tfrac{1}{2} I_0^2 R$$

$$\overline{P} = \frac{1}{2}\frac{V_0^2}{R}$$

18.7 Alternating Current

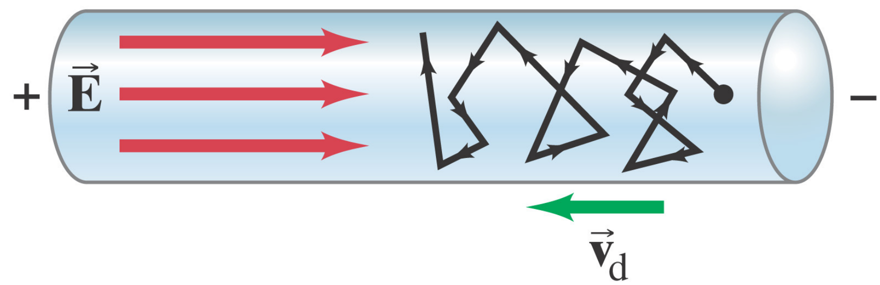
The current and voltage both have average values of zero, so we square them, take the average, then take the square root, yielding the root mean square (rms) value.

$$I_{\text{rms}} = \sqrt{\overline{I^2}} = \frac{I_0}{\sqrt{2}} = 0.707 I_0 \qquad \text{(18-8a)}$$

$$V_{\text{rms}} = \sqrt{\overline{V^2}} = \frac{V_0}{\sqrt{2}} = 0.707 V_0 \qquad \text{(18-8b)}$$

18.8 Microscopic View of Electric Current

Electrons in a conductor have large, random speeds just due to their temperature. When a potential difference is applied, the electrons also acquire an average drift velocity, which is generally considerably smaller than the thermal velocity.



18.8 Microscopic View of Electric Current

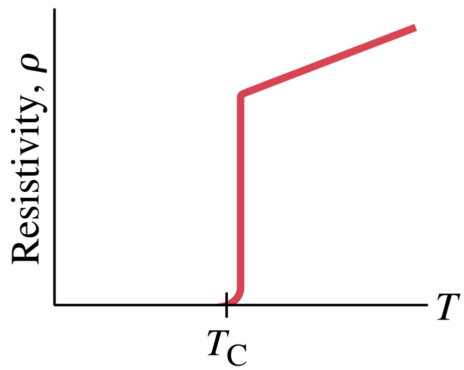
This drift speed is related to the current in the wire, and also to the number of electrons per unit volume.

$$\Delta Q = (\text{number of charges, } N) \times (\text{charge per particle}) = (nV)(e) = (nAv_d\,\Delta t)(e).$$

$$I = \frac{\Delta Q}{\Delta t} = neAv_d \qquad \textbf{(18-10)}$$

18.9 Superconductivity

In general, resistivity decreases as temperature decreases. Some materials, however, have resistivity that falls abruptly to zero at a very low temperature, called the critical temperature, T_C.



18.9 Superconductivity

Experiments have shown that currents, once started, can flow through these materials for years without decreasing even without a potential difference.

Critical temperatures are low; for many years no material was found to be superconducting above 23 K.

More recently, novel materials have been found to be superconducting below 90 K, and work on higher temperature superconductors is continuing.

18.10 Electrical Conduction in the Human Nervous System

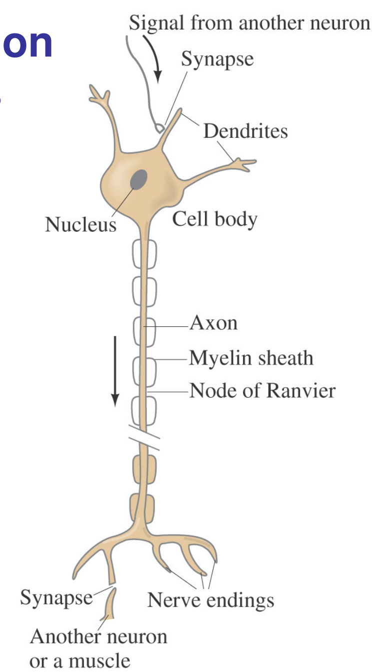
The human nervous system depends on the flow of electric charge.

The basic elements of the nervous system are cells called neurons.

Neurons have a main cell body, small attachments called dendrites, and a long tail called the axon.

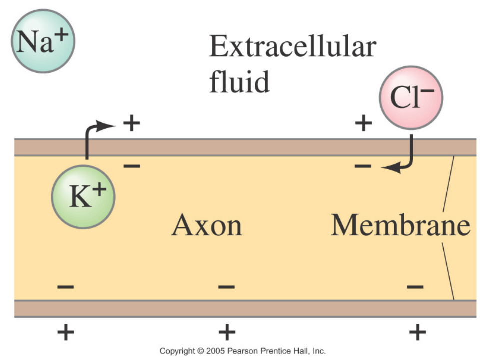
18.10 Electrical Conduction in the Human Nervous System

Signals are received by the dendrites, propagated along the axon, and transmitted through a connection called a synapse.



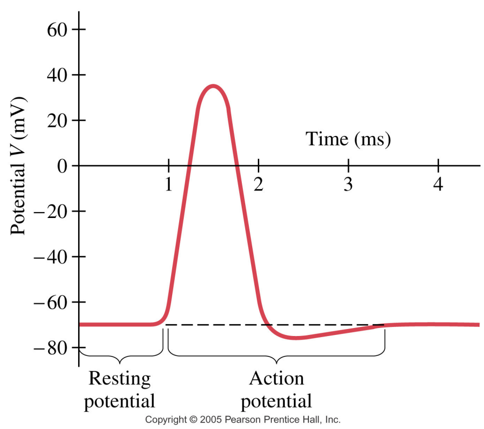
18.10 Electrical Conduction in the Human Nervous System

This process depends on there being a dipole layer of charge on the cell membrane, and different concentrations of ions inside and outside the cell.



18.10 Electrical Conduction in the Human Nervous System

This applies to most cells in the body. Neurons can respond to a stimulus and conduct an electrical signal. This signal is in the form of an action potential.



18.10 Electrical Conduction in the Human Nervous System

The action potential propagates along the axon membrane.

Summary of Chapter 18

• A battery is a source of constant potential difference.

• Electric current is the rate of flow of electric charge.

• Conventional current is in the direction that positive charge would flow.

• Resistance is the ratio of voltage to current:

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

Summary of Chapter 18

- Ohmic materials have constant resistance, independent of voltage.
- Resistance is determined by shape and material:

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

- ρ is the resistivity.

Summary of Chapter 18

- Power in an electric circuit:

$$P = IV$$

- Direct current is constant
- Alternating current varies sinusoidally

$$I = \frac{V}{R} = \frac{V_0}{R} \sin \omega t = I_0 \sin \omega t$$

Summary of Chapter 18

- **The average (rms) current and voltage:**

$$I_{\text{rms}} = \sqrt{\overline{I^2}} = \frac{I_0}{\sqrt{2}} = 0.707 I_0$$

$$V_{\text{rms}} = \sqrt{\overline{V^2}} = \frac{V_0}{\sqrt{2}} = 0.707 V_0$$

- **Relation between drift speed and current:**

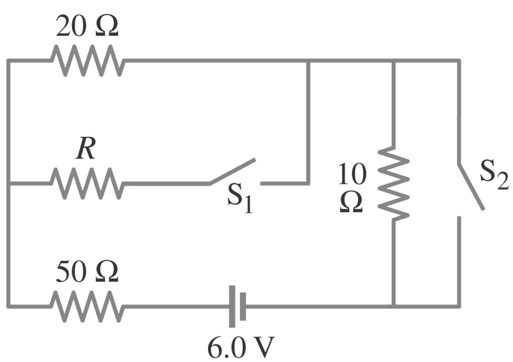
$$I = \frac{\Delta Q}{\Delta t} = neAv_{\text{d}}$$

Homework

- Chp 18 Problems: # 5, 7, 11, 13, 27, 33, 43

Chapter 19

DC Circuits



Units of Chapter 19

- EMF and Terminal Voltage
- Resistors in Series and in Parallel
- Kirchhoff's Rules
- EMFs in Series and in Parallel; Charging a Battery
- Circuits Containing Capacitors in Series and in Parallel

Units of Chapter 19

- RC Circuits – Resistor and Capacitor in Series
- Electric Hazards
- Ammeters and Voltmeters

19.1 EMF and Terminal Voltage

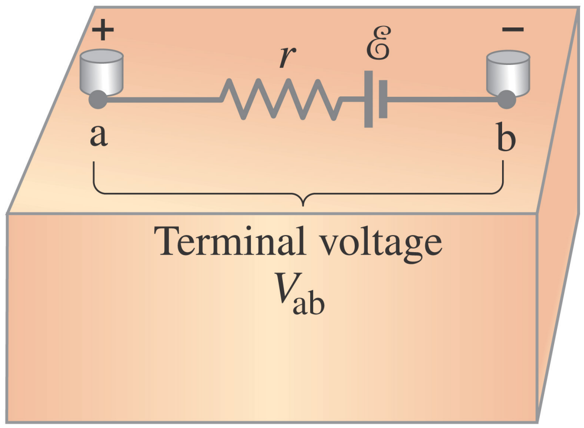
Electric circuit needs battery or generator to produce current – these are called sources of emf.

Battery is a nearly constant voltage source, but does have a small internal resistance, which reduces the actual voltage from the ideal emf:

$$V_{ab} = \mathscr{E} - Ir \qquad \text{(19-1)}$$

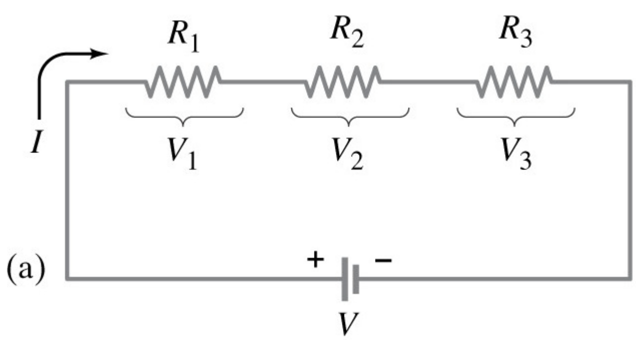
19.1 EMF and Terminal Voltage

This resistance behaves as though it were in series with the emf.



19.2 Resistors in Series and in Parallel

A series connection has a single path from the battery, through each circuit element in turn, then back to the battery.



19.2 Resistors in Series and in Parallel

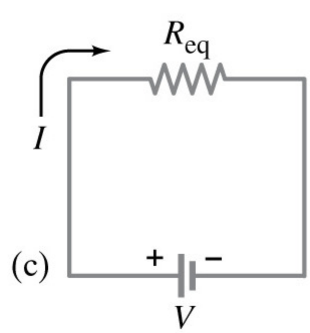
The current through each resistor is the same; the voltage depends on the resistance. The sum of the voltage drops across the resistors equals the battery voltage.

$$V = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3 \quad \text{(19-2)}$$

19.2 Resistors in Series and in Parallel

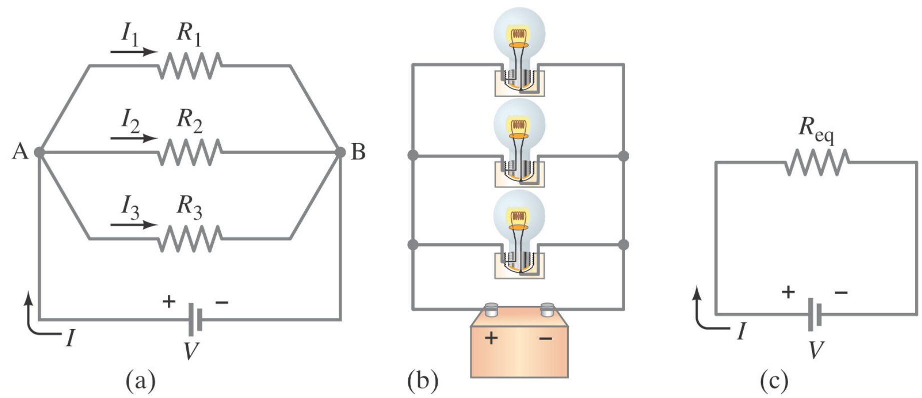
From this we get the equivalent resistance (that single resistance that gives the same current in the circuit).

$$R_{eq} = R_1 + R_2 + R_3 \quad \text{(19-3)}$$



19.2 Resistors in Series and in Parallel

A parallel connection splits the current; the voltage across each resistor is the same:



19.2 Resistors in Series and in Parallel

The total current is the sum of the currents across each resistor:

$$I = I_1 + I_2 + I_3$$

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

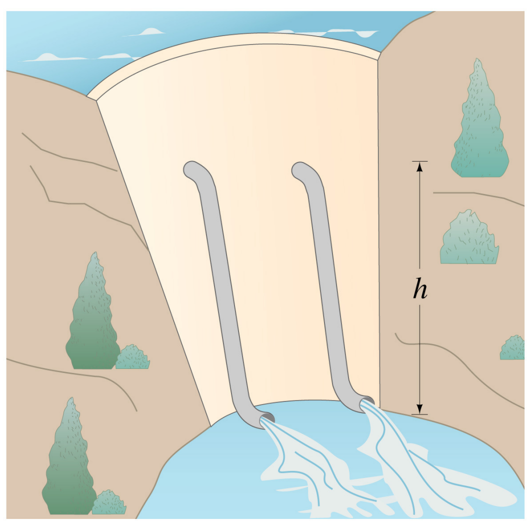
19.2 Resistors in Series and in Parallel

This gives the reciprocal of the equivalent resistance:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad \textbf{(19-4)}$$

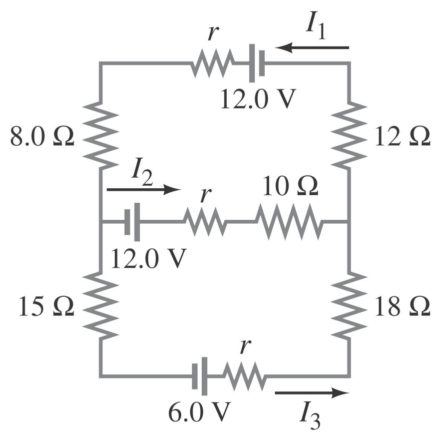
19.2 Resistors in Series and in Parallel

An analogy using water may be helpful in visualizing parallel circuits:



19.3 Kirchhoff's Rules

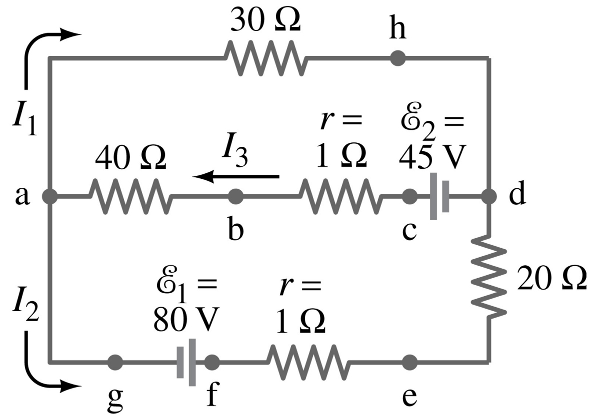
Some circuits cannot be broken down into series and parallel connections.



19.3 Kirchhoff's Rules

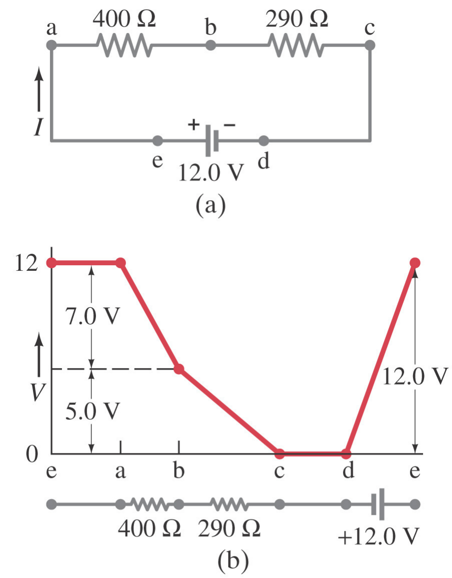
For these circuits we use Kirchhoff's rules.

Junction rule: The sum of currents entering a junction equals the sum of the currents leaving it.



19.3 Kirchhoff's Rules

Loop rule: The sum of the changes in potential around a closed loop is zero.



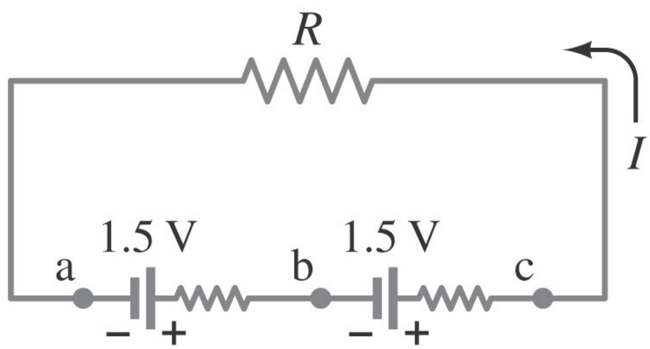
19.3 Kirchhoff's Rules

Problem Solving: Kirchhoff's Rules

1. Label each current.
2. Identify unknowns.
3. Apply junction and loop rules; you will need as many independent equations as there are unknowns.
4. Solve the equations, being careful with signs.

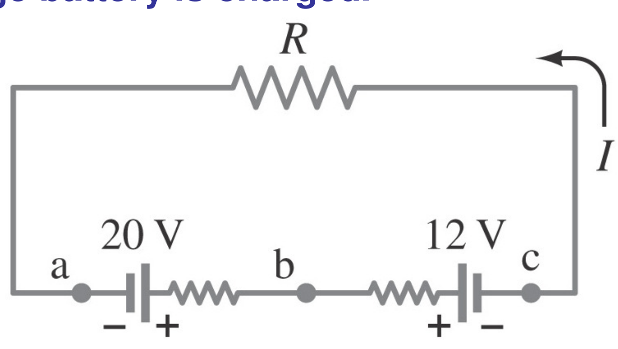
19.4 EMFs in Series and in Parallel; Charging a Battery

EMFs in series in the same direction: total voltage is the sum of the separate voltages



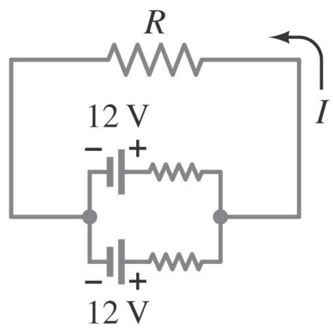
19.4 EMFs in Series and in Parallel; Charging a Battery

EMFs in series, opposite direction: total voltage is the difference, but the lower-voltage battery is charged.



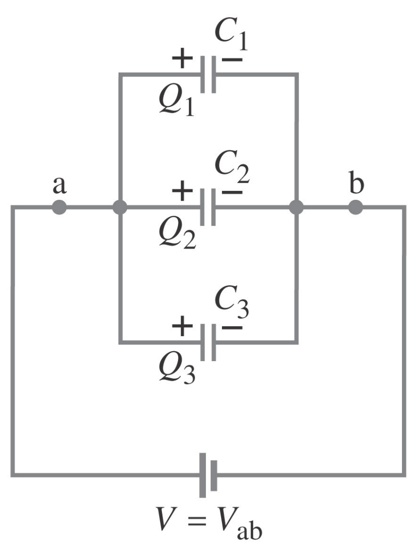
19.4 EMFs in Series and in Parallel; Charging a Battery

EMFs in parallel only make sense if the voltages are the same; this arrangement can produce more current than a single emf.



19.5 Circuits Containing Capacitors in Series and in Parallel

Capacitors in parallel have the same voltage across each one:



19.5 Circuits Containing Capacitors in Series and in Parallel

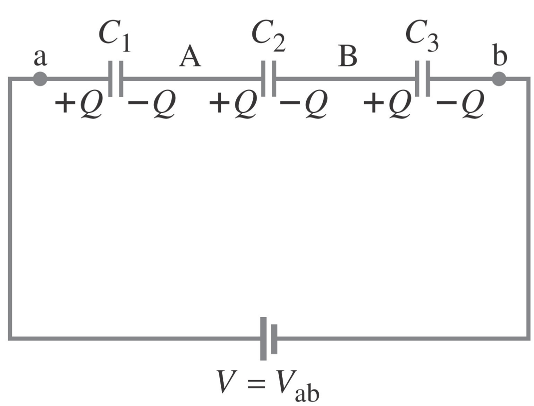
In this case, the total capacitance is the sum:

$$C_{eq}V = C_1V + C_2V + C_3V = (C_1 + C_2 + C_3)V$$

$$C_{eq} = C_1 + C_2 + C_3 \qquad \textbf{(19-5)}$$

19.5 Circuits Containing Capacitors in Series and in Parallel

Capacitors in series have the same charge:



19.5 Circuits Containing Capacitors in Series and in Parallel

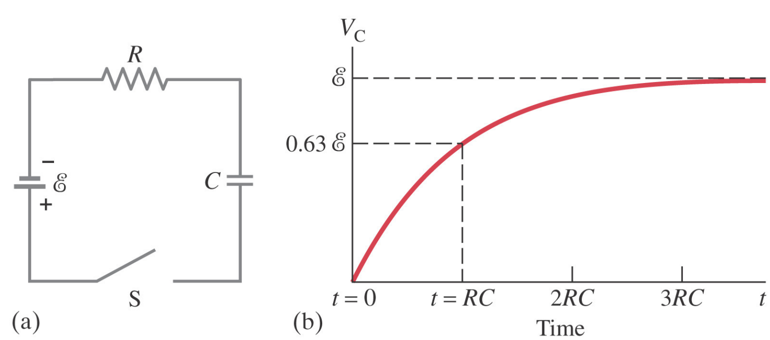
In this case, the reciprocals of the capacitances add to give the reciprocal of the equivalent capacitance:

$$\frac{Q}{C_{\text{eq}}} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3} = Q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)$$

$$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \qquad \text{(19-6)}$$

19.6 RC Circuits – Resistor and Capacitor in Series

When the switch is closed, the capacitor will begin to charge.



19.6 RC Circuits – Resistor and Capacitor in Series

The voltage across the capacitor increases with time:

$$V_C = \mathscr{E}\left(1 - e^{-t/RC}\right)$$

This is a type of exponential.

19.6 RC Circuits – Resistor and Capacitor in Series

The charge follows a similar curve:

$$Q = Q_0\left(1 - e^{-t/RC}\right)$$

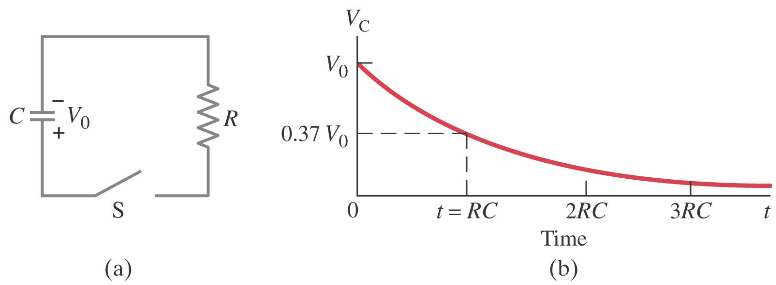
This curve has a characteristic time constant:

$$\tau = RC \qquad \text{(19-7)}$$

19.6 RC Circuits – Resistor and Capacitor in Series

If an isolated charged capacitor is connected across a resistor, it discharges:

$$Q = Q_0 e^{-t/RC}$$



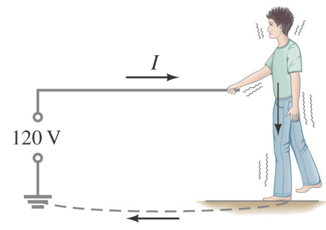
19.7 Electric Hazards

Even very small currents – 10 to 100 mA can be dangerous, disrupting the nervous system. Larger currents may also cause burns.

Household voltage can be lethal if you are wet and in good contact with the ground. Be careful!

19.7 Electric Hazards

A person receiving a shock has become part of a complete circuit.

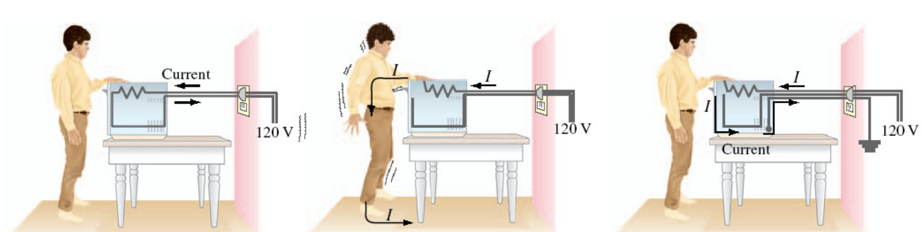


(a)

(b)

19.7 Electric Hazards

Faulty wiring and improper grounding can be hazardous. Make sure electrical work is done by a professional.

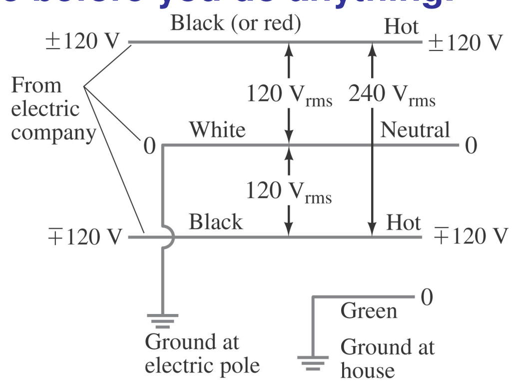


(a) (b) (c)

19.7 Electric Hazards

The safest plugs are those with three prongs; they have a separate ground line.

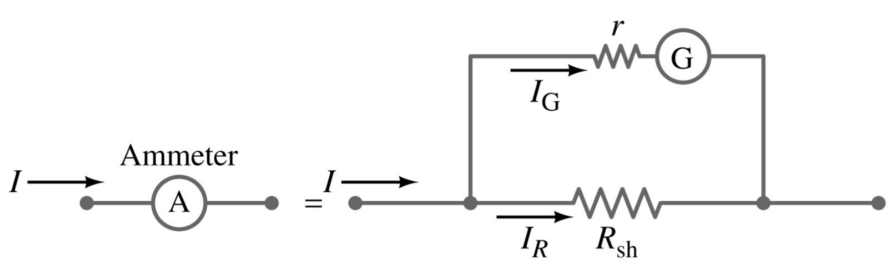
Here is an example of household wiring – colors can vary, though! Be sure you know which is the hot wire before you do anything.



19.8 Ammeters and Voltmeters

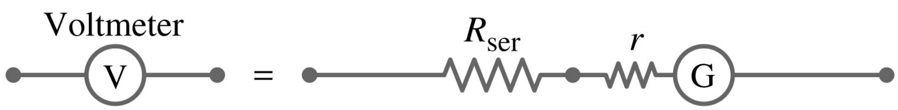
An ammeter measures current; a voltmeter measures voltage. Both are based on galvanometers, unless they are digital.

The current in a circuit passes through the ammeter; the ammeter should have low resistance so as not to affect the current.



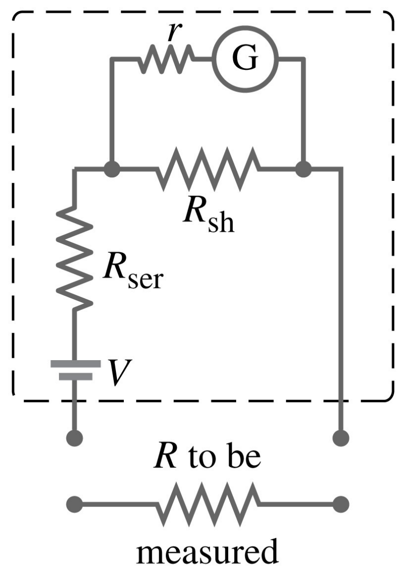
19.8 Ammeters and Voltmeters

A voltmeter should not affect the voltage across the circuit element it is measuring; therefore its resistance should be very large.



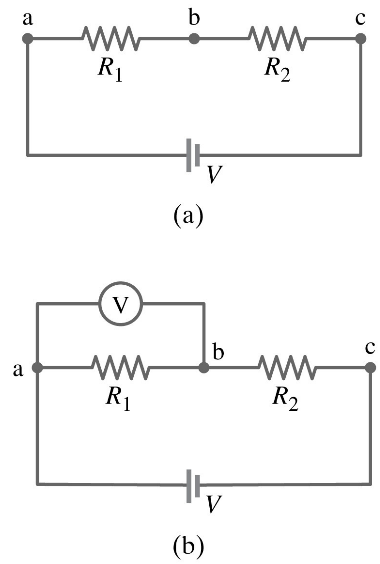
19.8 Ammeters and Voltmeters

An ohmmeter measures resistance; it requires a battery to provide a current



19.8 Ammeters and Voltmeters

If the meter has too much or (in this case) too little resistance, it can affect the measurement.



Summary of Chapter 19

- A source of emf transforms energy from some other form to electrical energy
- A battery is a source of emf in parallel with an internal resistance
- Resistors in series:

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

Summary of Chapter 19

• Resistors in parallel:

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

• Kirchhoff's rules:

1. sum of currents entering a junction equals sum of currents leaving it
2. total potential difference around closed loop is zero

Summary of Chapter 19

• Capacitors in parallel:

$$C_{\text{eq}} = C_1 + C_2 + C_3$$

• Capacitors in series:

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

Summary of Chapter 19

- **RC circuit has a characteristic time constant:**

$$\tau = RC$$

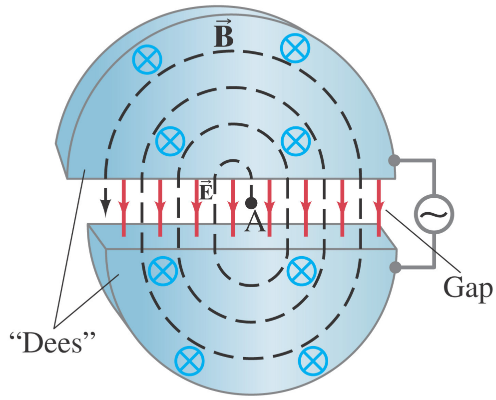
- **To avoid shocks, don't allow your body to become part of a complete circuit**
- **Ammeter: measures current**
- **Voltmeter: measures voltage**

Homework

- Chp 19 Problems: # 5, 7, 9, 17, 23, 27, 35, 37

Chapter 20

Magnetism



Units of Chapter 20

- Magnets and Magnetic Fields
- Electric Currents Produce Magnetic Fields
- Force on an Electric Current in a Magnetic Field; Definition of **B**
- Force on Electric Charge Moving in a Magnetic Field
- Magnetic Field Due to a Long Straight Wire
- Force between Two Parallel Wires

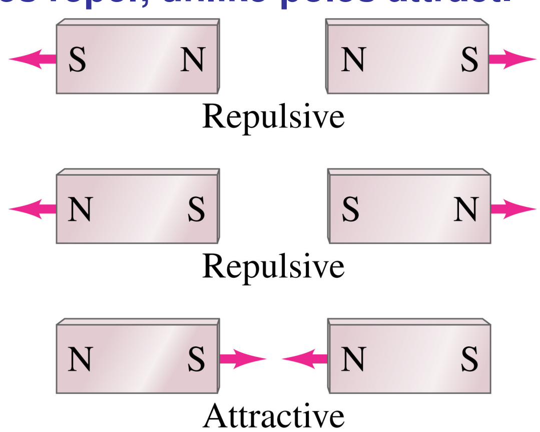
Units of Chapter 20

- Solenoids and Electromagnets
- Torque on a Current Loop; Magnetic Moment
- Applications: Galvanometers, Motors, Loudspeakers
- Mass Spectrometer
- Ferromagnetism: Domains and Hysteresis

20.1 Magnets and Magnetic Fields

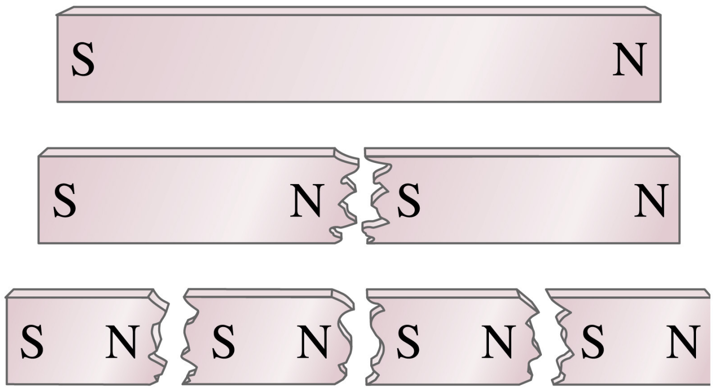
Magnets have two ends – poles – called north and south.

Like poles repel; unlike poles attract.



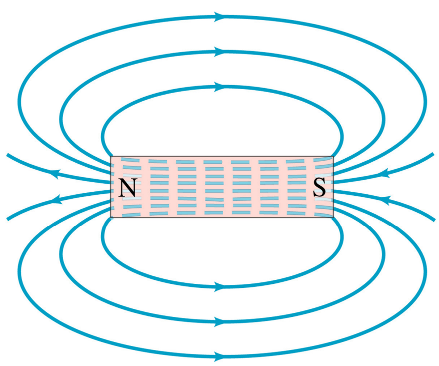
20.1 Magnets and Magnetic Fields

However, if you cut a magnet in half, you don't get a north pole and a south pole – you get two smaller magnets.



20.1 Magnets and Magnetic Fields

Magnetic fields can be visualized using magnetic field lines, which are always closed loops.

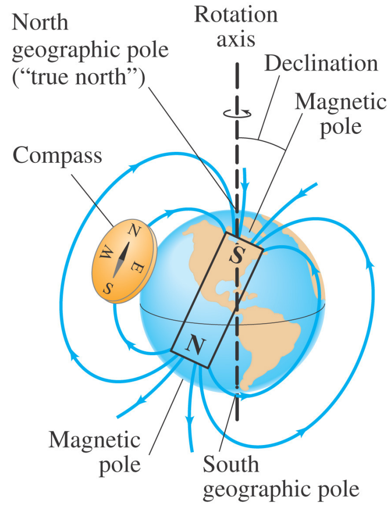


(b)

20.1 Magnets and Magnetic Fields

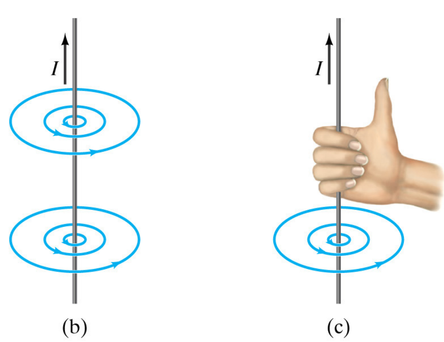
The Earth's magnetic field is similar to that of a bar magnet.

Note that the Earth's "North Pole" is really a south magnetic pole, as the north ends of magnets are attracted to it.



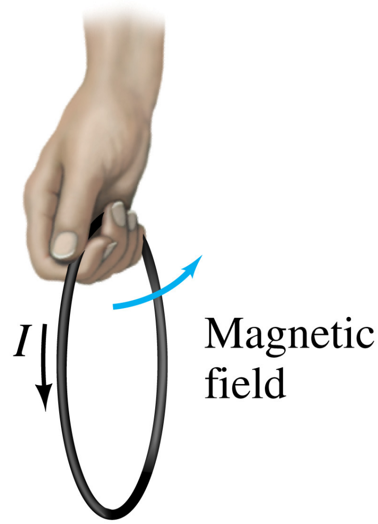
20.2 Electric Currents Produce Magnetic Fields

Experiment shows that an electric current produces a magnetic field.



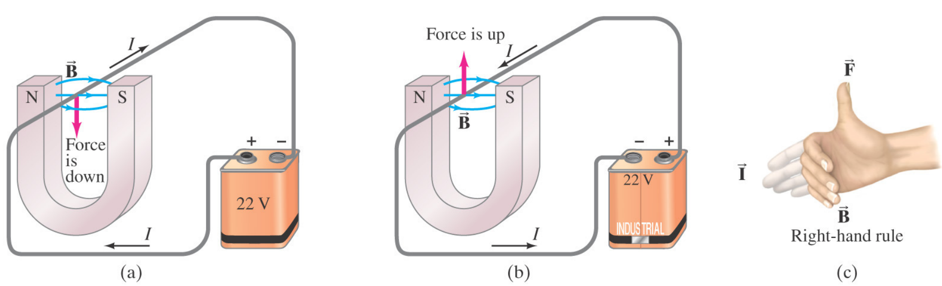
20.2 Electric Currents Produce Magnetic Fields

The direction of the field is given by a right-hand rule.



20.3 Force on an Electric Current in a Magnetic Field; Definition of B

A magnet exerts a force on a current-carrying wire. The direction of the force is given by a right-hand rule.



20.3 Force on an Electric Current in a Magnetic Field; Definition of B

The force on the wire depends on the current, the length of the wire, the magnetic field, and its orientation.

$$F = IlB\sin\theta \qquad \text{(20-1)}$$

This equation defines the magnetic field B.

20.3 Force on an Electric Current in a Magnetic Field; Definition of B

Unit of B: the tesla, T.

1 T = 1 N/A·m.

Another unit sometimes used: the gauss (G).

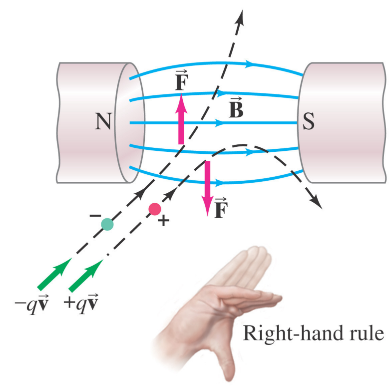
1 G = 10^{-4} T.

20.4 Force on Electric Charge Moving in a Magnetic Field

The force on a moving charge is related to the force on a current:

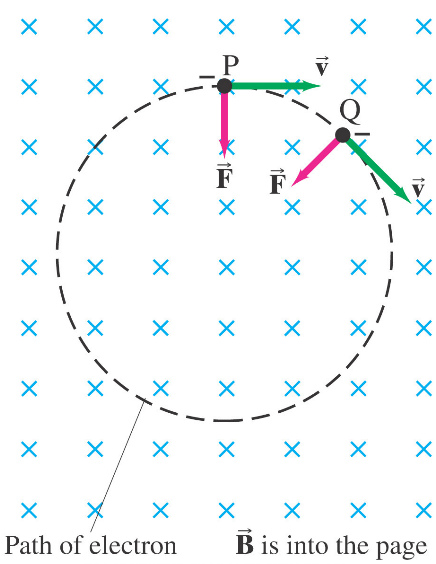
$$F = qvB \sin \theta \quad \text{(20-3)}$$

Once again, the direction is given by a right-hand rule.



20.4 Force on Electric Charge Moving in a Magnetic Field

If a charged particle is moving perpendicular to a uniform magnetic field, its path will be a circle.



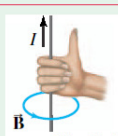
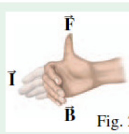
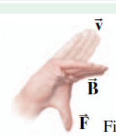
20.4 Force on Electric Charge Moving in a Magnetic Field

Problem solving: Magnetic fields – things to remember

1. **The magnetic force is perpendicular to the magnetic field direction.**
2. **The right-hand rule is useful for determining directions.**
3. **Equations in this chapter give magnitudes only. The right-hand rule gives the direction.**

20.4 Force on Electric Charge Moving in a Magnetic Field

TABLE 20–1 Summary of Right-hand Rules (= RHR)

Physical Situation	Example	How to Orient Right Hand	Result
1. Magnetic field produced by current (RHR-1)	 Fig. 20–8c	Wrap fingers around wire with thumb pointing in direction of current I	Fingers point in direction of $\vec{\mathbf{B}}$
2. Force on electric current I due to magnetic field (RHR-2)	 Fig. 20–11c	Fingers point straight along current I, then bent along magnetic field $\vec{\mathbf{B}}$	Thumb points in direction of force
3. Force on electric charge $+q$ due to magnetic field (RHR-3)	 Fig. 20–14	Fingers point along particle's velocity $\vec{\mathbf{v}}$, then along $\vec{\mathbf{B}}$	Thumb points in direction of force

20.5 Magnetic Field Due to a Long Straight Wire

The field is inversely proportional to the distance from the wire:

$$B = \frac{\mu_0}{2\pi}\frac{I}{r} \qquad \text{(20-6)}$$

The constant μ_0 is called the permeability of free space, and has the value:

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T\cdot m/A}$$

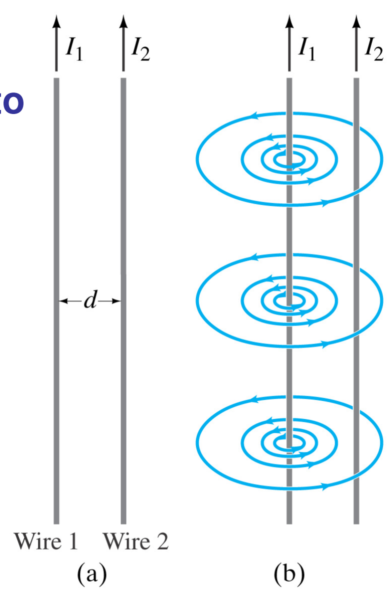
20.6 Force between Two Parallel Wires

The magnetic field produced at the position of wire 2 due to the current in wire 1 is:

$$B_1 = \frac{\mu_0}{2\pi}\frac{I_1}{d}$$

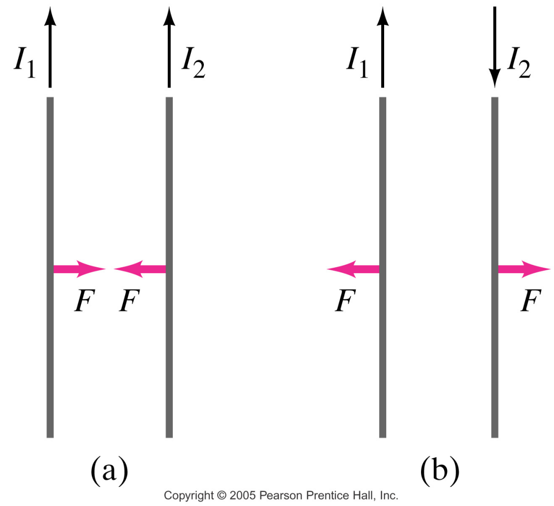
The force this field exerts on a length l_2 of wire 2 is:

$$F_2 = \frac{\mu_0}{2\pi}\frac{I_1 I_2}{d} l_2 \qquad \text{(20-7)}$$



20.6 Force between Two Parallel Wires

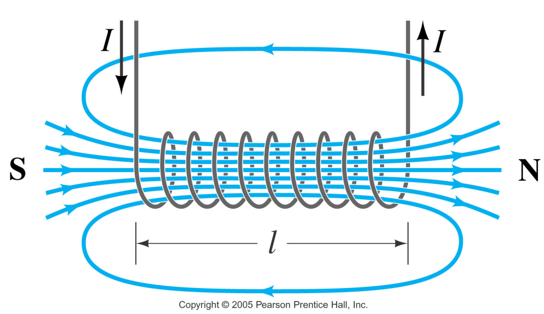
Parallel currents attract; antiparallel currents repel.



20.7 Solenoids and Electromagnets

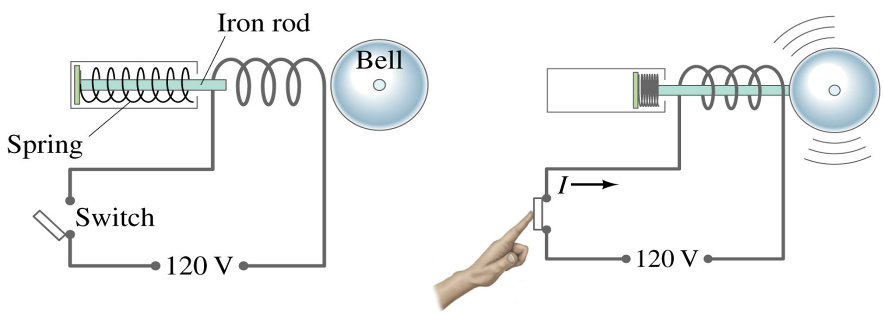
A solenoid is a long coil of wire. If it is tightly wrapped, the magnetic field in its interior is almost uniform:

$$B = \mu_0 I N / l \qquad \textbf{(20-8)}$$



20.7 Solenoids and Electromagnets

If a piece of iron is inserted in the solenoid, the magnetic field greatly increases. Such electromagnets have many practical applications.



20.9 Torque on a Current Loop; Magnetic Moment

The forces on opposite sides of a current loop will be equal and opposite (if the field is uniform and the loop is symmetric), but there may be a torque.

The magnitude of the torque is given by:

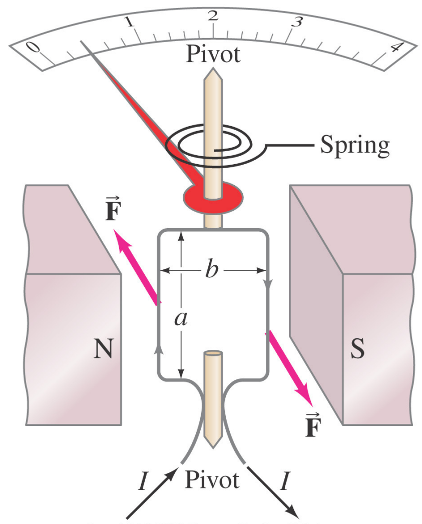
$$\tau = NIAB\sin\theta \qquad \text{(20-10)}$$

The quantity NIA is called the magnetic dipole moment, M:

$$M = NIA \qquad \text{(20-11)}$$

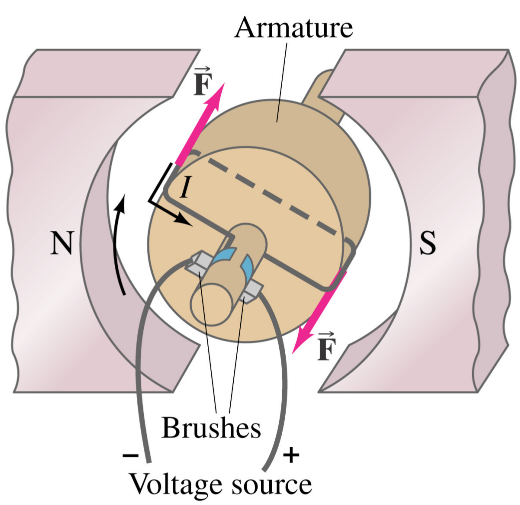
20.10 Applications: Galvanometers, Motors, Loudspeakers

A galvanometer takes advantage of the torque on a current loop to measure current.



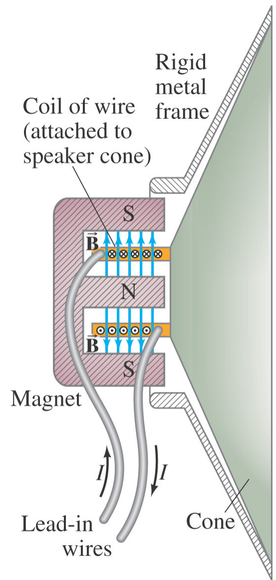
20.10 Applications: Galvanometers, Motors, Loudspeakers

An electric motor also takes advantage of the torque on a current loop, to change electrical energy to mechanical energy.



20.10 Applications: Galvanometers, Motors, Loudspeakers

Loudspeakers use the principle that a magnet exerts a force on a current-carrying wire to convert electrical signals into mechanical vibrations, producing sound.



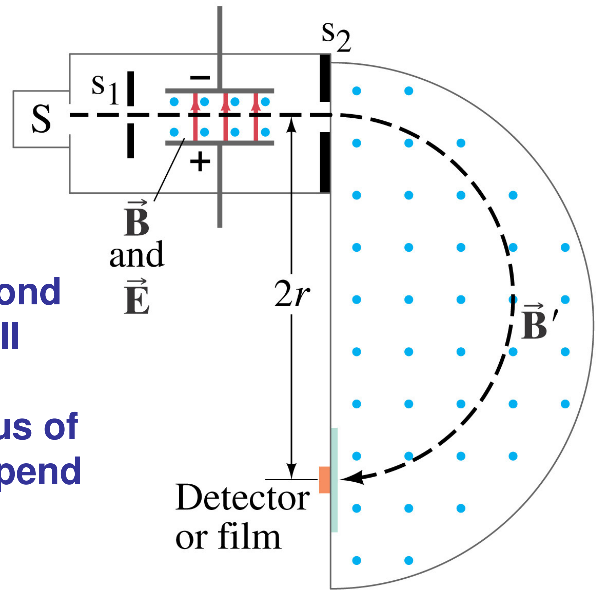
20.11 Mass Spectrometer

A mass spectrometer measures the masses of atoms. If a charged particle is moving through perpendicular electric and magnetic fields, there is a particular speed at which it will not be deflected:

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

20.11 Mass Spectrometer

All the atoms reaching the second magnetic field will have the same speed; their radius of curvature will depend on their mass.



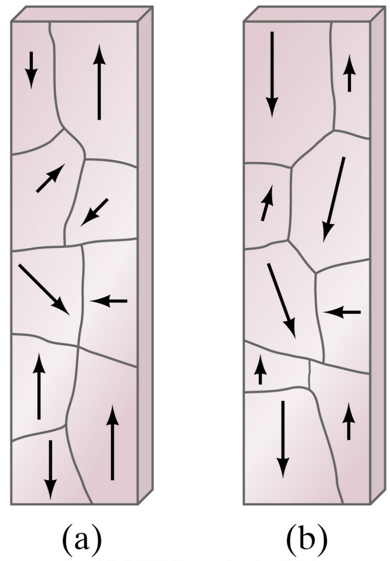
20.12 Ferromagnetism: Domains and Hysteresis

Ferromagnetic materials are those that can become strongly magnetized, such as iron and nickel.

These materials are made up of tiny regions called domains; the magnetic field in each domain is in a single direction.

20.12 Ferromagnetism: Domains and Hysteresis

When the material is unmagnetized, the domains are randomly oriented. They can be partially or fully aligned by placing the material in an external magnetic field.



20.12 Ferromagnetism: Domains and Hysteresis

A magnet, if undisturbed, will tend to retain its magnetism. It can be demagnetized by shock or heat.

The relationship between the external magnetic field and the internal field in a ferromagnet is not simple, as the magnetization can vary.

Summary of Chapter 20

- Magnets have north and south poles
- Like poles repel, unlike attract
- Unit of magnetic field: tesla
- Electric currents produce magnetic fields
- A magnetic field exerts a force on an electric current:

$$F = IlB\sin\theta$$

Summary of Chapter 20

- A magnetic field exerts a force on a moving charge:

$$F = qvB\sin\theta$$

- Magnitude of the field of a long, straight current-carrying wire:

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

- Parallel currents attract; antiparallel currents repel

Summary of Chapter 20

- **Magnetic field inside a solenoid:**

$$B = \mu_0 I N / l$$

- **Torque on a current loop:**

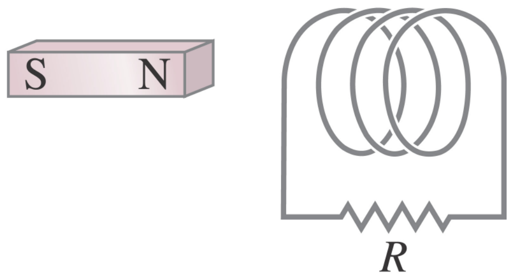
$$\tau = NIAB \sin\theta$$

Homework

- Chp 20 Problems: # 1,3,9,11,13, 27,29,49

Chapter 21

Electromagnetic Induction and Faraday's Law



Units of Chapter 21

- Induced EMF
- Faraday's Law of Induction; Lenz's Law
- EMF Induced in a Moving Conductor
- Changing Magnetic Flux Produces an Electric Field
- Electric Generators
- Transformers and Transmission of Power

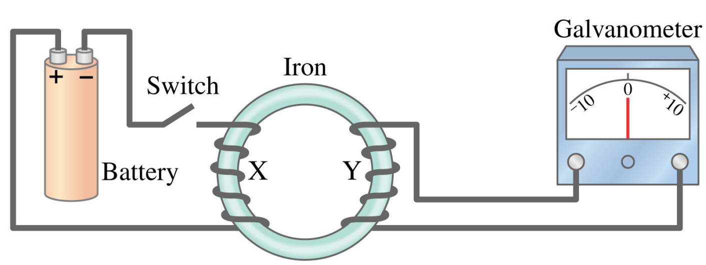
Units of Chapter 21

• Applications of Induction: Sound Systems, Computer Memory, Seismograph, GFCI

• Inductance

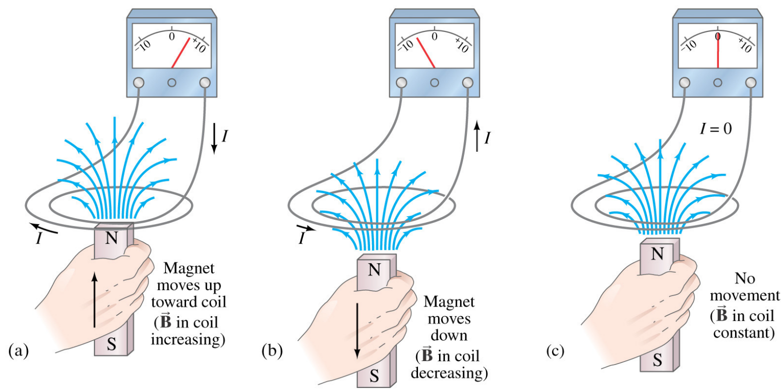
21.1 Induced EMF

Almost 200 years ago, Faraday looked for evidence that a magnetic field would induce an electric current with this apparatus:



21.1 Induced EMF

He found no evidence when the current was steady, but did see a current induced when the switch was turned on or off.



21.1 Induced EMF

Therefore, a changing magnetic field induces an emf.

Faraday's experiment used a magnetic field that was changing because the current producing it was changing; the previous graphic shows a magnetic field that is changing because the magnet is moving.

21.2 Faraday's Law of Induction; Lenz's Law

The induced emf in a wire loop is proportional to the rate of change of magnetic flux through the loop.

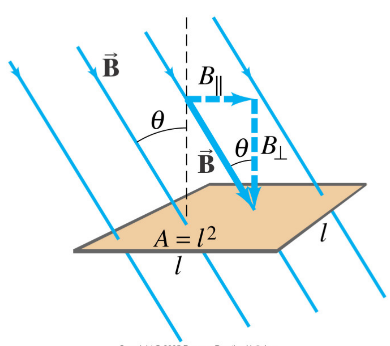
Magnetic flux: $\Phi_B = B_\perp A = BA\cos\theta$ (21-1)

Unit of magnetic flux: weber, Wb.

1 Wb = 1 T·m^2

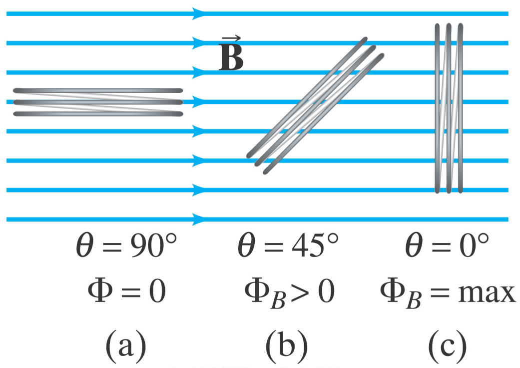
21.2 Faraday's Law of Induction; Lenz's Law

This drawing shows the variables in the flux equation:



21.2 Faraday's Law of Induction; Lenz's Law

The magnetic flux is analogous to the electric flux – it is proportional to the total number of lines passing through the loop.



21.2 Faraday's Law of Induction; Lenz's Law

Faraday's law of induction:

$$\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t}$$ [1 loop] (21-2a)

$$\mathcal{E} = -N\frac{\Delta \Phi_B}{\Delta t}$$ [N loops] (21-2b)

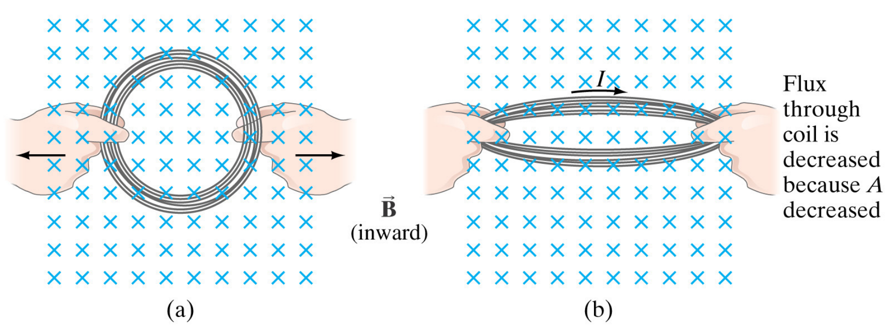
21.2 Faraday's Law of Induction; Lenz's Law

The minus sign gives the direction of the induced emf:

A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed field.

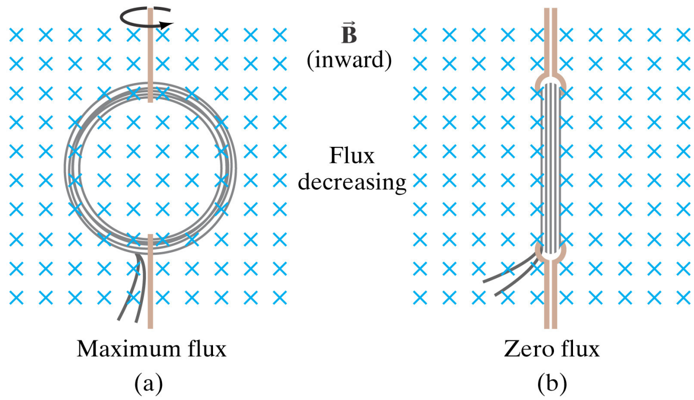
21.2 Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the area of the loop changes:



21.2 Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the angle between the loop and the field changes:



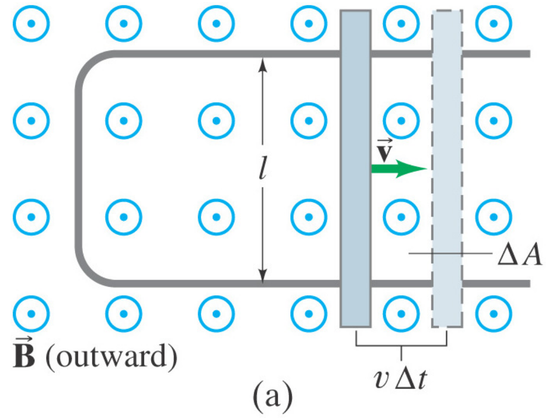
21.2 Faraday's Law of Induction; Lenz's Law

Problem Solving: Lenz's Law

1. Determine whether the magnetic flux is increasing, decreasing, or unchanged.
2. The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.
3. Use the right-hand rule to determine the direction of the current.
4. Remember that the external field and the field due to the induced current are different.

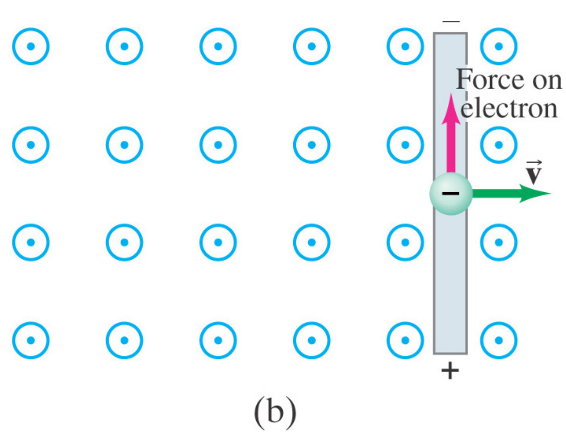
21.3 EMF Induced in a Moving Conductor

This image shows another way the magnetic flux can change:



21.3 EMF Induced in a Moving Conductor

The induced current is in a direction that tends to slow the moving bar – it will take an external force to keep it moving.

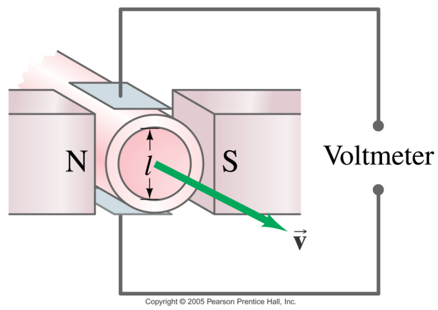


21.3 EMF Induced in a Moving Conductor

The induced emf has magnitude

$$\mathscr{E} = \frac{\Delta \Phi_B}{\Delta t} = \frac{B\,\Delta A}{\Delta t} = \frac{Blv\,\Delta t}{\Delta t} = Blv \qquad \text{(21-3)}$$

Measurement of blood velocity from induced emf:



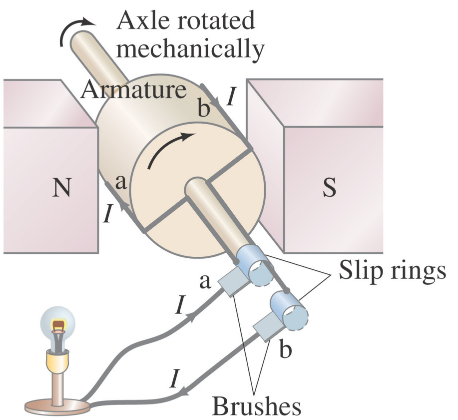
21.4 Changing Magnetic Flux Produces an Electric Field

A changing magnetic flux induces an electric field; this is a generalization of Faraday's law. The electric field will exist regardless of whether there are any conductors around.

21.5 Electric Generators

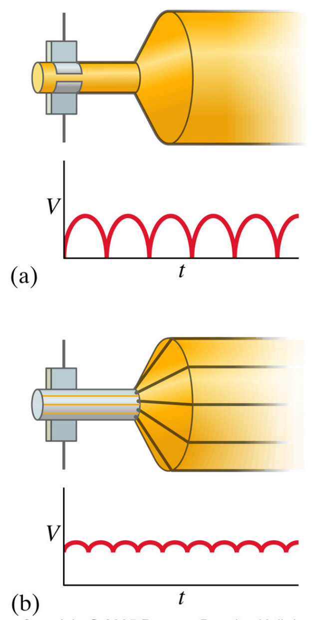
A generator is the opposite of a motor – it transforms mechanical energy into electrical energy. This is an ac generator:

The axle is rotated by an external force such as falling water or steam. The brushes are in constant electrical contact with the slip rings.



21.5 Electric Generators

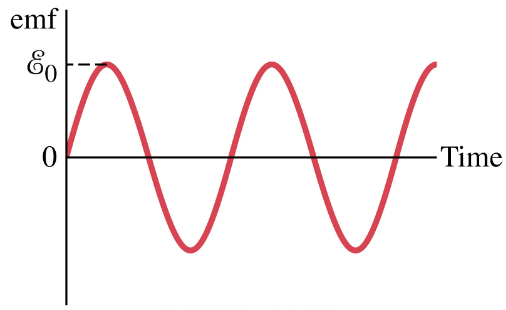
A dc generator is similar, except that it has a split-ring commutator instead of slip rings.



21.5 Electric Generators

A sinusoidal emf is induced in the rotating loop (N is the number of turns, and A the area of the loop):

$$\mathcal{E} = NB\omega A \sin \omega t \quad \text{(21-5)}$$



21.7 Transformers and Transmission of Power

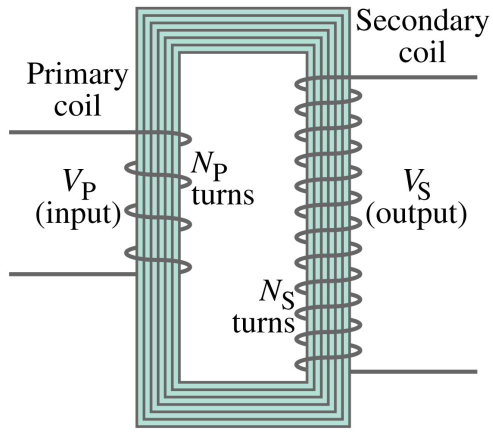
A transformer consists of two coils, either interwoven or linked by an iron core. A changing emf in one induces an emf in the other.

The ratio of the emfs is equal to the ratio of the number of turns in each coil:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad \text{(21-6)}$$

21.7 Transformers and Transmission of Power

This is a step-up transformer – the emf in the secondary coil is larger than the emf in the primary:



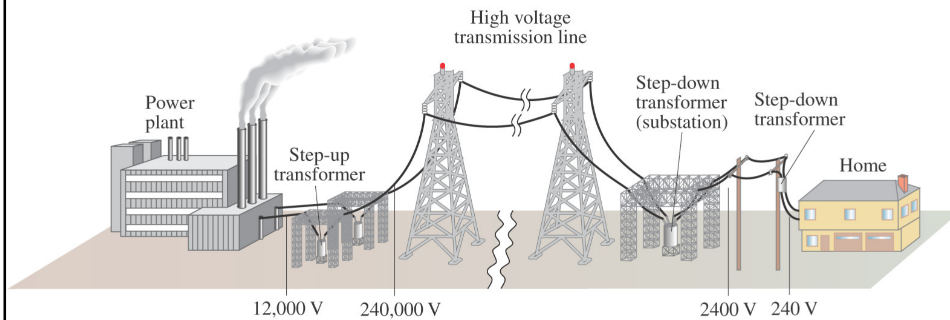
21.7 Transformers and Transmission of Power

Energy must be conserved; therefore, in the absence of losses, the ratio of the currents must be the inverse of the ratio of turns:

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \qquad \textbf{(21-6)}$$

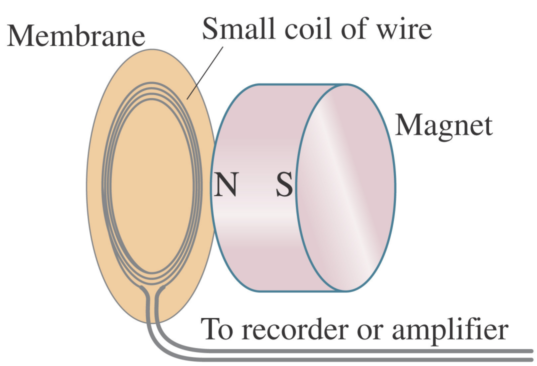
21.7 Transformers and Transmission of Power

Transformers work only if the current is changing; this is one reason why electricity is transmitted as ac.



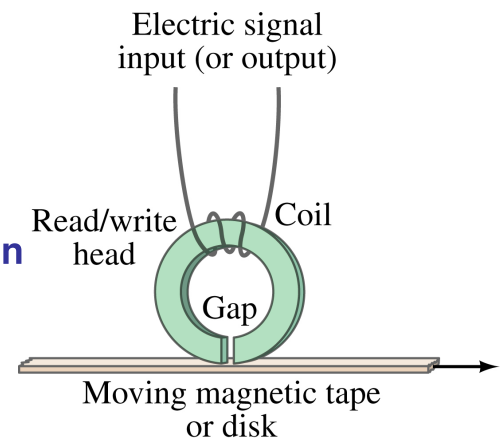
21.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph, GFCI

This microphone works by induction; the vibrating membrane induces an emf in the coil



21.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph, GFCI

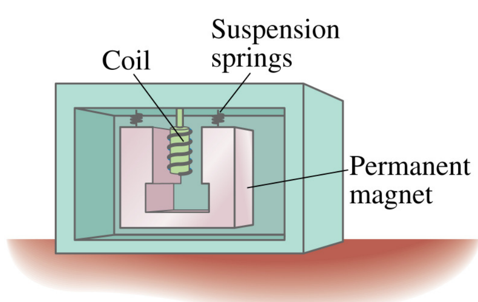
Differently magnetized areas on an audio tape or disk induce signals in the read/write heads.



(a)

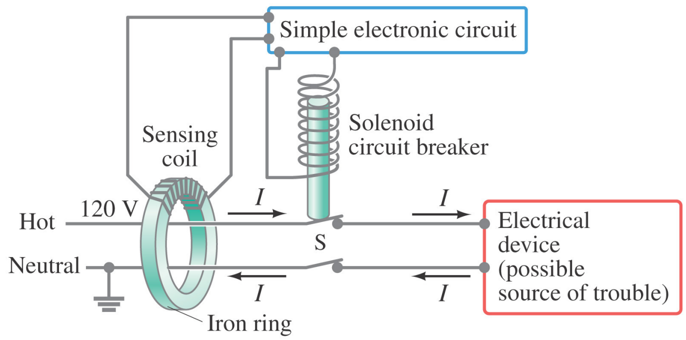
21.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph, GFCI

A seismograph has a fixed coil and a magnet hung on a spring (or vice versa), and records the current induced when the earth shakes.



21.8 Applications of Induction: Sound Systems, Computer Memory, Seismograph, GFCI

A ground fault circuit interrupter (GFCI) will interrupt the current to a circuit that has shorted out in a very short time, preventing electrocution.



21.9 Inductance

Mutual inductance: a changing current in one coil will induce a current in a second coil.

$$\mathscr{E}_2 = -M\frac{\Delta I_1}{\Delta t} \qquad \text{(21-8a)}$$

And vice versa; note that the constant M, known as the mutual inductance, is the same:

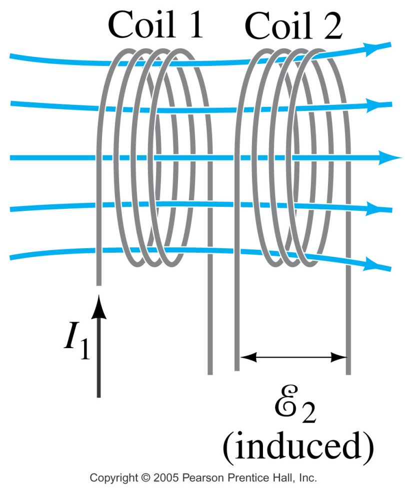
$$\mathscr{E}_1 = -M\frac{\Delta I_2}{\Delta t} \qquad \text{(21-8b)}$$

21.9 Inductance

Unit of inductance: the henry, H.

1 H = 1 V·s/A = 1 Ω·s.

A transformer is an example of mutual inductance.



21.9 Inductance

A changing current in a coil will also induce an emf in itself:

$$\mathscr{E} = -L\frac{\Delta I}{\Delta t} \qquad \text{(21-9)}$$

Here, L is called the self-inductance.

Summary of Chapter 21

• Magnetic flux:

$$\Phi_B = B_\perp A = BA\cos\theta$$

• Changing magnetic flux induces emf:

$$\mathscr{E} = -N\frac{\Delta\Phi_B}{\Delta t}$$

• Induced emf produces current that opposes original flux change

Summary of Chapter 21

• Changing magnetic field produces an electric field

• Electric generator changes mechanical energy to electrical energy; electric motor does the opposite

• Transformer uses induction to change voltage:

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

Summary of Chapter 21

- **Mutual inductance:**

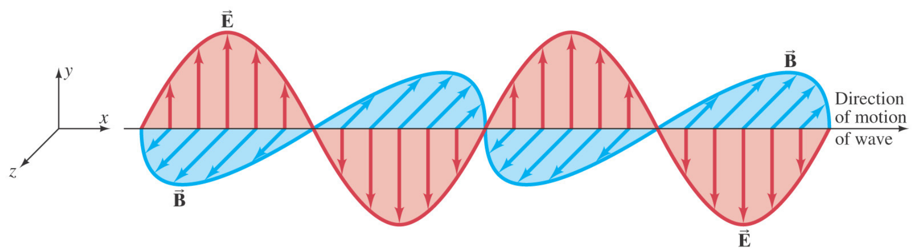
$$\mathscr{E}_2 = -M \frac{\Delta I_1}{\Delta t}$$

Homework

- Chp 21 Problems: # 1, 3, 5, 7, 9, 21, 31, 35, 39

Chapter 22

Electromagnetic Waves



Units of Chapter 22

• Changing Electric Fields Produce Magnetic Fields; Maxwell's Equations

• Production of Electromagnetic Waves

• Light as an Electromagnetic Wave and the Electromagnetic Spectrum

• Measuring the Speed of Light

• Energy in EM Waves

• Momentum Transfer and Radiation Pressure

• Radio and Television; Wireless Communication

22.1 Changing Electric Fields Produce Magnetic Fields; Maxwell's Equations

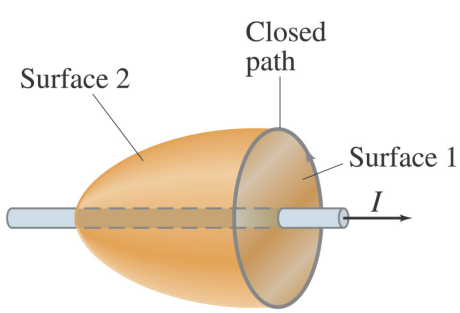
Maxwell's equations are the basic equations of electromagnetism. They involve calculus; here is a summary:

1. Gauss's law relates electric field to charge
2. A law stating there are no magnetic "charges"
3. A changing electric field produces a magnetic field
4. A magnetic field is produced by an electric current, and also by a changing electric field

22.1 Changing Electric Fields Produce Magnetic Fields; Maxwell's Equations

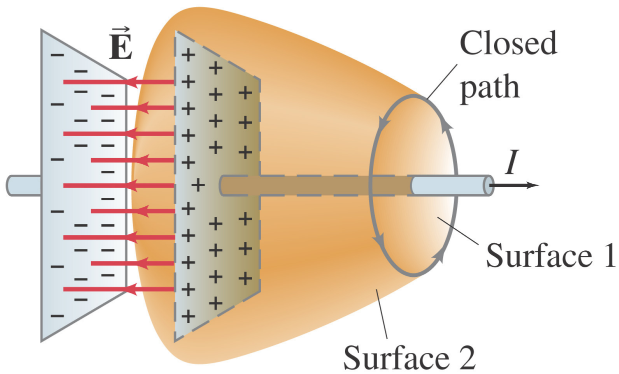
Only one part of this is new – that a changing electric field produces a magnetic field.

Ampère's law relates the magnetic field around a current to the current through a surface.



22.1 Changing Electric Fields Produce Magnetic Fields; Maxwell's Equations

In order for Ampère's law to hold, it can't matter which surface we choose. But look at a discharging capacitor; there is a current through surface 1 but none through surface 2:



22.1 Changing Electric Fields Produce Magnetic Fields; Maxwell's Equations

Therefore, Ampère's law is modified to include the creation of a magnetic field by a changing electric field – the field between the plates of the capacitor in this example.

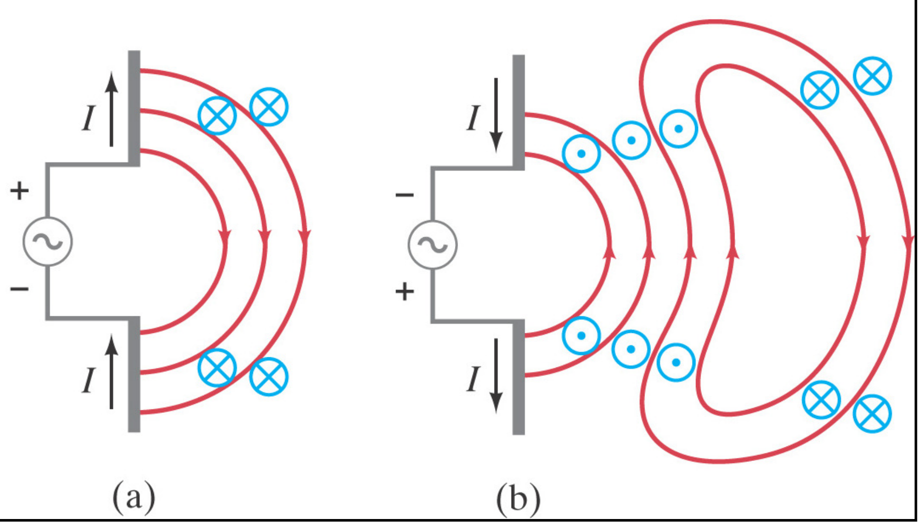
22.2 Production of Electromagnetic Waves

Since a changing electric field produces a magnetic field, and a changing magnetic field produces an electric field, once sinusoidal fields are created they can propagate on their own.

These propagating fields are called electromagnetic waves.

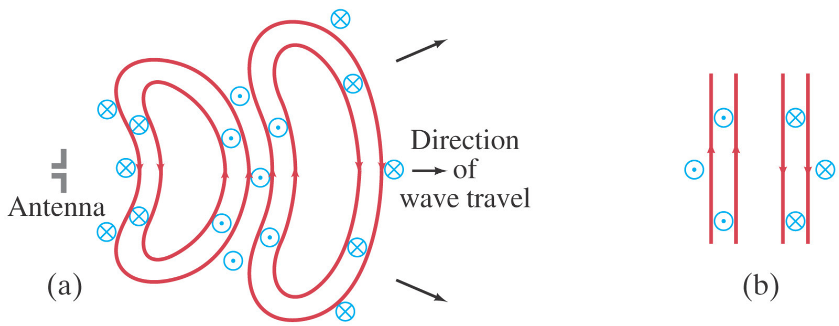
22.2 Production of Electromagnetic Waves

Oscillating charges will produce electromagnetic waves:



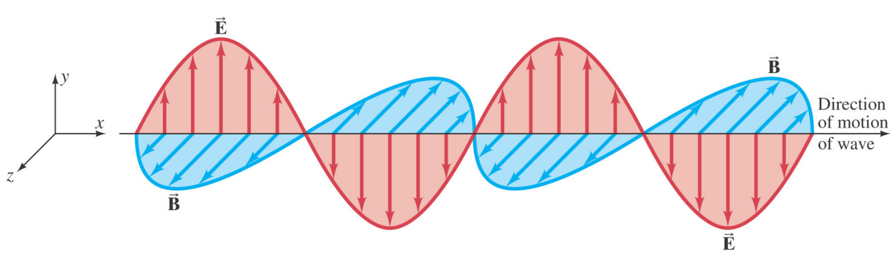
22.2 Production of Electromagnetic Waves

Far from the source, the waves are plane waves:



22.2 Production of Electromagnetic Waves

The electric and magnetic waves are perpendicular to each other, and to the direction of propagation.



22.2 Production of Electromagnetic Waves

When Maxwell calculated the speed of propagation of electromagnetic waves, he found:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = \frac{1}{\sqrt{(8.85 \times 10^{-12}\, \mathrm{C^2/N \cdot m^2})(4\pi \times 10^{-7}\, \mathrm{N \cdot s^2/C^2})}}$$
$$= 3.00 \times 10^8\, \mathrm{m/s}$$

This is the speed of light in a vacuum.

22.3 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

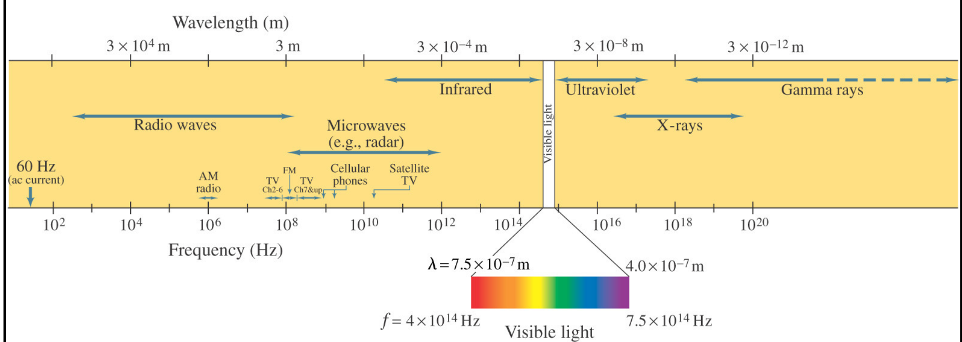
Light was known to be a wave; after producing electromagnetic waves of other frequencies, it was known to be an electromagnetic wave as well.

The frequency of an electromagnetic wave is related to its wavelength:

$$c = \lambda f \qquad \text{(22-4)}$$

22.3 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

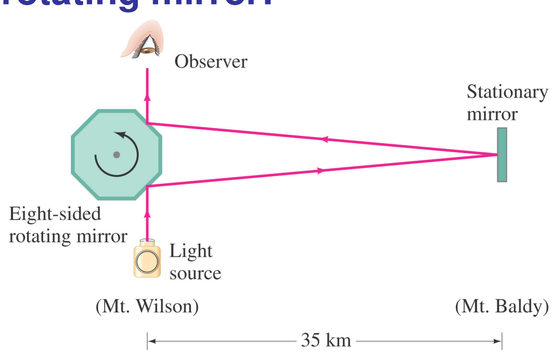
Electromagnetic waves can have any wavelength; we have given different names to different parts of the wavelength spectrum.



22.4 Measuring the Speed of Light

The speed of light was known to be very large, although careful studies of the orbits of Jupiter's moons showed that it is finite.

One important measurement, by Michelson, used a rotating mirror:



22.4 Measuring the Speed of Light

Over the years, measurements have become more and more precise; now the speed of light is defined to be:

$$c = 2.99792458 \times 10^8 \text{ m/s}$$

This is then used to define the meter.

22.5 Energy in EM Waves

Energy is stored in both electric and magnetic fields, giving the total energy density of an electromagnetic wave:

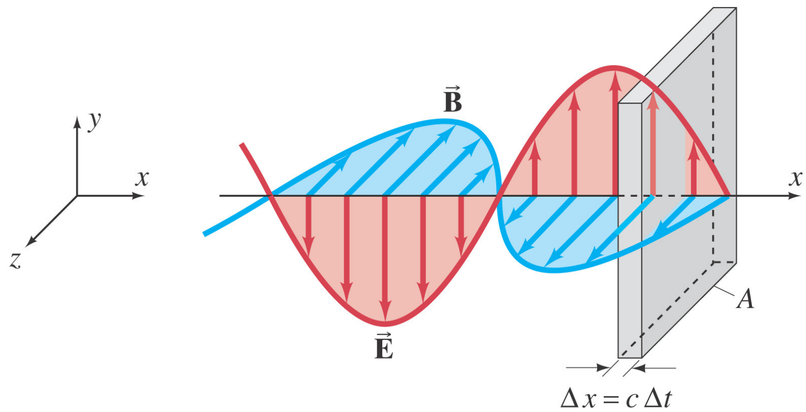
$$u = u_E + u_B = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{B^2}{\mu_0} \qquad \text{(22-5)}$$

Each field contributes half the total energy density.

$$u = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2}\frac{\epsilon_0 \mu_0 E^2}{\mu_0} = \epsilon_0 E^2 \qquad \text{(22-6a)}$$

22.5 Energy in EM Waves

This energy is transported by the wave.



22.5 Energy in EM Waves

The energy transported through a unit area per unit time is called the intensity:

$$I = \frac{\Delta U}{A\,\Delta t} = \frac{(\epsilon_0 E^2)(Ac\,\Delta t)}{A\,\Delta t} = \epsilon_0 c E^2 \qquad \text{(22-7)}$$

Its average value is given by:

$$\overline{I} = \frac{E_{\text{rms}} B_{\text{rms}}}{\mu_0}$$

22.6 Momentum Transfer and Radiation Pressure

In addition to carrying energy, electromagnetic waves also carry momentum. This means that a force will be exerted by the wave.

The radiation pressure is related to the average intensity. It is a minimum if the wave is fully absorbed:

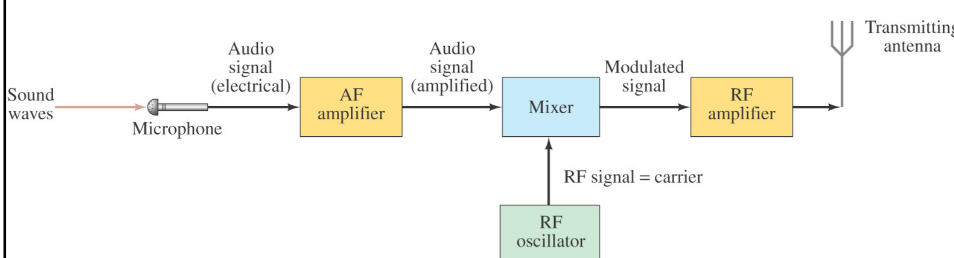
$$P = \frac{\overline{I}}{c}$$

And a maximum if it is fully reflected:

$$P = \frac{2\overline{I}}{c}$$

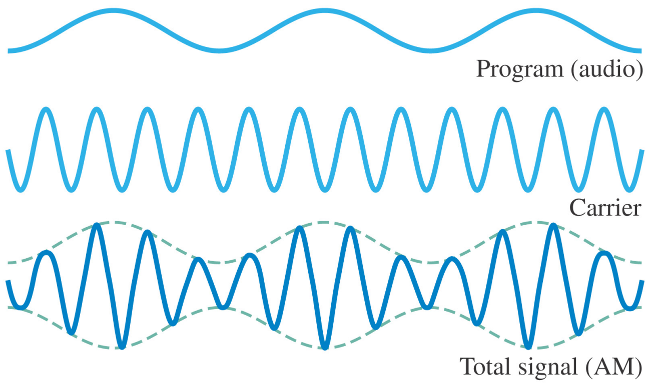
22.7 Radio and Television; Wireless Communication

This figure illustrates the process by which a radio station transmits information. The audio signal is combined with a carrier wave:



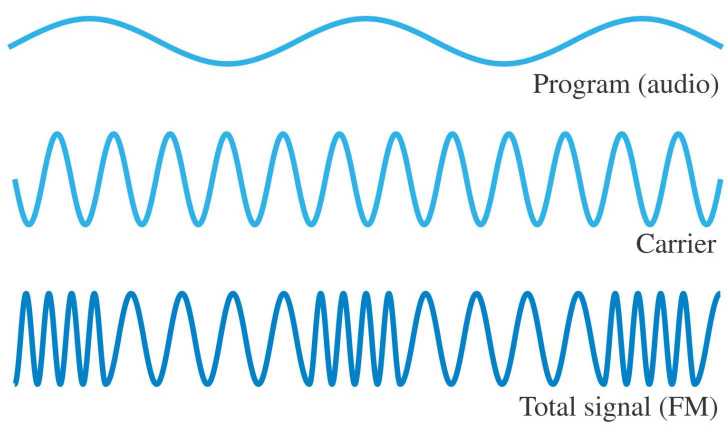
22.7 Radio and Television; Wireless Communication

The mixing of signal and carrier can be done two ways. First, by using the signal to modify the amplitude of the carrier (AM):



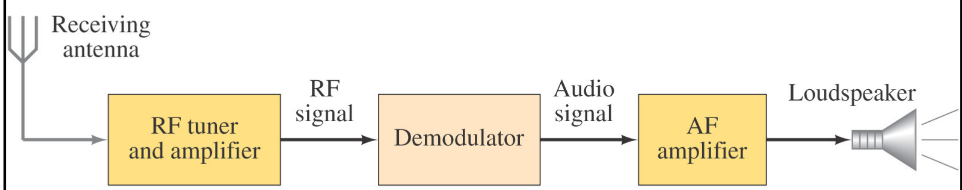
22.7 Radio and Television; Wireless Communication

Second, by using the signal to modify the frequency of the carrier (FM):



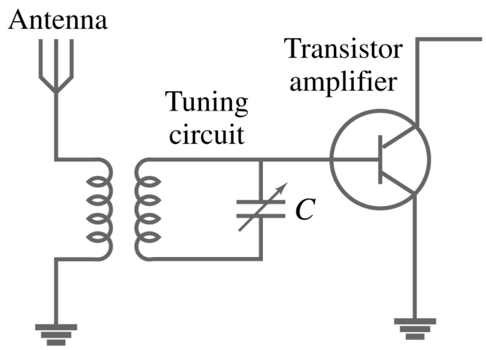
22.7 Radio and Television; Wireless Communication

At the receiving end, the wave is received, demodulated, amplified, and sent to a loudspeaker:



22.7 Radio and Television; Wireless Communication

The receiving antenna is bathed in waves of many frequencies; a tuner is used to select the desired one:



Summary of Chapter 22

• Maxwell's equations are the basic equations of electromagnetism

• Electromagnetic waves are produced by accelerating charges; the propagation speed is given by:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

• The fields are perpendicular to each other and to the direction of propagation.

Summary of Chapter 22

• The wavelength and frequency of EM waves are related:

$$c = \lambda f$$

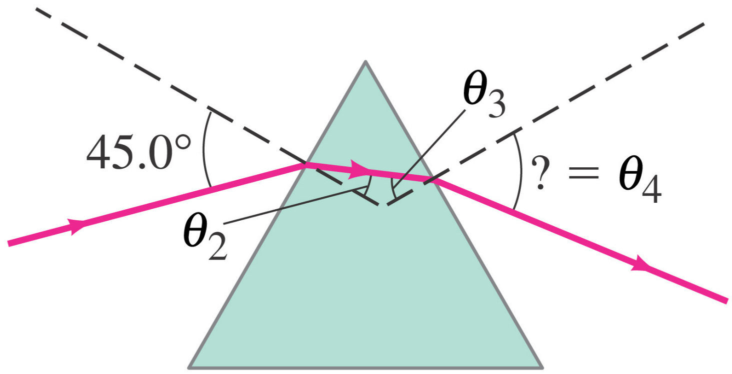
• The electromagnetic spectrum includes all wavelengths, from radio waves through visible light to gamma rays.

Homework

- Chp 22 Problems: # 3, 9, 21, 25, 33

Light: Geometric Optics

(Chapter 23)



Units of Chapter 23

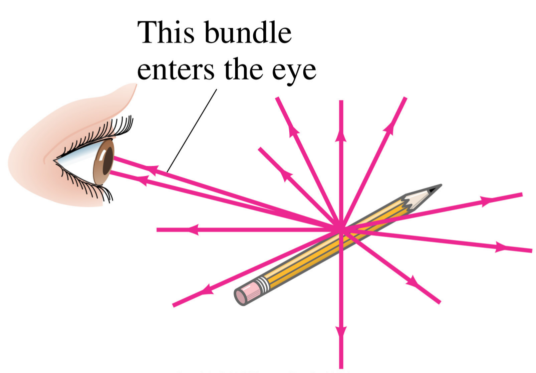
- The Ray Model of Light
- Reflection; Image Formed by a Plane Mirror
- Formation of Images by Spherical Mirrors
- Index of Refraction
- Refraction: Snell's Law

Units of Chapter 23

- Total Internal Reflection; Fiber Optics
- Thin Lenses; Ray Tracing
- The Thin Lens Equation; Magnification
- Combinations of Lenses
- Lensmaker's Equation

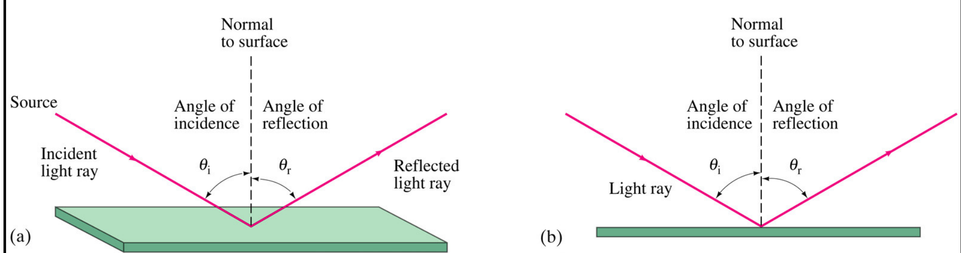
23.1 The Ray Model of Light

Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.



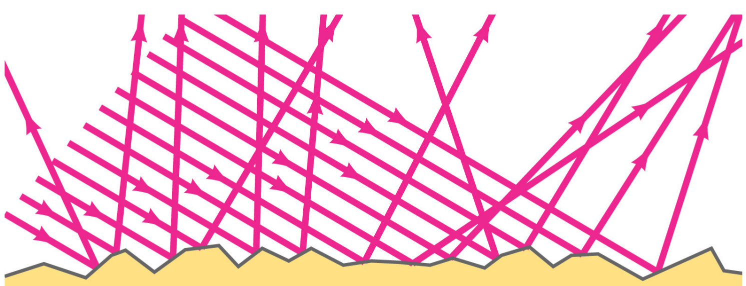
23.2 Reflection; Image Formation by a Plane Mirror

Law of reflection: the angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.



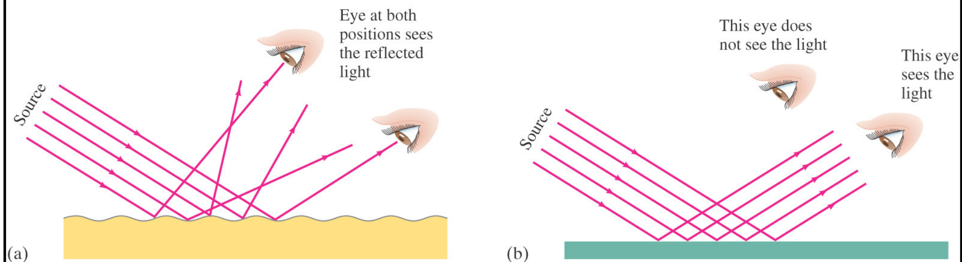
23.2 Reflection; Image Formation by a Plane Mirror

When light reflects from a rough surface, the law of reflection still holds, but the angle of incidence varies. This is called diffuse reflection.



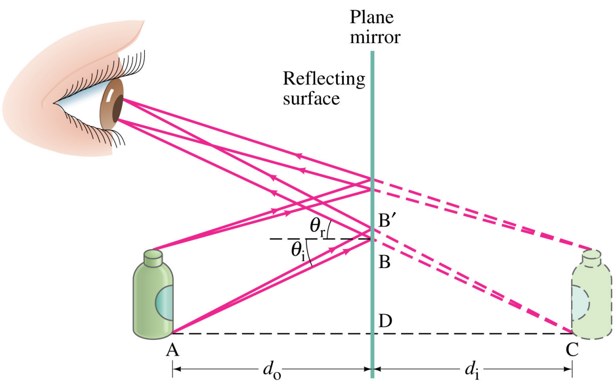
23.2 Reflection; Image Formation by a Plane Mirror

With diffuse reflection, your eye sees reflected light at all angles. With specular reflection (from a mirror), your eye must be in the correct position.



23.2 Reflection; Image Formation by a Plane Mirror

What you see when you look into a plane (flat) mirror is an image, which appears to be behind the mirror.

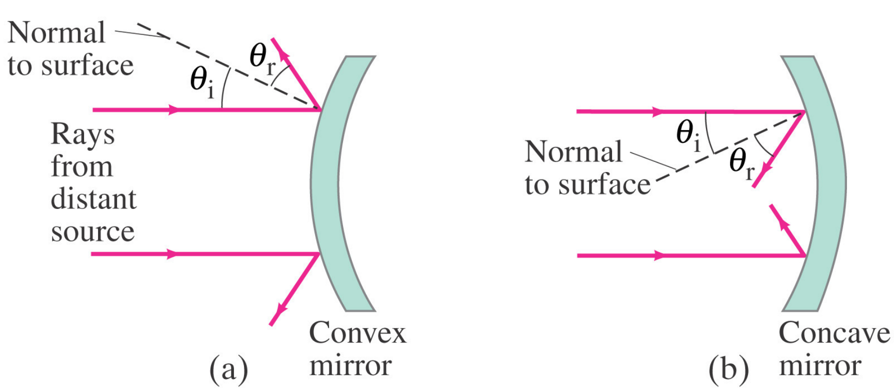


23.2 Reflection; Image Formation by a Plane Mirror

This is called a virtual image, as the light does not go through it. The distance of the image from the mirror is equal to the distance of the object from the mirror.

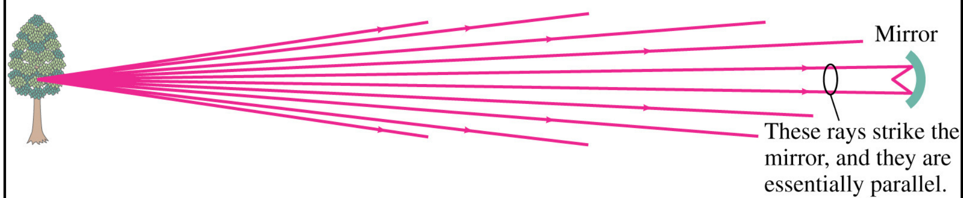
23.3 Formation of Images by Spherical Mirrors

Spherical mirrors are shaped like sections of a sphere, and may be reflective on either the inside (concave) or outside (convex).



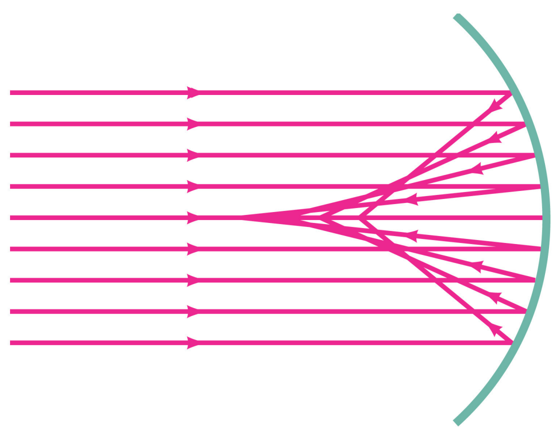
23.3 Formation of Images by Spherical Mirrors

Rays coming from a faraway object are effectively parallel.



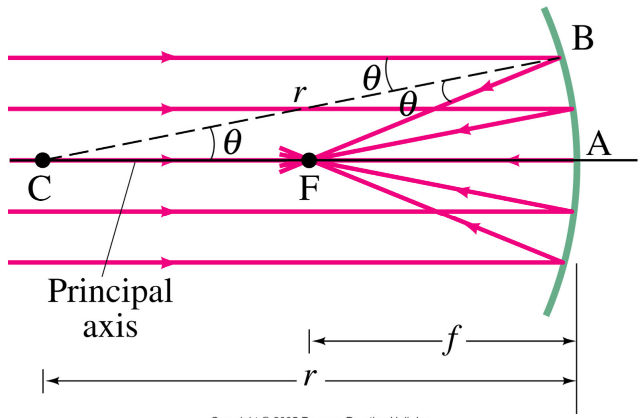
23.3 Formation of Images by Spherical Mirrors

Parallel rays striking a spherical mirror do not all converge at exactly the same place if the curvature of the mirror is large; this is called spherical aberration.



23.3 Formation of Images by Spherical Mirrors

If the curvature is small, the focus is much more precise; the focal point is where the rays converge.



23.3 Formation of Images by Spherical Mirrors

Using geometry, we find that the focal length is half the radius of curvature:

$$f = \frac{r}{2} \qquad \text{(23-1)}$$

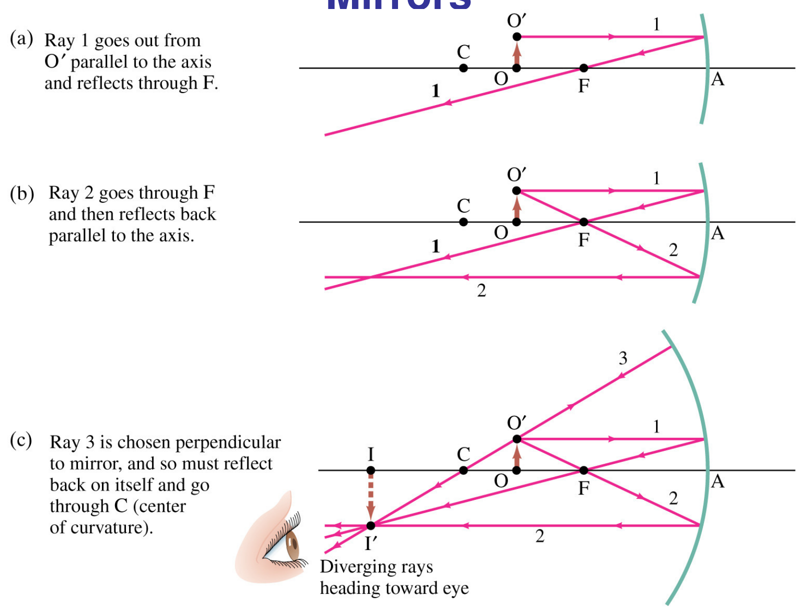
Spherical aberration can be avoided by using a parabolic reflector; these are more difficult and expensive to make, and so are used only when necessary, such as in research telescopes.

23.3 Formation of Images by Spherical Mirrors

We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:

1. A ray parallel to the axis; after reflection it passes through the focal point
2. A ray through the focal point; after reflection it is parallel to the axis
3. A ray perpendicular to the mirror; it reflects back on itself

23.3 Formation of Images by Spherical Mirrors



23.3 Formation of Images by Spherical Mirrors

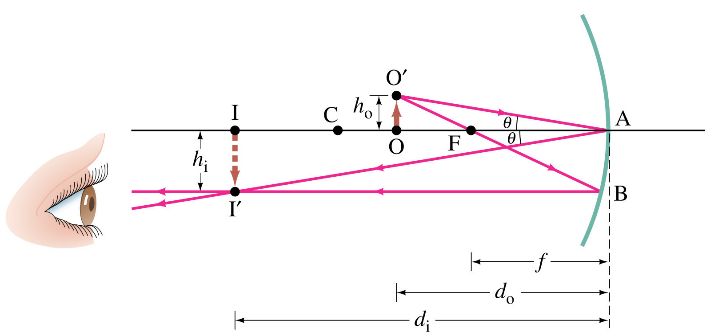
The intersection of these three rays gives the position of the image of that point on the object. To get a full image, we can do the same with other points (two points suffice for many purposes).

23.3 Formation of Images by Spherical Mirrors

Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

(23-2)



23.3 Formation of Images by Spherical Mirrors

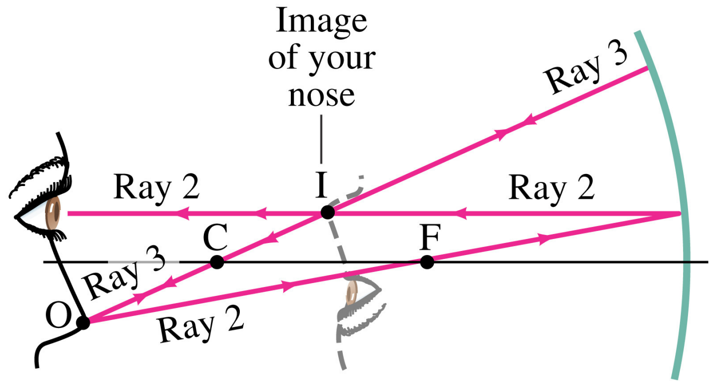
We can also find the magnification (ratio of image height to object height).

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \qquad \text{(23-3)}$$

The negative sign indicates that the image is inverted. This object is between the center of curvature and the focal point, and its image is larger, inverted, and real.

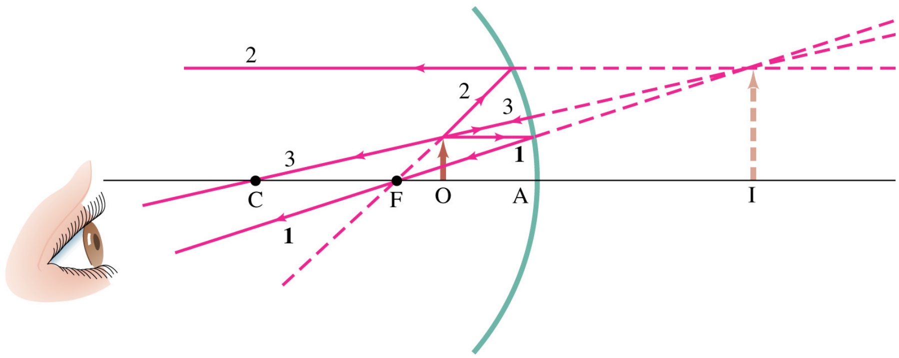
23.3 Formation of Images by Spherical Mirrors

If an object is outside the center of curvature of a concave mirror, its image will be inverted, smaller, and real.



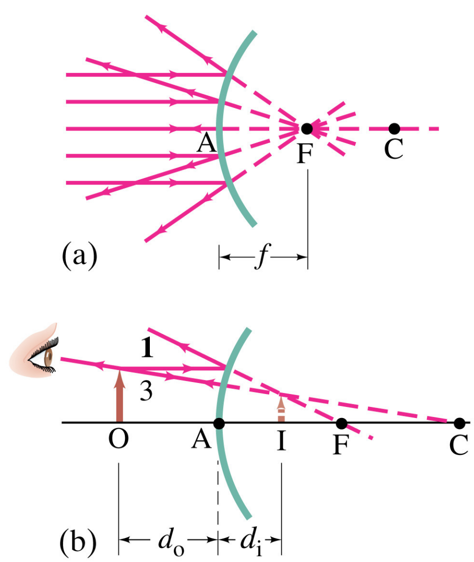
23.3 Formation of Images by Spherical Mirrors

If an object is inside the focal point, its image will be upright, larger, and virtual.



23.3 Formation of Images by Spherical Mirrors

For a convex mirror, the image is always virtual, upright, and smaller.



23.3 Formation of Images by Spherical Mirrors

Problem Solving: Spherical Mirrors

1. Draw a ray diagram; the image is where the rays intersect.
2. Apply the mirror and magnification equations.
3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.
4. Check that your solution agrees with the ray diagram.

23.4 Index of Refraction

In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

$$n = \frac{c}{v} \qquad (23\text{-}4)$$

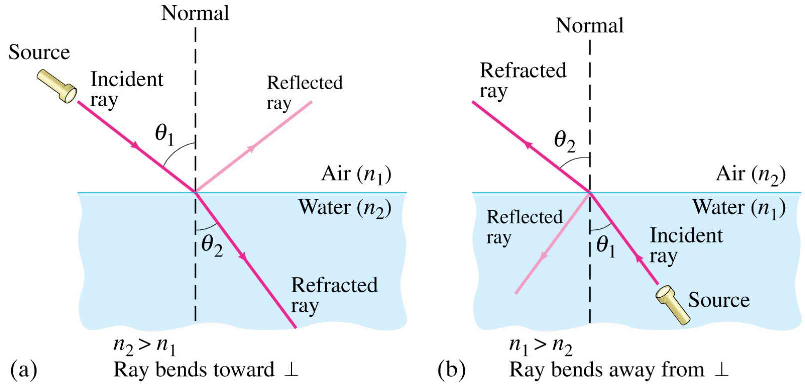
TABLE 23–1
Indices of Refraction[†]

Medium	$n = c/v$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

[†] λ = 589 nm.

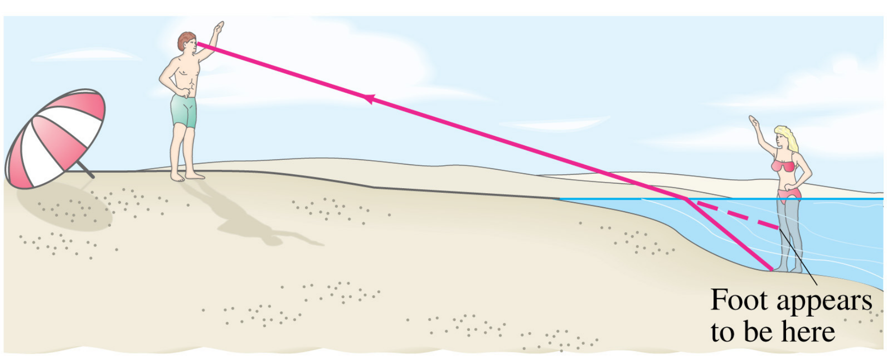
23.5 Refraction: Snell's Law

Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.



23.5 Refraction: Snell's Law

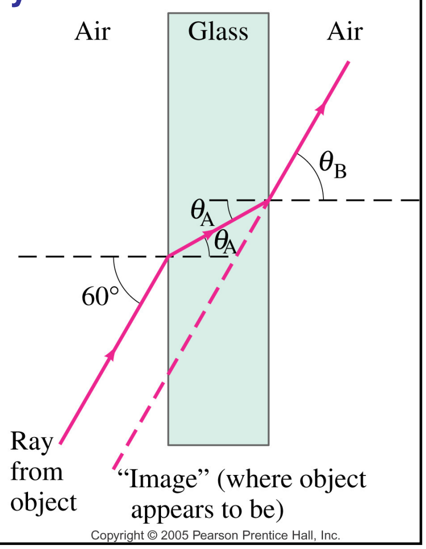
Refraction is what makes objects half-submerged in water look odd.



23.5 Refraction: Snell's Law

The angle of refraction depends on the indices of refraction, and is given by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{(23-5)}$$



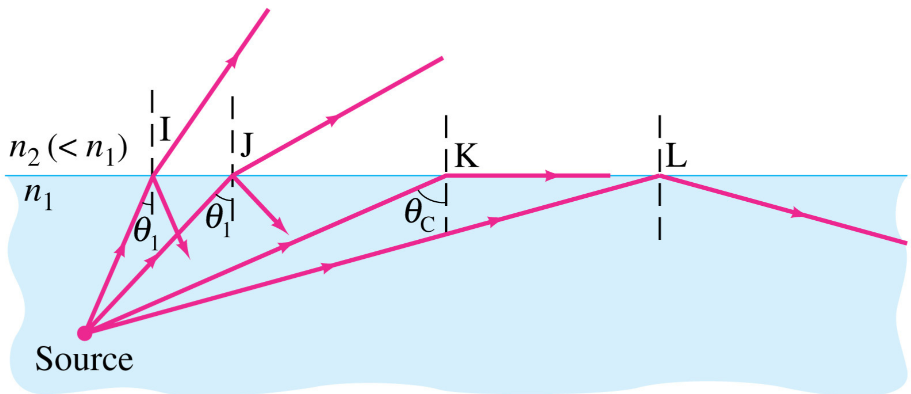
23.6 Total Internal Reflection; Fiber Optics

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; this is called the critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90^\circ = \frac{n_2}{n_1} \qquad \text{(23-5)}$$

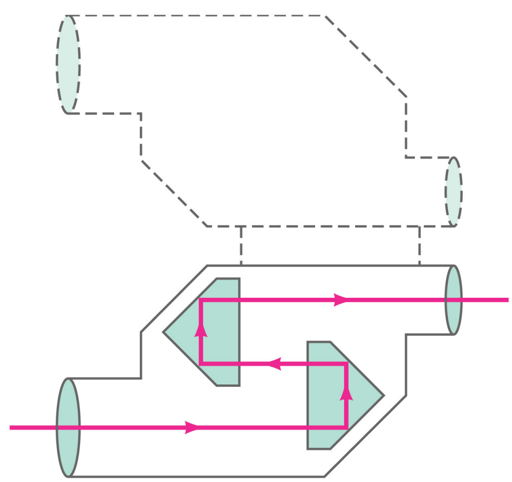
23.6 Total Internal Reflection; Fiber Optics

If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.



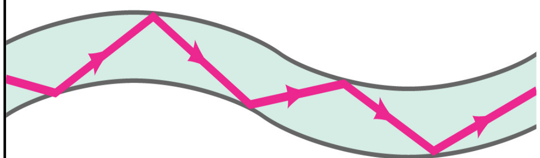
23.6 Total Internal Reflection; Fiber Optics

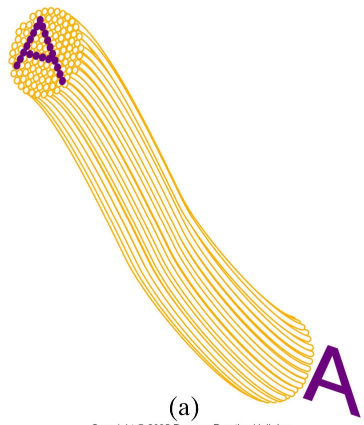
Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.



23.6 Total Internal Reflection; Fiber Optics

Total internal reflection is also the principle behind fiber optics. Light will be transmitted along the fiber even if it is not straight. An image can be formed using multiple small fibers.





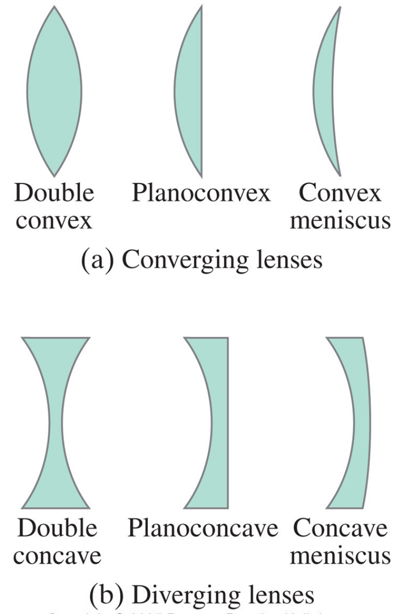
(a)

Total Internal Reflection

- Light - Laser waterfall - total int reflect.asf

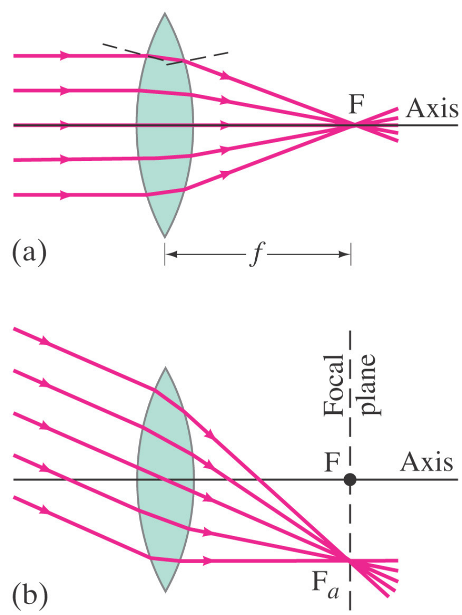
23.7 Thin Lenses; Ray Tracing

Thin lenses are those whose thickness is small compared to their radius of curvature. They may be either converging (a) or diverging (b).



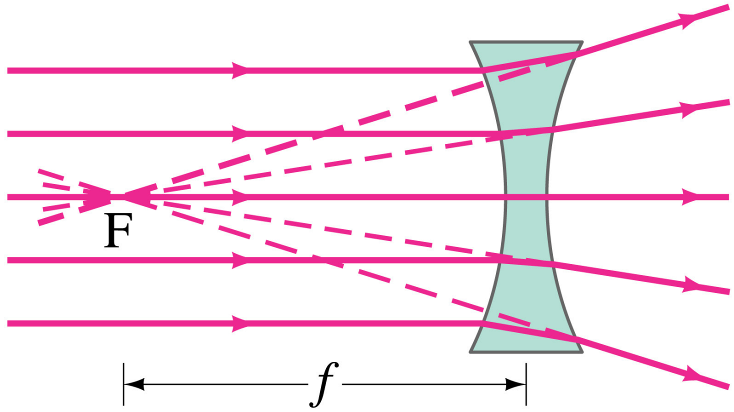
23.7 Thin Lenses; Ray Tracing

Parallel rays are brought to a focus by a converging lens (one that is thicker in the center than it is at the edge).



23.7 Thin Lenses; Ray Tracing

A diverging lens (thicker at the edge than in the center) make parallel light diverge; the focal point is that point where the diverging rays would converge if projected back.



23.7 Thin Lenses; Ray Tracing

The power of a lens is the inverse of its focal length.

$$P = \frac{1}{f} \qquad \text{(23-7)}$$

Lens power is measured in diopters, D.

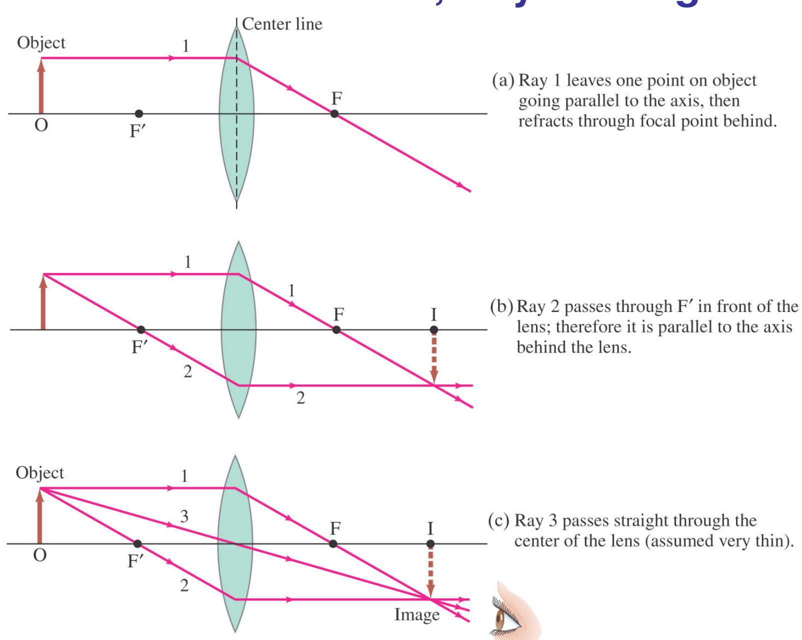
1 D = 1 m^{-1}

23.7 Thin Lenses; Ray Tracing

Ray tracing for thin lenses is similar to that for mirrors. We have three key rays:

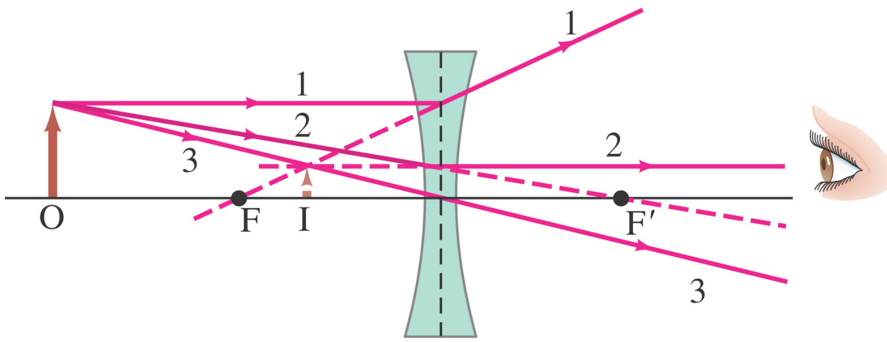
1. This ray comes in parallel to the axis and exits through the focal point.
2. This ray comes in through the focal point and exits parallel to the axis.
3. This ray goes through the center of the lens and is undeflected.

23.7 Thin Lenses; Ray Tracing



23.7 Thin Lenses; Ray Tracing

For a diverging lens, we can use the same three rays; the image is upright and virtual.



23.8 The Thin Lens Equation; Magnification

The thin lens equation is the same as the mirror equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \qquad \text{(23-8)}$$

23.8 The Thin Lens Equation; Magnification

The sign conventions are slightly different:

1. **The focal length is positive for converging lenses and negative for diverging.**
2. **The object distance is positive when the object is on the same side as the light entering the lens (not an issue except in compound systems); otherwise it is negative.**
3. **The image distance is positive if the image is on the opposite side from the light entering the lens; otherwise it is negative.**
4. **The height of the image is positive if the image is upright and negative otherwise.**

23.8 The Thin Lens Equation; Magnification

The magnification formula is also the same as that for a mirror:

$$m = \frac{h_{\mathrm{i}}}{h_{\mathrm{o}}} = -\frac{d_{\mathrm{i}}}{d_{\mathrm{o}}} \qquad (23\text{-}9)$$

The power of a lens is positive if it is converging and negative if it is diverging.

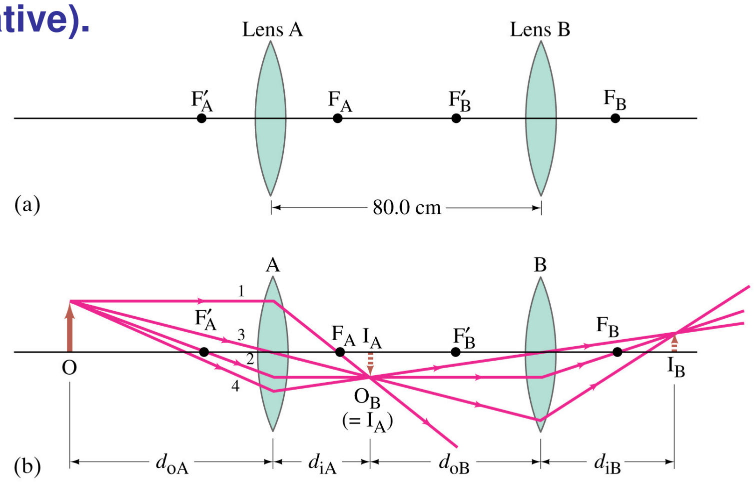
23.8 The Thin Lens Equation; Magnification

Problem Solving: Thin Lenses

1. Draw a ray diagram. The image is located where the key rays intersect.
2. Solve for unknowns.
3. Follow the sign conventions.
4. Check that your answers are consistent with the ray diagram.

23.9 Combinations of Lenses

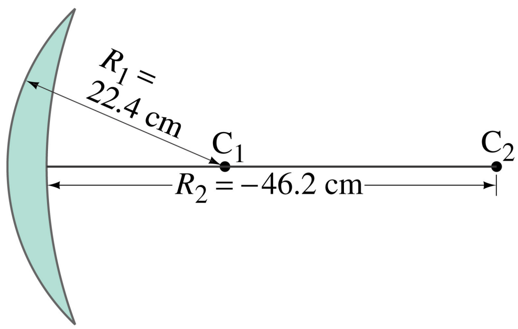
In lens combinations, the image formed by the first lens becomes the object for the second lens (this is where object distances may be negative).



23.10 Lensmaker's Equation

This useful equation relates the radii of curvature of the two lens surfaces, and the index of refraction, to the focal length.

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad \text{(23-10)}$$



Summary of Chapter 23

- Light paths are called rays
- Index of refraction: $n = \frac{c}{v}$
- Angle of reflection equals angle of incidence
- Plane mirror: image is virtual, upright, and the same size as the object
- Spherical mirror can be concave or convex
- Focal length of the mirror: $f = \frac{r}{2}$

Summary of Chapter 23

• Mirror equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

• Magnification:

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

• Real image: light passes through it

• Virtual image: light does not pass through

Summary of Chapter 23

• Law of refraction (Snell's law):

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

• Total internal reflection occurs when angle of incidence is greater than critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}$$

• A converging lens focuses incoming parallel rays to a point

Summary of Chapter 23

- A diverging lens spreads incoming rays so that they appear to come from a point
- Power of a lens: $P = 1/f$
- Thin lens equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

- Magnification:

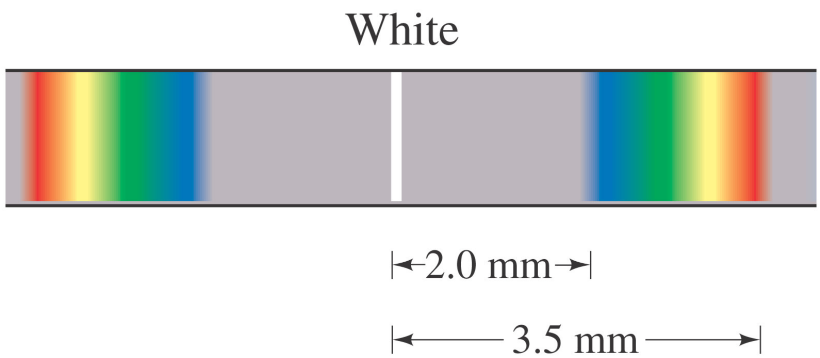
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Homework

- Chp 23 Problems: # 5, 15, 17, 29, 35, 43, 55,

Chapter 24

The Wave Nature of Light



Units of Chapter 24

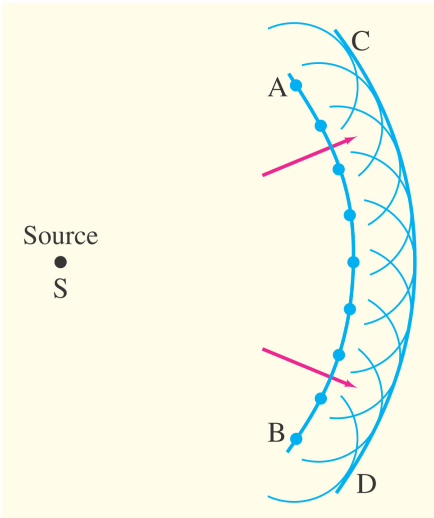
- Waves Versus Particles; Huygens' Principle and Diffraction
- Huygens' Principle and the Law of Refraction
- Interference – Young's Double Slit Experiment
- The Visible Spectrum and Dispersion
- Diffraction by a Single Slit or Disk
- Diffraction Grating
- The Spectrometer and Spectroscopy

Units of Chapter 24

- Interference by Thin Films
- Michelson Interferometer
- Polarization
- Liquid Crystal Displays
- Scattering of Light by the Atmosphere

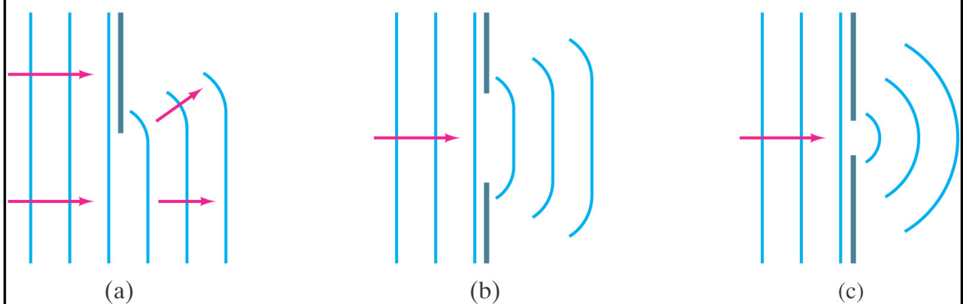
24.1 Waves Versus Particles; Huygens' Principle and Diffraction

Huygens' principle: Every point on a wave front acts as a point source; the wavefront as it develops is tangent to their envelope

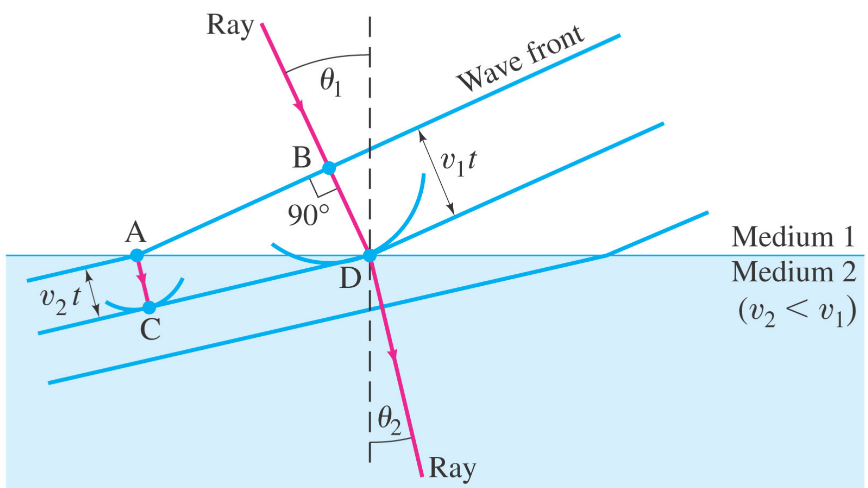


24.1 Waves Versus Particles; Huygens' Principle and Diffraction

Huygens' principle is consistent with diffraction:



24.2 Huygens' Principle and the Law of Refraction



24.2 Huygens' Principle and the Law of Refraction

Huygens' principle can also explain the law of refraction.

As the wavelets propagate from each point, they propagate more slowly in the medium of higher index of refraction.

This leads to a bend in the wavefront and therefore in the ray.

24.2 Huygens' Principle and the Law of Refraction

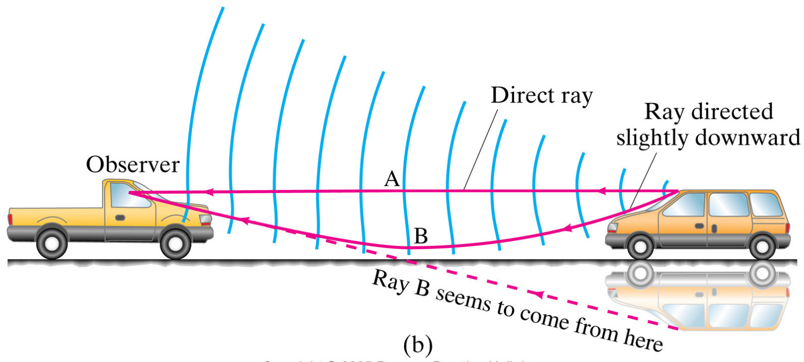
The frequency of the light does not change, but the wavelength does as it travels into a new medium.

$$\frac{\lambda_2}{\lambda_1} = \frac{v_2 t}{v_1 t} = \frac{v_2}{v_1} = \frac{n_1}{n_2}$$

$$\lambda_n = \frac{\lambda}{n} \qquad \text{(24-1)}$$

24.2 Huygens' Principle and the Law of Refraction

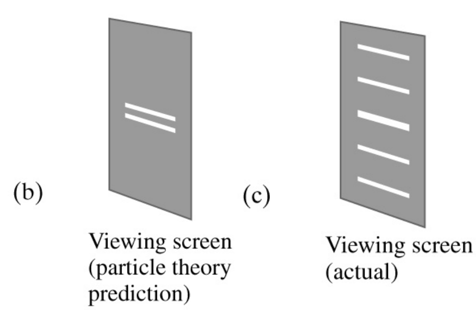
Highway mirages are due to a gradually changing index of refraction in heated air.



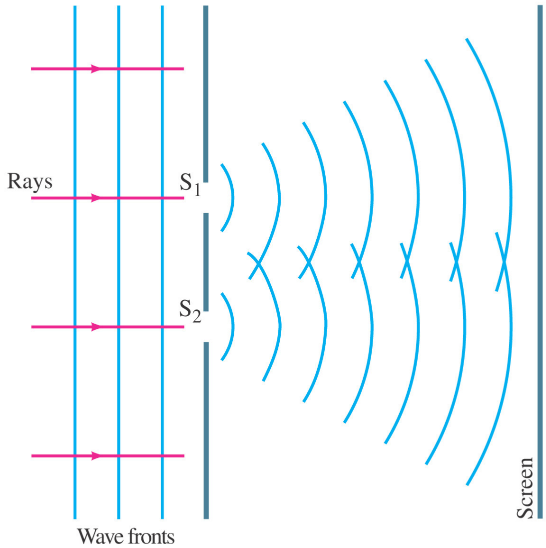
24.3 Interference – Young's Double-Slit Experiment

If light is a wave, interference effects will be seen, where one part of wavefront can interact with another part.

One way to study this is to do a double-slit experiment:



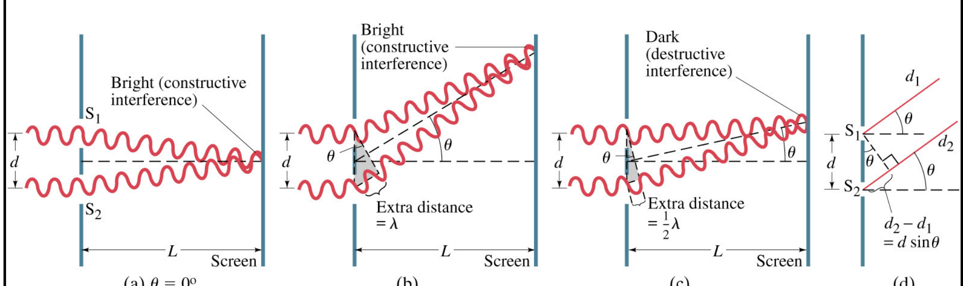
24.3 Interference – Young's Double-Slit Experiment



If light is a wave, there should be an interference pattern.

24.3 Interference – Young's Double-Slit Experiment

The interference occurs because each point on the screen is not the same distance from both slits. Depending on the path length difference, the wave can interfere constructively (bright spot) or destructively (dark spot).



24.3 Interference – Young's Double-Slit Experiment

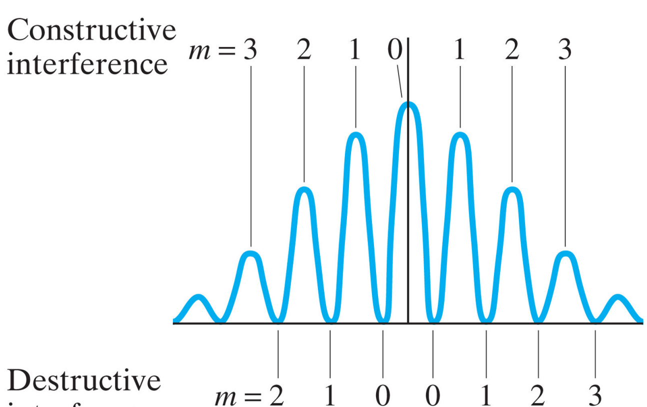
We can use geometry to find the conditions for constructive and destructive interference:

$$d \sin\theta = m\lambda, \qquad m = 0, 1, 2, \cdots. \qquad \text{(24-2a)} \quad \left[\begin{array}{c}\text{constructive}\\ \text{interference}\\ \text{(bright)}\end{array}\right]$$

$$d \sin\theta = \left(m + \tfrac{1}{2}\right)\lambda, \qquad m = 0, 1, 2, \cdots. \qquad \text{(24-2b)} \quad \left[\begin{array}{c}\text{destructive}\\ \text{interference}\\ \text{(dark)}\end{array}\right]$$

24.3 Interference – Young's Double-Slit Experiment

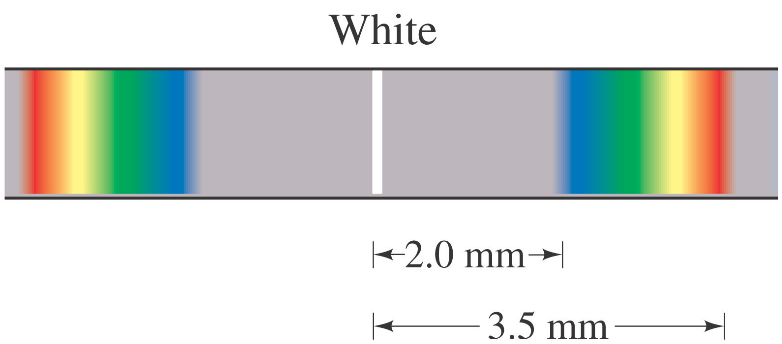
Between the maxima and the minima, the interference varies smoothly.



(b)

24.3 Interference – Young's Double-Slit Experiment

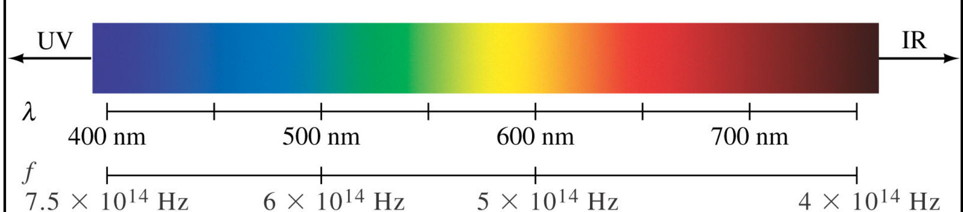
Since the position of the maxima (except the central one) depends on wavelength, the first- and higher-order fringes contain a spectrum of colors.



24.4 The Visible Spectrum and Dispersion

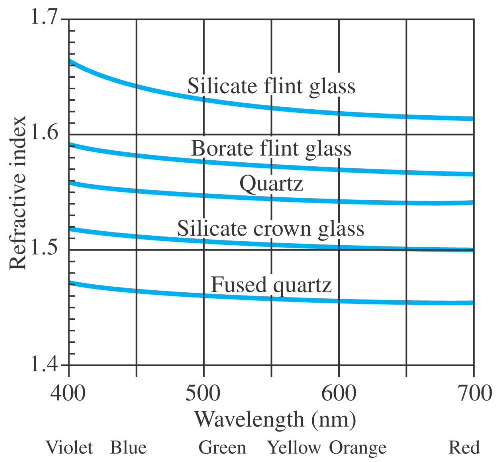
Wavelengths of visible light: 400 nm to 750 nm

Shorter wavelengths are ultraviolet; longer are infrared



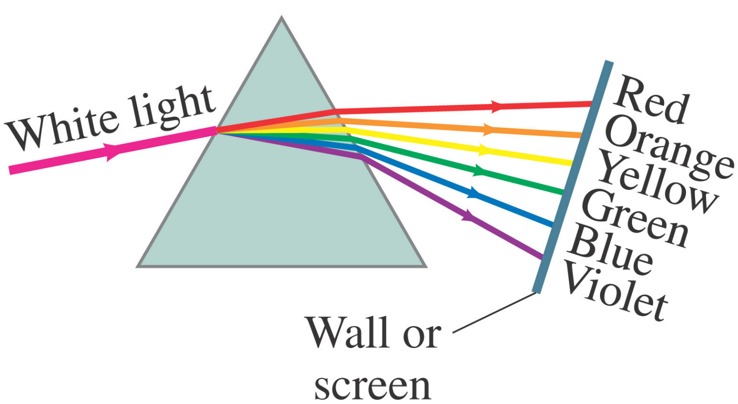
24.4 The Visible Spectrum and Dispersion

The index of refraction of a material varies somewhat with the wavelength of the light.



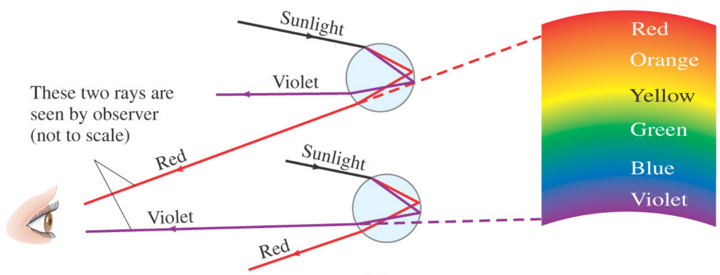
24.4 The Visible Spectrum and Dispersion

This variation in refractive index is why a prism will split visible light into a rainbow of colors.



24.4 The Visible Spectrum and Dispersion

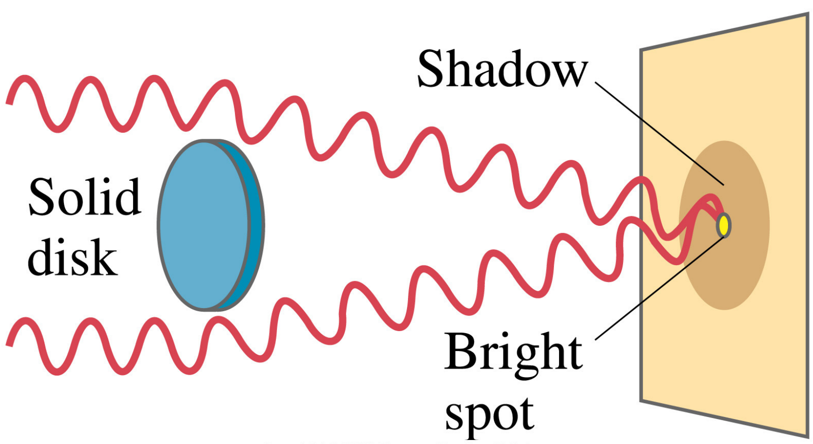
Actual rainbows are created by dispersion in tiny drops of water.



(a)

24.5 Diffraction by a Single Slit or Disk

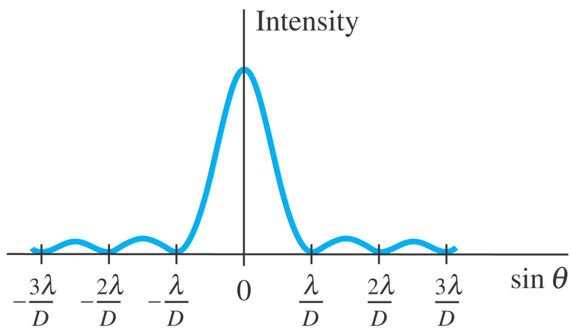
Light will also diffract around a single slit or obstacle.



24.5 Diffraction by a Single Slit or Disk

The resulting pattern of light and dark stripes is called a diffraction pattern.

This pattern arises because different points along a slit create wavelets that interfere with each other just as a double slit would.



24.5 Diffraction by a Single Slit or Disk

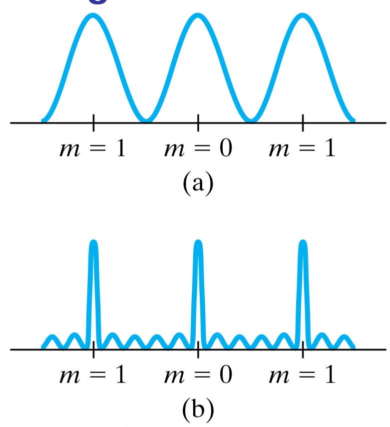
The minima of the single-slit diffraction pattern occur when

$$D \sin\theta = m\lambda, \qquad m = 1, 2, 3, \cdots \quad \text{(24-3b)}$$

24.6 Diffraction Grating

A diffraction grating consists of a large number of equally spaced narrow slits or lines. A transmission grating has slits, while a reflection grating has lines that reflect light.

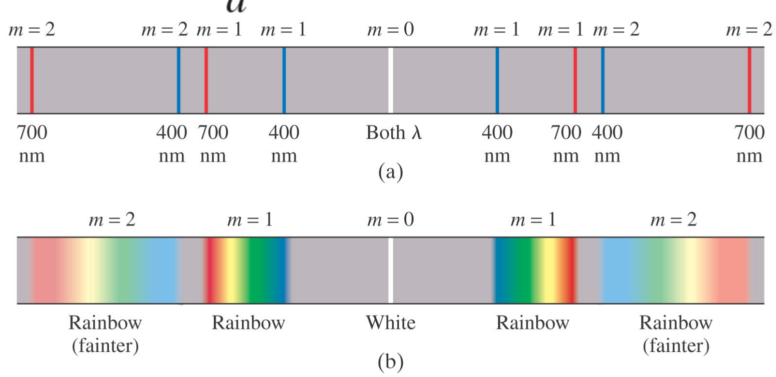
The more lines or slits there are, the narrower the peaks.



24.6 Diffraction Grating

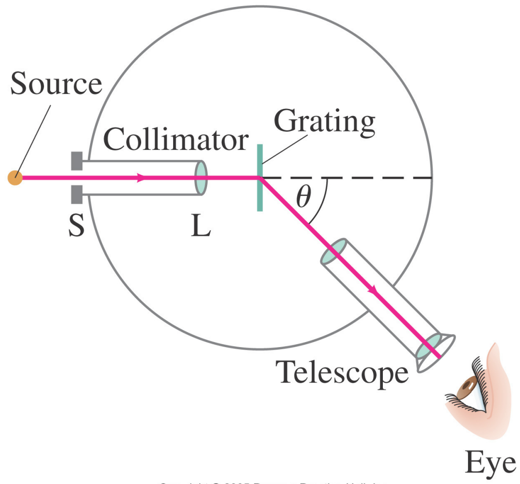
The maxima of the diffraction pattern are defined by

$$\sin\theta = \frac{m\lambda}{d}, \qquad m = 0, 1, 2, \qquad \textbf{(24-4)}$$



24.7 The Spectrometer and Spectroscopy

A spectrometer makes accurate measurements of wavelengths using a diffraction grating or prism.



24.7 The Spectrometer and Spectroscopy

The wavelength can be determined to high accuracy by measuring the angle at which the light is diffracted.

$$\lambda = \frac{d}{m}\sin\theta$$

Atoms and molecules can be identified when they are in a thin gas through their characteristic emission lines.

24.8 Interference by Thin Films

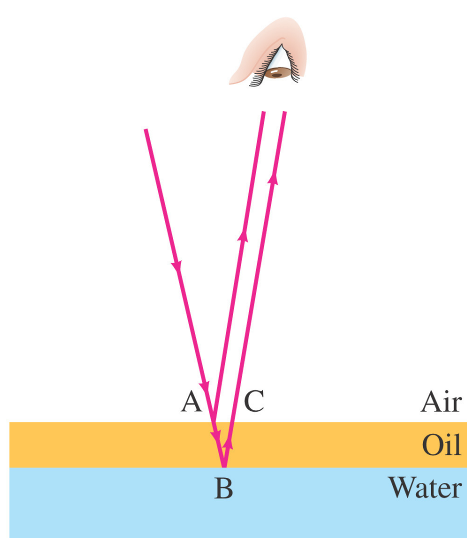
Another way path lengths can differ, and waves interfere, is if the travel through different media.

If there is a very thin film of material – a few wavelengths thick – light will reflect from both the bottom and the top of the layer, causing interference.

This can be seen in soap bubbles and oil slicks, for example.

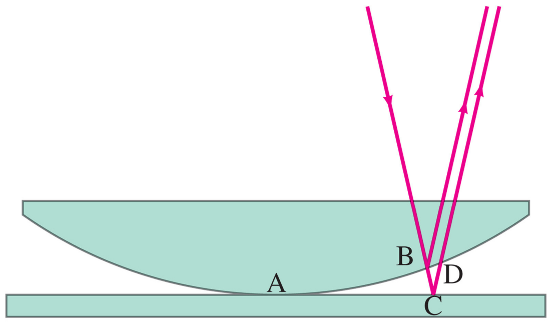
24.8 Interference by Thin Films

The wavelength of the light will be different in the oil and the air, and the reflections at points A and B may or may not involve reflection.



24.8 Interference by Thin Films

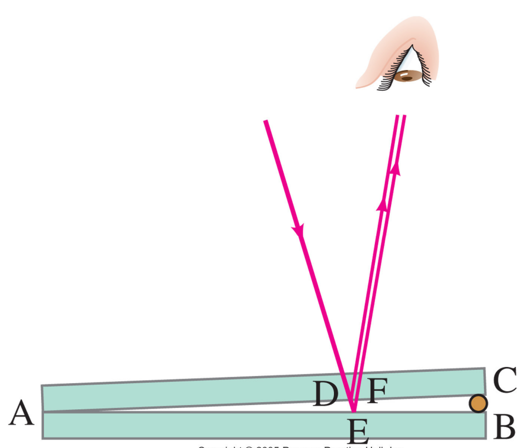
A similar effect takes place when a shallowly curved piece of glass is placed on a flat one. When viewed from above, concentric circles appear that are called Newton's rings.



(a)

24.8 Interference by Thin Films

One can also create a thin film of air by creating a wedge-shaped gap between two pieces of glass.



(a)

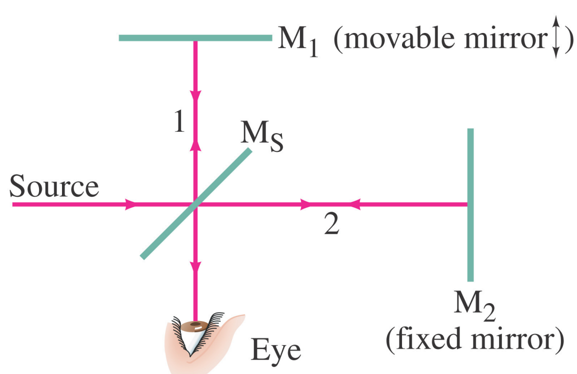
24.8 Interference by Thin Films

Problem Solving: Interference

1. Interference occurs when two or more waves arrive simultaneously at the same point in space.
2. Constructive interference occurs when the waves are in phase.
3. Destructive interference occurs when the waves are out of phase.
4. An extra half-wavelength shift occurs when light reflects from a medium with higher refractive index.

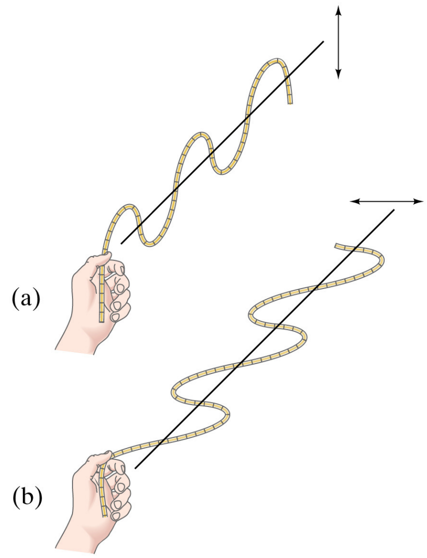
24.9 Michelson Interferometer

The Michelson interferometer is centered around a beam splitter, which transmits about half the light hitting it and reflects the rest. It can be a very sensitive measure of length.



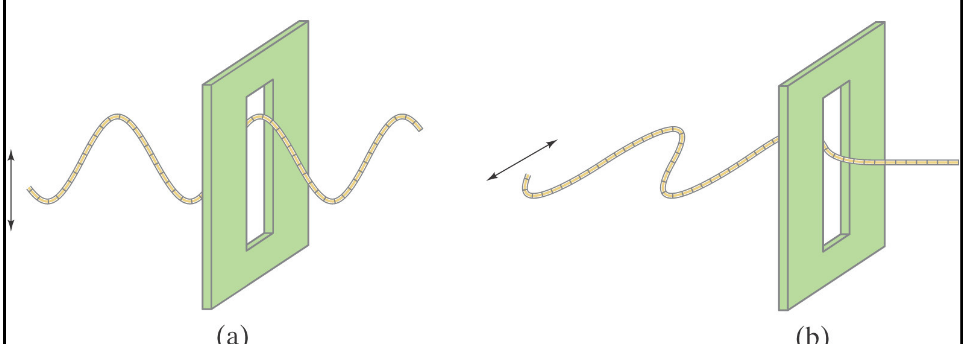
24.10 Polarization

Light is polarized when its electric fields oscillate in a single plane, rather than in any direction perpendicular to the direction of propagation.



24.10 Polarization

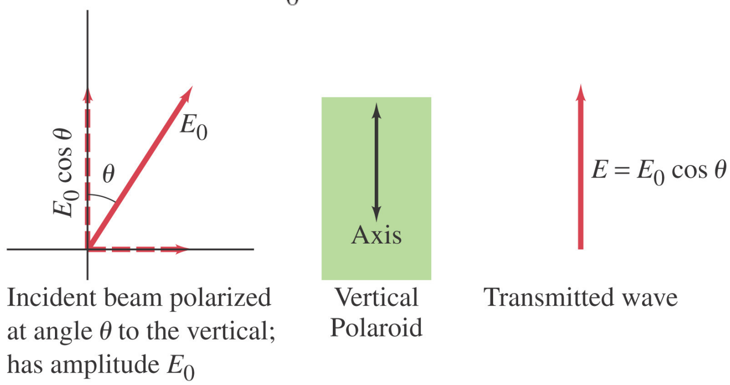
Polarized light will not be transmitted through a polarized film whose axis is perpendicular to the polarization direction.



24.10 Polarization

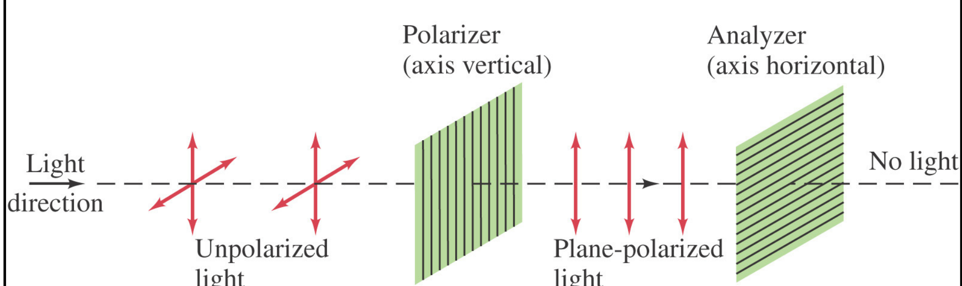
When light passes through a polarizer, only the component parallel to the polarization axis is transmitted. If the incoming light is plane-polarized, the outgoing intensity is:

$$I = I_0 \cos^2 \theta \qquad \text{(24-5)}$$



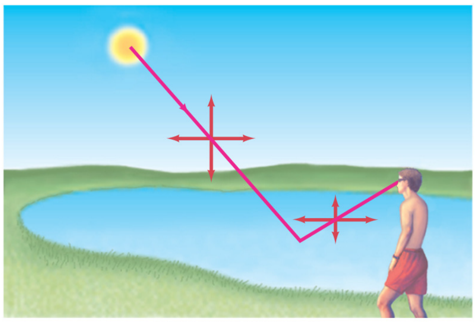
24.10 Polarization

This means that if initially unpolarized light passes through crossed polarizers, no light will get through the second one.



24.10 Polarization

Light is also partially polarized after reflecting from a nonmetallic surface. At a special angle, called the polarizing angle or Brewster's angle, the polarization is 100%.



$$\tan \theta_p = \frac{n_2}{n_1} \quad \text{(24-6a)}$$

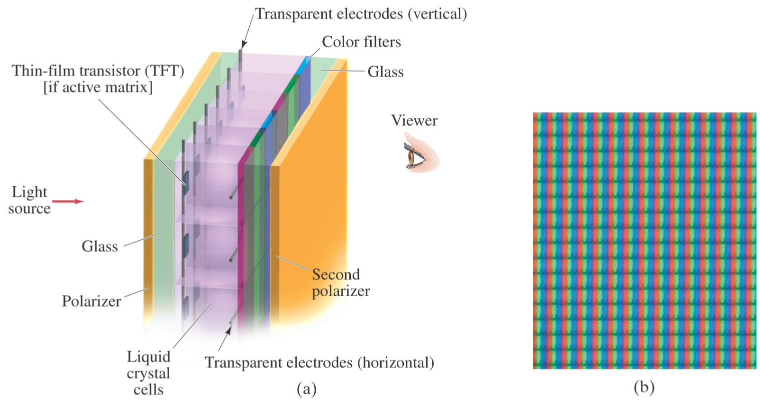
24.11 Liquid Crystal Displays (LCD)

Liquid crystals are unpolarized in the absence of an external voltage, and will easily transmit light. When an external voltage is applied, the crystals become polarized and no longer transmit; they appear dark.

Liquid crystals can be found in many familiar applications, such as calculators and digital watches.

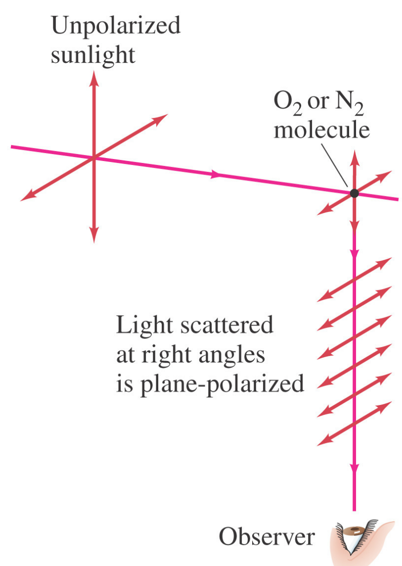
24.11 Liquid Crystal Displays (LCD)

Color LCD displays are more complicated; each pixel has three subpixels to provide the different colors. A source of light is behind the display (unlike calculators and watches, which use ambient light). The pixels must be able to make finer adjustments than just on and off to provide a clear image.



24.12 Scattering of Light by the Atmosphere

Skylight is partially polarized due to scattering from molecules in the air. The amount of polarization depends on the angle that your line of sight makes with the sun.



Summary of Chapter 24

• The wave theory of light is strengthened by the interference and diffraction of light

• Huygens' principle: every point on a wavefront is a source of spherical wavelets

• Wavelength of light in a medium with index of refraction n:

$$\lambda_n = \frac{\lambda}{n}$$

• Young's double-slit experiment demonstrated interference

Summary of Chapter 24

• In the double-slit experiment, constructive interference occurs when

$$\sin\theta = m\frac{\lambda}{d}$$

• and destructive interference when

$$\sin\theta = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{d}$$

• Two sources of light are coherent if they have the same frequency and maintain the same phase relationship

Summary of Chapter 24

• Visible spectrum of light ranges from 400 nm to 750 nm (approximately)

• Index of refraction varies with wavelength, leading to dispersion

• Diffraction grating has many small slits or lines, and the same condition for constructive interference

• Wavelength can be measured precisely with a spectroscope

Summary of Chapter 24

• Light bends around obstacles and openings in its path, yielding diffraction patterns

• Light passing through a narrow slit will produce a central bright maximum of width

$$\sin\theta = \frac{\lambda}{D}$$

• Interference can occur between reflections from the front and back surfaces of a thin film

• Light whose electric fields are all in the same plane is called plane polarized

Summary of Chapter 24

- **The intensity of plane polarized light is reduced after it passes through another polarizer:**

$$I = I_0 \cos^2 \theta$$

- **Light can also be polarized by reflection; it is completely polarized when the reflection angle is the polarization angle:**

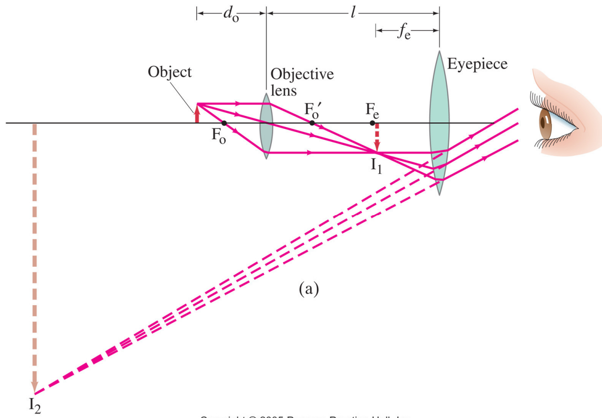
$$\tan \theta_p = n$$

Homework

- Chp 24 Problems: # 5, 9, 15, 23, 29, 41

Chapter 25

Optical Instruments



Units of Chapter 25

- Cameras, Film, and Digital
- The Human Eye; Corrective Lenses
- Magnifying Glass
- Telescopes
- Compound Microscope
- Aberrations of Lenses and Mirrors

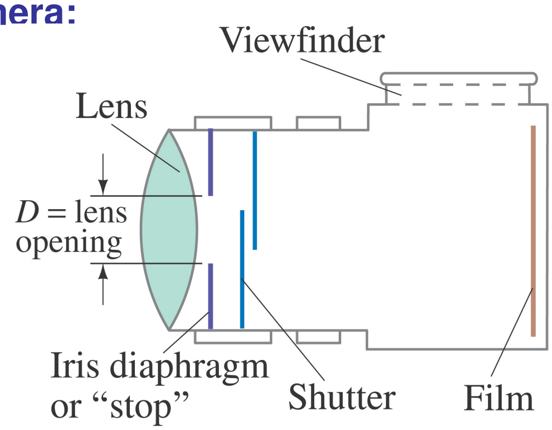
Units of Chapter 25

- Resolution of the Human Eye and Useful Magnification
- Specialty Microscopes and Contrast
- X-Rays and X-Ray Diffraction
- X-Ray Imaging and Computed Tomography (CT Scan)

25.1 Cameras, Film, and Digital

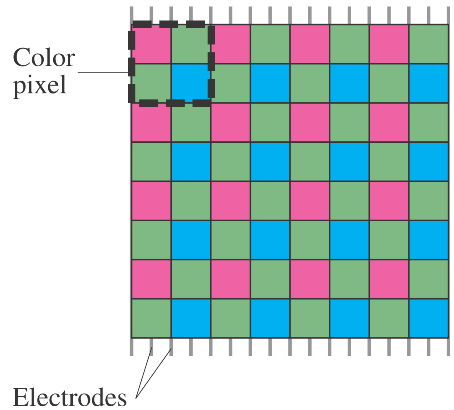
Basic parts of a camera:

- Lens
- Light-tight box
- Shutter
- Film or electronic sensor



25.1 Cameras, Film, and Digital

A digital camera uses CCD sensors instead of film. The digitized image is sent to a processor for storage and later retrieval.



25.1 Cameras, Film, and Digital

Camera adjustments:

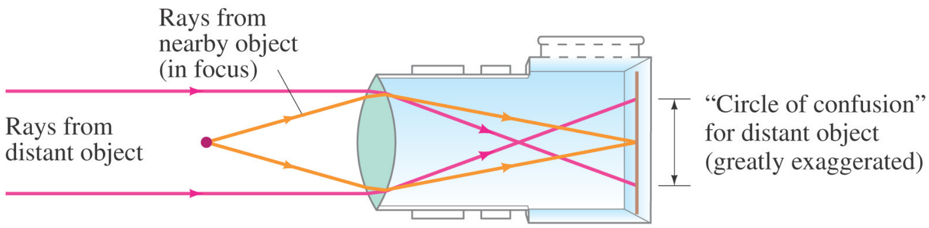
• Shutter speed: controls the amount of time light enters the camera. A faster shutter speed makes a sharper picture.

• f-stop: controls the maximum opening of the shutter. This allows the right amount of light to enter to properly expose the film, and must be adjusted for external light conditions.

• Focusing: this adjusts the position of the lens so that the image is positioned on the film.

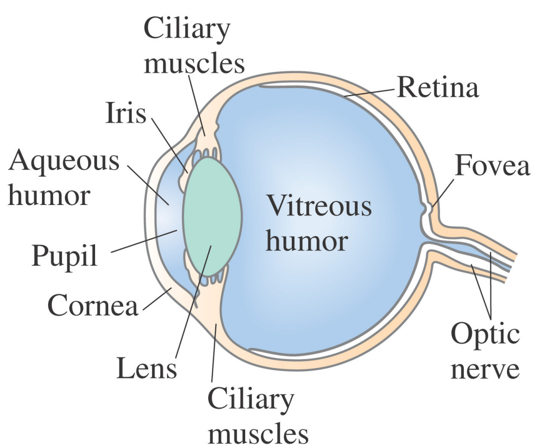
25.1 Cameras, Film, and Digital

There is a certain range of distances over which objects will be in focus; this is called the depth of field of the lens. Objects closer or farther will be blurred.



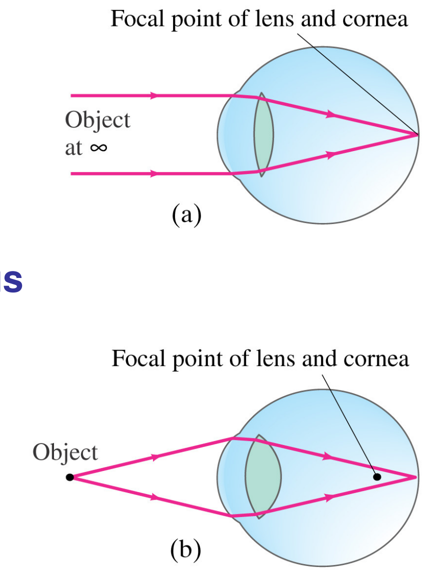
25.2 The Human Eye; Corrective Lenses

The human eye resembles a camera in its basic functioning, with an adjustable lens, the iris, and the retina.



25.2 The Human Eye; Corrective Lenses

Most of the refraction is done at the surface of the cornea; the lens makes small adjustments to focus at different distances.



25.2 The Human Eye; Corrective Lenses

Near point: closest distance at which eye can focus clearly. Normal is about 25 cm.

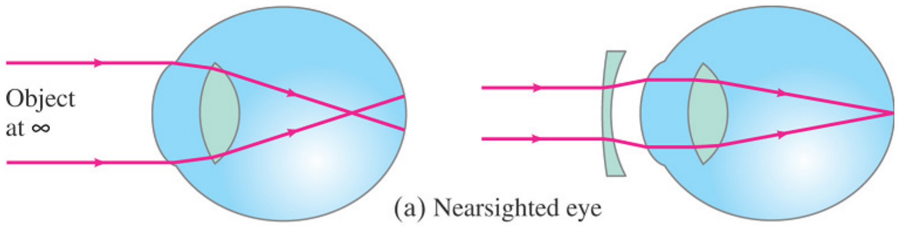
Far point: farthest distance at which object can be seen clearly. Normal is at infinity.

Nearsightedness: far point is too close.

Farsightedness: near point is too far away.

25.2 The Human Eye; Corrective Lenses

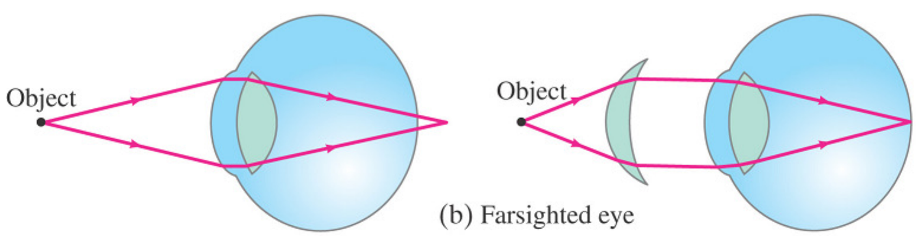
Nearsightedness can be corrected with a diverging lens.



(a) Nearsighted eye

25.2 The Human Eye; Corrective Lenses

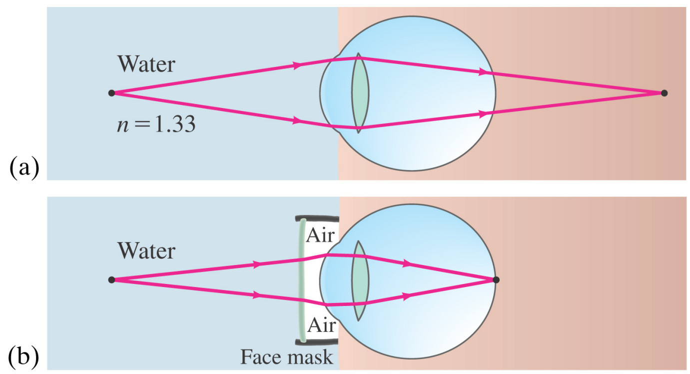
And farsightedness with a diverging lens.



(b) Farsighted eye

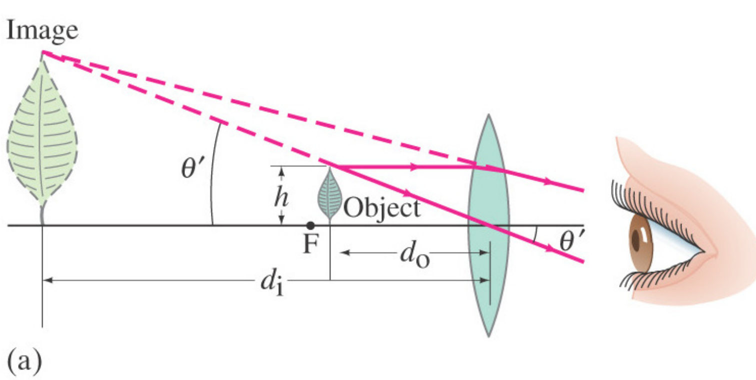
25.2 The Human Eye; Corrective Lenses

Vision is blurry underwater because light rays are bent much less than they would be if entering the eye from air. This can be avoided by wearing goggles.



25.3 Magnifying Glass

A magnifying glass (simple magnifier) is a converging lens. It allows us to focus on objects closer than the near point, so that they make a larger, and therefore clearer, image on the retina.



25.3 Magnifying Glass

The power of a magnifying glass is described by its angular magnification:

$$M = \frac{\theta'}{\theta} \qquad \text{(25-1)}$$

If the eye is relaxed (N is the near point distance and f the focal length):

$$M = \frac{\theta'}{\theta} = \frac{h/f}{h/N} = \frac{N}{f} \qquad \text{(25-2a)}$$

If the eye is focused at the near point:

$$M = \frac{N}{f} + 1 \qquad \text{(25-2b)}$$

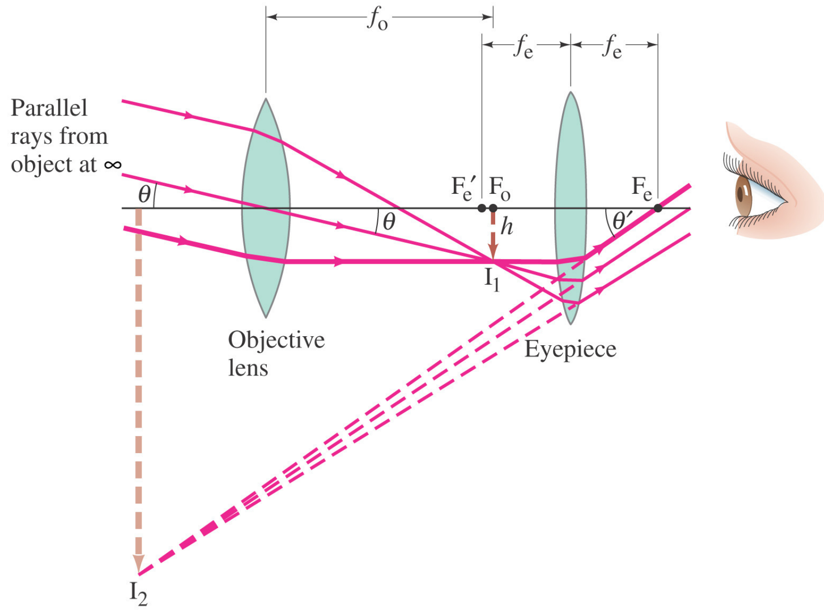
25.4 Telescopes

A refracting telescope consists of two lenses at opposite ends of a long tube. The objective lens is closest to the object, and the eyepiece is closest to the eye.

The magnification is given by:

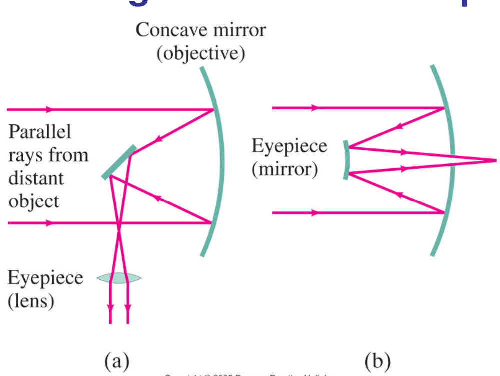
$$M = \frac{\theta'}{\theta} = \frac{(h/f_e)}{(h/f_o)} = -\frac{f_o}{f_e} \qquad \text{(25-3)}$$

25.4 Telescopes



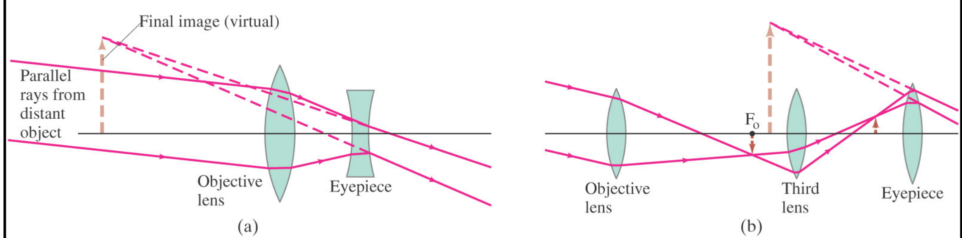
25.4 Telescopes

Astronomical telescopes need to gather as much light as possible, meaning that the objective must be as large as possible. Hence, mirrors are used instead of lenses, as they can be made much larger and with more precision.



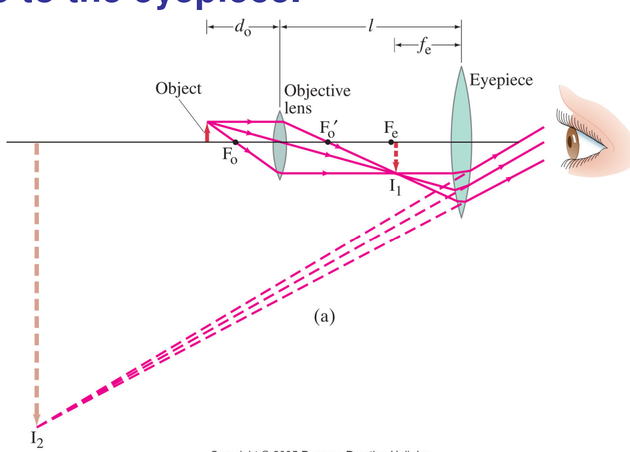
25.4 Telescopes

A terrestrial telescope, used for viewing objects on Earth, should produce an upright image. Here are two models, a Galilean type and a spyglass:



25.5 Compound Microscope

A compound microscope also has an objective and an eyepiece; it is different from a telescope in that the object is placed very close to the eyepiece.



25.5 Compound Microscope

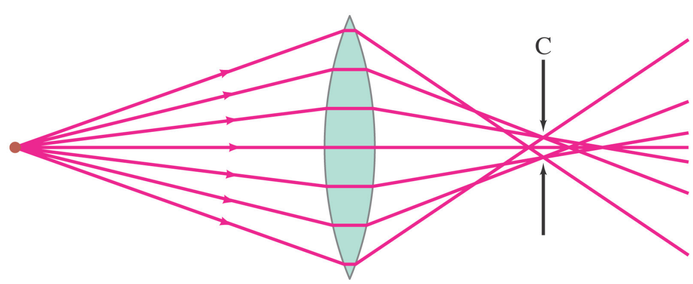
The magnification is given by:

$$M = M_e m_o = \left(\frac{N}{f_e}\right)\left(\frac{l - f_e}{d_o}\right) \qquad \text{(25-6a)}$$

$$\approx \frac{Nl}{f_e f_o}. \qquad [f_o \text{ and } f_e \ll l] \qquad \text{(25-6b)}$$

25.6 Aberrations of Lenses and Mirrors

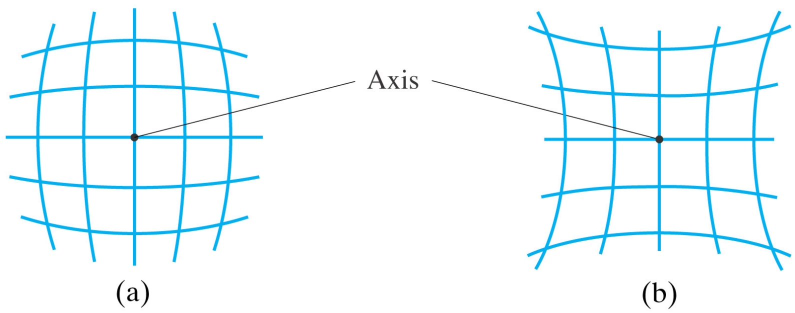
Spherical aberration: rays far from the lens axis do not focus at the focal point.



Solutions: compound-lens systems; use only central part of lens

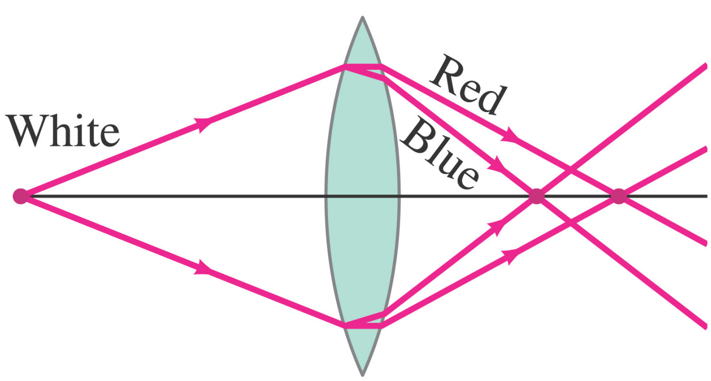
25.6 Aberrations of Lenses and Mirrors

Distortion: caused by variation in magnification with distance from the lens. Barrel and pincushion distortion:



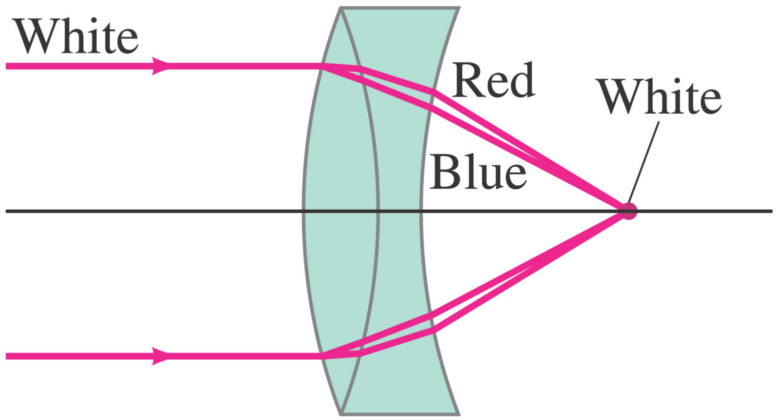
25.6 Aberrations of Lenses and Mirrors

Chromatic aberration: light of different wavelengths has different indices of refraction and focuses at different points



25.6 Aberrations of Lenses and Mirrors

Solution: Achromatic doublet, made of lenses of two different materials



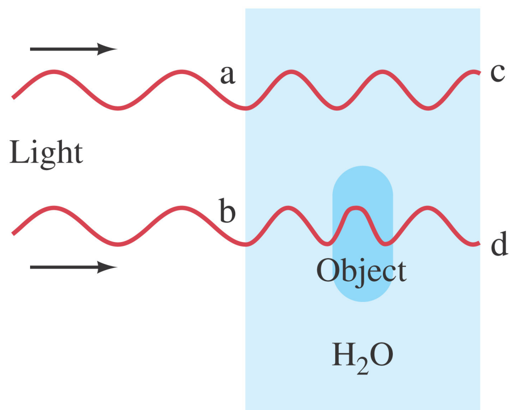
25.9 Resolution of the Human Eye and Useful Magnification

The human eye can resolve objects that are about 1 cm apart at a distance of 20 m, or 0.1 mm apart at the near point.

This limits the useful magnification of a light microscope to about 500x – 1000x.

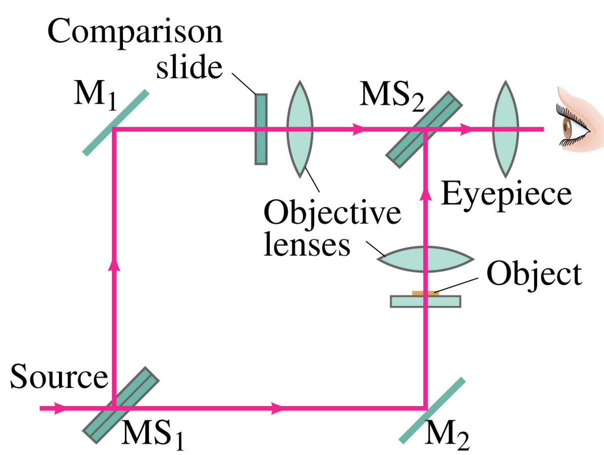
25.10 Specialty Microscopes and Contrast

In addition to sufficient resolving power, a microscope must be able to distinguish the object from its background.



25.10 Specialty Microscopes and Contrast

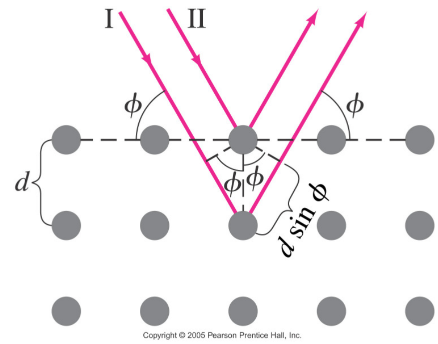
One way to do this is by using an interference microscope, which can detect objects by the change in wavelength as the light passes through them.



25.11 X-Rays and X-Ray Diffraction

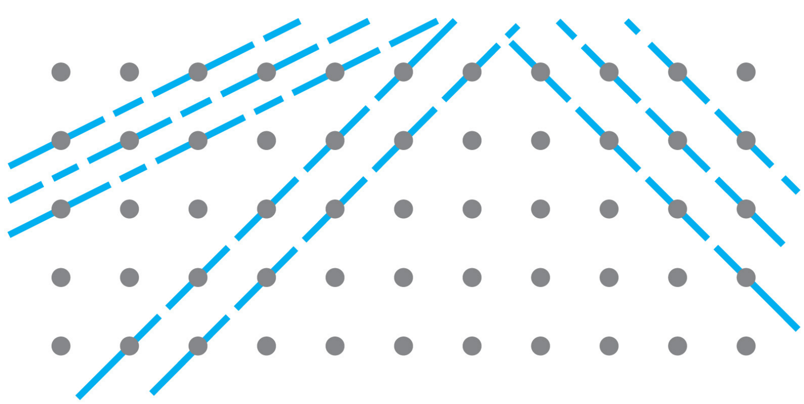
The wavelengths of X-rays are very short. Diffraction experiments are impossible to do with conventional diffraction gratings.

Crystals have spacing between their layers that is ideal for diffracting X-rays:



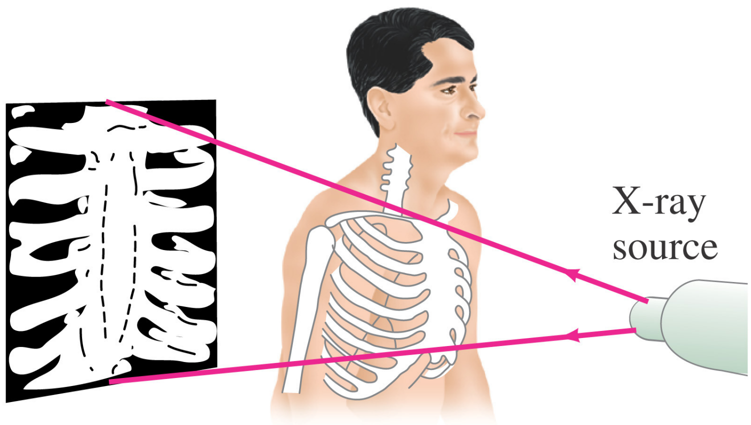
25.11 X-Rays and X-Ray Diffraction

X-ray diffraction is now used to study the internal structure of crystals; this is how the helical structure of DNA was determined.



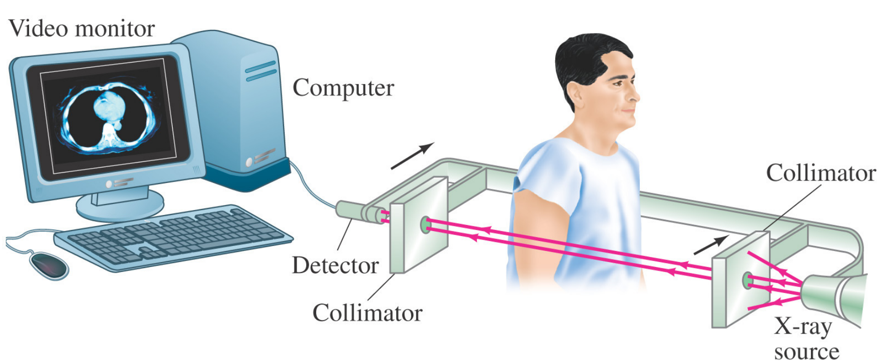
25.12 X-Ray Imaging and Computed Tomography (CT Scan)

A conventional X-ray is essentially a shadow; there are no lenses involved.



25.12 X-Ray Imaging and Computed Tomography (CT Scan)

Computed tomography uses a narrow beam of X-rays, and takes measurements at many different angles. The measurements are sent to a computer, which combines them into a detailed image.



Summary of Chapter 25

- Camera lens forms image by letting light through a shutter; can be adjusted for different light levels using f-stop and focused by moving lens
- Human eye forms image by letting light through pupil; adjusts to different light levels using iris and focuses by changing thickness of lens
- Nearsighted vision is corrected by diverging lens, farsighted by converging

Summary of Chapter 25

- Simple magnifier: object at focal point
- Angular modification:

$$M = \frac{N}{f}$$

- Astronomical telescope: objective and eyepiece; object infinitely far away
- Magnification:

$$M = -\frac{f_o}{f_e}$$

Summary of Chapter 25

• Spherical aberration: rays far from axis do not go through focal point

• Chromatic aberration: different wavelengths have different focal points

• Resolution of optical devices is limited by diffraction

Homework

• Chp 25 Problems: # 7, 15, 23, 33, 41